On the interplay between MHD instabilities and turbulent transport in magnetically confined plasmas

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Abstract
The interplay between MHD and turbulence is an interesting topic in magnetically confined plasma and solar plasma. The experimental observations made recently, shown below, suggest coupling and interplay between MHD and turbulence in magnetically confined toroidal plasmas. (1) Turbulence spreading into the magnetic island, (2) there is a self-organized change in topology and turbulence in the magnetic island, (3) the flow is damped by a stochastic magnetic field, (4) the trigger mechanism for the MHD bursts, (5) MHD bursts have an impact on the ion velocity distribution and potential, and (6) turbulence exhausts are created at the MHD burst event. In this paper, experimental evidence for the interplay between MHD and turbulence in toroidal plasmas is reviewed. The physics mechanism of the interplay and a possible link to astrophysical plasma physics are also discussed.

Keywords: turbulence, MHD, interplay, plasma

(Some figures may appear in colour only in the online journal)

1. Introduction
The interplay between MHD and turbulence is an interesting topic in magnetically confined plasma and solar plasma research. The fast reconnection of magnetic fields in solar flares is well known; however, the mechanism is not fully understood. Turbulence in the current sheet is a strong candidate for explaining fast reconnection in solar flares [1, 2]. In magnetically confined plasmas, MHD instabilities and electrostatic turbulence have been investigated independently. No coupling between the electrostatic turbulence and MHD instability is assumed.

However, recent experimental observations, shown below, suggest coupling and interplay between MHD and turbulence in magnetically confined toroidal plasmas [3], turbulence spreads into the magnetic island [4]. There is a self-organized change in topology and turbulence in the magnetic island [5], the flow is damped by a stochastic magnetic field [6], the trigger mechanism for the MHD bursts [7], the MHD bursts have an impact on the ion velocity distribution and potential [8, 9], and turbulence exhausts are created at the MHD burst event [10]. Evidence for the interplay between MHD and turbulence in toroidal plasma is reviewed and the physics mechanism of the interplay is also discussed in section 2. For example, in the heat pulse experiment in the DIII-D tokamak plasma, the turbulence increase occurs after the arrival of the heat pulse with a significant delay at the X-point, while it occurs before the radial propagation of the heat pulse at the O-point of the magnetic island. This is due to the turbulence spreading from the X-point to the O-point of the magnetic island faster than the heat pulse, determined by the transport time scale inside the magnetic island. In the D-IIID tokamak, two states of magnetic islands are observed. The ‘high-accessibility’ state is when the heat pulse propagating from outside a magnetic island can penetrate the magnetic island, while the ‘low-accessibility’ state is when penetration of the heat pulse into the magnetic island is prevented at the boundary. Oscillations between these states are self-regulated and the change in magnetic topology, such as the stochasticization of the magnetic field at the boundary of the magnetic island, is one possible

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MHD instability causes a change of magnetic topology in the plasma. The magnetic island and the stochastic magnetic field are topology effects commonly observed in a toroidal plasma. The oscillations are observed in the magnetic probe signal or temperature due to the plasma rotation. The oscillation frequency is finite in the laboratory frame but zero in the plasma frame. Therefore, when the plasma does not have rotations, the oscillations owing to this topology effect disappear. In contrast, the MHD has a characteristic magnetic field oscillation frequency in the plasma frame and sometimes grows nonlinearly, triggering the collapse of the plasma. Energetic-particle-driven modes, edge-localized mode (ELM), the sawtooth crash and disruptions are included in this category.

2. Interplay between turbulence and topology

2.1. Turbulence spreading into magnetic island

In the local transport model, the turbulence level in the plasma is assumed to be determined by the local plasma parameters such as temperature and density, their gradients, the magnetic field and the potential structure (the magnetic shear and radial electric field shear). However, various nonlocal phenomena that cannot be explained by the local transport model have been observed in experiments in toroidal plasma [15]. These experimental results are evidence that the local closure of the flux-gradient (turbulence-gradient) relation has been violated. Several of the mechanisms causing the violation of these relations have been proposed in theory. The coupling between the turbulence of meso- or long-range correlation and micro turbulence have been proposed to explain the strong core-edge coupling of turbulence and transport observed in experiment. In the avalanche model, the strong nonlinearity of the growth rate of micro-scale turbulence can cause the simultaneous fast radial propagation of both micro-turbulence and gradients, and consequently in ballistic transport and super diffusion. Turbulence coupling and turbulence spreading are the most likely mechanisms to cause nonlocal transport. It was recently shown that turbulence spreading from the pedestal region to the scrape off layer (SOL) is expected to be beneficial in broadening the SOL power decay length [16–21]. Therefore, the experimental identification of turbulence spreading becomes one of the crucial issues in edge transport.

In spite of the importance of turbulence spreading, there are only a few measurements on turbulence. This is because the separation of the turbulence origin (spreading turbulence and locally driven turbulence) is impossible in the usual turbulence measurements. The novel analysis of turbulence to distinguish its origin from the modulation of bias was reported in TJ-II. The time evolution of free turbulent energy \( \langle \tilde{v}^2 \rangle \) (where \( \hat{n} = n - \langle n \rangle \) is obtained from the radial part of the continuity equation by neglecting cross-field coupling and damping as well as the effect of background flows as [22]

\[
\frac{1}{2} \frac{\partial}{\partial t} \langle \tilde{v}^2 \rangle = \langle \frac{\partial n}{\partial r} \rangle \langle \tilde{v} \tilde{n} \rangle - \frac{1}{2} \frac{\partial}{\partial r} \langle \tilde{v} \tilde{n} \rangle. \tag{1}
\]
The angular brackets $\langle \ldots \rangle$ indicate a running average over a time interval much larger than the turbulence correlation time. The first term is a product of the turbulent particle flux and density gradient and the second term is the diffusion of turbulent energy. With the normalization of the local turbulence amplitude, $\langle \tilde{n}^2 \rangle$, two rates of turbulence are defined. One is the rate of turbulence drive due to the density gradient as

$$\omega_D = -2 \left[ \frac{\partial}{\partial r} \langle \tilde{n} \tilde{r} \rangle \right] / \langle \tilde{n}^2 \rangle$$

(2)

and the other is the rate of turbulence spreading due to the turbulence intensity gradient as

$$\omega_S = -\frac{\partial}{\partial r} \langle \tilde{v} \tilde{n}^2 \rangle / \langle \tilde{n}^2 \rangle$$

(3).

These two quantities have quite a different response to edge biasing as seen in figure 2. The negative edge bias of the voltage of $-380$ V and the modulation frequency of $40$ Hz during the discharge (bias is off-on-off-on-off, about 1180–1240 ms). The rate of turbulence locally driven, $\omega_D$ inside LCFS ($r < r_0$), is significantly reduced during the on phase of edge biasing, while the reduction of the rate outside LCFS ($r > r_0$) is moderate. In contrast, the rate of the turbulence spreading, $\omega_S$ is significant outside LCFS ($r > r_0$), although there is almost no impact inside LCFS ($r < r_0$). The experimental data clearly shows the locally driven turbulence is suppressed at the plasma edge by the $E \times B$ shear produced by edge biasing, while the turbulence spreading observed in the SOL region is suppressed by $E \times B$ shear at the plasma boundary. This experiment suggests that the $E \times B$ flow shear suppresses the turbulence spreading from the core to the SOL.

The other approach to identify spreading turbulence is the measurement of the turbulence response in the region where the local driven turbulence is expected to be small. The magnetic island is an ideal region for spreading turbulence because there should be no driven turbulence inside the large magnetic island in which the temperature and the density flattening region are larger than the correlation length of micro-turbulence. Magnetic islands define a unique region in the plasma because the temperature and density gradients which drive the turbulence are much weaker inside than outside the magnetic island [23]. Since the heat propagation inside the magnetic island is relatively slow [24, 25], turbulence can propagate faster than the heat pulse if there is turbulence spreading [26, 27] from the X-point (or boundary) to the O-point of the magnetic island. In order to identify the spreading turbulence, the phase relation between the micro turbulence intensity measured with beam emission spectroscopy (BES [28, 29]) and the electron temperature measured with electron cyclotron emission (ECE) was investigated in the X-point and the O-point of the magnetic island in the heat pulse experiment produced by modulated electron cyclotron heating (MECH) in DIII-D [4]. Figures 3(a)–(d) show the time evolution of the perturbation of the electron temperature and density fluctuation intensity at the X-point and O-point of the magnetic island. In this experiment, the heat pulse propagates into magnetic islands. The modulation frequency is $50$ Hz and the density turbulence intensity measured with BES is integrated in the frequency range of $10–50$ kHz. At the X-point of the magnetic island, the delay time of the density fluctuation modulation with respect to the electron temperature modulation is positive. The heat pulse perturbation reaches the X-point before the density fluctuation perturbation. In contrast, the
delay time of the density fluctuation modulation with respect to the electron temperature modulation is negative at the O-point of the magnetic island, which indicates that the density fluctuation perturbation reaches the O-point before the heat pulse perturbation. As seen in figure 3(c), the negative delay time is observed in the low-field side of the O-point of the magnetic island ($R > R_{O\text{-point}}$), where the heat pulse propagates inward from the boundary to the O-point of the magnetic island.

Poincaré maps of the magnetic field at the X-point and O-point of the magnetic island, as well as the direction of heat pulse propagation and density fluctuation propagation indicated with arrows, are plotted in figure 4. Here, the perturbation fields are calculated using the Fourier analysis module in the trip3d code [30]. In general, the electron temperature becomes constant on a magnetic flux surface because the propagation speed of heat pulse parallel to the magnetic field is an order of the electron thermal velocity and much higher than the propagation speed perpendicular to the magnetic field. In contrast, the density fluctuation is not constant on a magnetic flux surface and has poloidal asymmetry. In the normal nested magnetic flux surface, the radial propagation speed of the heat pulse is equal to that of the density fluctuation. However, near the X-point of the magnetic island, the effective radial propagation speed of the heat pulse (the projection of parallel heat pulse propagation to the radial direction) becomes much higher than the speed of the density fluctuation propagating across the magnetic flux surface. Therefore, the heat pulse propagates to the X-point of the magnetic island before the turbulence. In the O-point, the heat pulse propagates from the boundary of the magnetic island of the O-point slowly due to the low level of fluctuation inside the magnetic island (due to the lack of locally driven turbulence). However, turbulence propagating from the X-point to the O-point is faster than the heat pulse and causes a negative turbulence perturbation delay time (turbulence increases before the heat pulse). This is clear evidence of turbulence propagation from the X-point to the O-point of the magnetic island.

2.2. Bifurcation of turbulence spreading at the boundary of the magnetic island

The amount of heat flux propagating through the X-point or O-point depends on the velocity of heat pulse propagation at the X-point or O-point region. As the heat pulse propagation becomes slow inside the magnetic island (O-point), the modulation amplitude decreases. Because the heat pulse propagates at the boundary of the O-point, the delay time of the heat pulse peaks at the O-point of the magnetic island [5]. There is a clear relation between the propagation speed (delay time) and a reduction of the modulation amplitude [31]. A large reduction of the modulation amplitude is a result of gradual heat pulse propagation due to the low turbulence level. Therefore, by measuring the modulation amplitude at the O-point of the magnetic island, one can estimate the level of transport and turbulence inside the magnetic island.

The time evolutions of the electron temperature measured with ECE at the O-point phase and the X-point phase of the magnetic island in DIII-D are plotted in figure 5. In this experiment, the toroidal phase of the resonant magnetic field perturbation (RMP) is flipped by 180 degrees during the discharge. Here, the O-point (X-point) phase stands for the phase when the O-point (X-point) of the magnetic island is located at the toroidal location of the ECE measurements. The heat pulse is produced by the modulation ECH and the modulation amplitude of the heat pulse is evaluated by ECE measurements. As seen in figure 5, the modulation amplitude at the X-point phase is larger than the modulation amplitude at the O-point phase. In the O-point phase, the flattening of the electron temperature is observed near 0.4 keV. There is periodic change in the modulation amplitude in the O-point phase, which shows that the reduction of the modulation amplitude is oscillating. One is a phase with a moderate reduction of modulation amplitude and the other has a significant reduction of modulation amplitude. The former is called a high-accessibility heat pulse state and the latter is called a low-accessibility heat pulse state.

Figures 5(b), (c) show the contour of the electron temperature modulation amplitude in time and space at the transition: (b) from high to low accessibility states, and (c) from low to high accessibility states. In the high accessibility states, the modulation amplitude gradually decreases from the boundary of the magnetic island ($\rho = 0.64$ and $\rho = 0.8$) to the O-point ($\rho = 0.72$) of the magnetic island. In contrast, the modulation amplitude sharply drops to a low level (1% of temperature). The time scale of the transition from high accessibility states to low accessibility states is 4 ms and the back transition from high to low accessibility states is 7 ms.

In general, a magnetic island is surrounded by a layer of stochastic magnetic field. Stochasticization of the magnetic field, i.e., magnetic braiding or the appearance of the secondary magnetic island [32–35], can occur when the island
size reaches a critical value. The width of the magnetic island in DIII-D is 15% of the minor radius and large enough to expect the appearance of a stochastic layer surrounding the magnetic island. When the stochastic layer surrounding the magnetic island appears, the second derivative of temperature decreases due to the enhancement of the effective radial transport. Since the $E \times B$ flow shear is roughly proportional to the second derivative of temperature, the $E \times B$ flow shear decreases with the appearance of a stochastic layer. Because the $E \times B$ flow shear plays an important role in preventing the turbulence spreading, the stochasticisation of the field outside the island should increase the rate of turbulence spreading into the island. Therefore, the change of the stochastic layer surrounding the magnetic island is a candidate for the bifurcation of the turbulence spreading state inside the magnetic island. Figure 6 shows a possible image of the electron temperature profile at the X-point and O-point of the magnetic island to explain the bifurcation of the high and low accessibility states of the magnetic island.

The width of the stochastic region at the boundary of the magnetic island except for the X-point region is smaller than the correlation length of the turbulence. However, at the X-point, the width of the stochastic region can be larger than the correlation length of the turbulence and should also have an impact on the turbulence. The suppression of turbulence spreading results in an increase of the second derivative of temperature (sharp boundary of magnetic island) and the narrow width of the stochastic region ($W_s$) at the X-point. The increase of the second derivative of the temperature ($\partial^2 T / \partial r^2$) contributes to the enhancement of the $E \times B$ flow and causes positive feedback. The reduction of the stochastic region width at the X-point of the magnetic island contributes to the reduction of turbulence spreading (narrow turbulence spreading window) from the X-point to the O-point of the magnetic island. Therefore, the low accessibility state is characterized by a strong $E \times B$ shear, a sharp boundary (large $\partial^2 T / \partial r^2$), and a narrow stochastic region (small $W_s$) at the X-point of the magnetic island (turbulence shielding state). In contrast, the high accessibility state is characterized by weak $E \times B$ shear, a broad boundary (small $\partial^2 T / \partial r^2$), and a wide stochastic region (large $W_s$) at the X-point of the magnetic island (turbulence penetration state). These two

![Figure 5](image_url)

**Figure 5.** (a) Time evolution of the electron temperature measured with the ECE at the O-point phase and the X-point phase of the magnetic island, and the contour of the electron temperature modulation amplitude in time and space at the transition: (b) from high to low accessibility states, and (c) from low to high accessibility states in DIII-D (Reproduced from [5], CC BY 4.0).
2.3. Flow damping due to stochastic magnetic field

Because the interplay between the stochastic magnetic field and plasma flow is important, how the stochastic magnetic field affects the plasma flow is an interesting issue. A helio-
tron plasma has a significant advantage in this study, because a large stochastic region up to 60% of the plasma minor radius can be produced in the plasma core without a disruption. In general, the magnetic flux surface becomes nested when the magnetic shear is large enough, while the magnetic flux surface becomes dominated by the lowest order magnetic island (e.g. 2/1 for $\eta = 0.5$) when the magnetic shear is small. Therefore, the control of the magnetic shear is key to pro-
ducing a large region with a stochastic magnetic field near a rational surface. Tangential neutral beams have been widely used as a convenient noninductive current drive tool in tor-
odal plasma, which is called the neutral beam current drive (NBCD). Because of the conservation of poloidal flux linking the plasma, the total current can only change on a resistive time scale. Therefore, when the NBI drives current to the plasma edge, this must induce a loop voltage that drives a compensating current in the opposite direction in the plasma core. In the high-temperature plasma, this compensating current can exceed the noninductive current by the NBCD locally, especially in the case of the off-axis NBCD. In LHD, this compensating current in the opposite direction becomes large enough to change the rotational transform, $\iota$, in the direction opposite to NBCD (e.g. decrease $\iota$ for co-NBCD and increase $\iota$ for counter-NBCD) near the magnetic axis in the discharge where the direction of the off-axis NBCD is exchanged in the middle of the discharge. The exchange of the NBCD in the opposite direction with each other (the NBCD direction switch) has been used to change the magnetic shear at half the radius of the plasma in LHD [38]. When the direction of the NBCD is switched from the co-direction (parallel to equivalent plasma current direction) to the count-
deriction (anti-parallel to equivalent plasma current direction), the edge $\iota$ decreases due to the counter NBCD, but the central $\iota$ increases due to the inductive current. Then the magnetic shear at half of the plasma minor radius decreases after the beam switch from co- to counter-NBCD.

Toroidal flow velocities at $r_{\text{eff}}/a_{99} = 0$, 0.25, 0.5 show an abrupt drop to almost zero after the magnetic shear at the rational surface of $\iota = 0.5$ at $r_{\text{eff}}/a_{99}$ decreases to $\sim 0.5$ as seen in figure 7 [6]. The magnetic shear at the rational surface of $\iota = 0.5$ decreases from 1.2 to 0.5 after the beam switch from co-NBI to counter-NBI in the $t = 5.3$ section. The magnetic shear is kept constant at 0.5 after $t = 5.8$ s and an abrupt drop of the toroidal rotation velocity is observed in the $t = 6.0$ section. The heat pulse propagation technique is used to determine the magnetic topology. A monotonic increase in the delay time of the heat pulse at $t = 5.75$ s shows that the magnetic flux surface is nested before an abrupt drop of the toroidal rotation velocity (flow damping). During the phase of flow damping, the delay time of the heat pulse shows a very large flattening region, flat up to $r_{\text{eff}}/a_{99} = 0.6$, which indicates that the magnetic flux surface in the core becomes stochastic [39, 40]. Later in the discharge, the toroidal rotation velocity begins to increase after $t = 6.7$ s and partially recovers. The radial profile of the heat pulse delay time peaks at the rational surface ($r_{\text{eff}}/a_{99} = 0.5$), which indicates the disappearance of a stochastic magnetic field region and the appearance of a magnetic island.

Figure 7(c) shows the radial profile of the onset of stochastization of the magnetic field. The stochastization of the magnetic field is initiated at the rational surface of $\iota = 0.5$ located at $r_{\text{eff}}/a_{99} = 0.5$. The region of the stochastic magnetic field expands both inward and outward, and the region of the stochastic magnetic becomes 20% of the minor radius in 10 ms, which is called partial stochastization. The outward propagation of the stochastic magnetic field stops at $r_{\text{eff}}/a_{99} = 0.6$ due to the higher magnetic shear towards the

Figure 7. The time evolution of (a) the toroidal flow velocity at $r_{\text{eff}}/a_{99} = 0$, 0.25, 0.5, (b) the magnetic shear at the rational surface of $\iota = 0.5$ at $r_{\text{eff}}/a_{99} \sim 0.5$, the radial profile of (c) the onset of stochastization of the magnetic field, and (d) the radial electric field in LHD (Reproduced from [6]. CC BY 4.0).
plasma periphery. However, the inward propagation of the stochastic magnetic field continues until the stochastic magnetic field region expands to the magnetic axis in 40 ms, which is called a full stochastization.

Figure 7(d) shows the radial profile of a radial electric field before stochastization (with a nested magnetic flux surface) and after the stochastization of magnetic field. The positive radial electric field in the core region \( \left( r_{\text{eff}}/\theta_{\text{gyr}} < 0.4 \right) \) decreases and the negative radial electric field outside this region increases after stochastization of the magnetic field. The change in the radial electric field is more significant near the rational surface, where the dominant modes are resonant, while the flattening of the electron temperature is observed in the whole core region. This observation is consistent with the fact that the transport enhancement due to the stochastization of magnetic field is ambipolar, except for the region near locations where the dominant modes are resonant \([41]\).

The radial propagation of stochastic magnetic field is considered to be due to the consequence of interplay between stochastization and plasma flow damping. The stochastization of the magnetic field causes strong flow damping. The plasma flow is also expected to play a role in preventing the magnetic field from becoming stochastic. Therefore, once the plasma flow starts to decrease due to enhanced damping from stochastization, the region of flow damping and stochastization expands due to the positive feedback until the stochastic region reaches the plasma axis. In contrast, when the stochastic region starts to shrink, the plasma flow recovers due to the external torque input. The stochastic region disappears and the magnetic island appears or is completely healed (stochastization healing \([42]\)).

3. Interplay between turbulence and MHD

Energetic particle-driven MHD instabilities have been studied intensively in nuclear fusion research \([43–46]\). MHD instability driven by energetic particles often shows nonlinear characteristics and can cause a minor collapse of the helical plasma \([47, 48]\). In LHD, various MHD instabilities driven by energetic particles are observed when high-power neutral beams (∼30 MW) are injected into a low-density (∼1 × 10^{19} \text{ m}^{-3}) target plasma \([49, 50]\). The minor collapse of the plasma associated with the burst of oscillation of the magnetic field observed with magnetic probe arrays is characterized by the sudden decrease of the neutron emission rate, central ion temperature, and kinetic energy of the plasma \([51, 52]\).

3.1. Energetic particle-driven MHD collapse

Toroidal Alfven eigenmodes (TAEs) driven by energetic particles are widely observed in tokamaks and helical plasma when the fast ion pressure gradient is large enough \([53–55]\). Recently, the abrupt onset of a perturbation with tongue-shaped topology (localized in the poloidal and toroidal directions), leading to the sudden redistribution of energetic ions and MHD burst associated with the sudden increase of plasma rotation, was brought about by changing the radial electric field. This new type of MHD burst is characterized by a unique trigger mechanism. It is triggered by the tongue-shaped deformation that appears between the low order of a rational surface. The MHD instability causing the tongue-shaped deformation is highly nonlinear, grows within one cycle and triggers the redistribution and loss of energetic trapped ions, which are indicated by a sharp jump of RF intensity. The plasma starts to rotate after the loss of ions and the MHD burst starts due to the resonance between the mode frequency and the precession frequency of the trapped particle.

As seen in figures 8(a)–(c), the repeated burst of the magnetic field perturbation with a large amplitude is observed with magnetic probes at a toroidal angle of 90, 198 and 270 degrees \([56]\), called an MHD burst in the LHD. The similar magnitude of the oscillation amplitude in these three
probes indicates that the MHD perturbations are rotating toroidally. However, the magnetic perturbation amplitude in the 198 degree probes is much smaller than those in the 90 and 270 degree probes between the MHD burst. This indicates that the MHD oscillation between the MHD burst is caused by the standing wave. Figures 8 indicates that the MHD oscillation between the MHD burst is the 198 degree probes is much smaller than those in the toroidally. However, the magnetic perturbation amplitude in Plasma Phys. Control. Fusion.

Figure 8. Time evolution of (a) the perturbation of the magnetic field, (b) the effective ion temperature and (c) the effective toroidal rotation velocity; the radial profile of (d) the effective ion temperature and (e) effective toroidal rotation velocity in LHD.

3.2. Impact of tongue collapse on ion velocity distribution

The MHD burst triggered by the tongue collapse has a strong effect on plasma velocity distribution and alters the effective ion temperature and effective toroidal rotation velocity. At each MHD burst, the abrupt increase of effective ion temperature and an increase of effective toroidal rotation velocity in the counter-direction is observed, as seen in figures 9(a)–(c). The change of effective ion temperature and effective toroidal rotation velocity is within 1 ms and much faster than the transport time scale. This is due to the redistribution of ions in space, where the hot ions and counter-traveling ions in the core region \(r_{\text{eff}}/a_{99} < 0.4\) move outward in a short time associated with tongue formation and collapse. The increase of effective ion temperature and effective toroidal rotation velocity shows the relaxation in the ion–ion collision time scale.

The radial profiles of effective ion temperature and effective toroidal rotation velocity 4 ms before and 1 ms after the tongue collapse are plotted in figures 9(d)–(e). The increase of effective ion temperature is 0.5 keV and relatively constant in space, and the ion temperature gradient is almost unchanged. Before the tongue collapse the effective toroidal rotation velocity is co-directional (parallel to the equivalent plasma current direction) and it is in the counter-direction after the tongue collapse. The rapid change in the effective
toroidal rotation velocity is the consequence of outward movement of counter-traveling particles, because the time scale of the change is much faster than the time scale of the momentum transport.

In order to investigate the mechanism for the rapid change of effective ion temperature and effective toroidal velocity, the distortion of the ion velocity distribution from the Maxwell–Boltzmann distribution is evaluated by the moment analysis of ion velocity distribution measured with charge exchange spectroscopy viewing the plasma toroidally [58]. The zeroth to the 4th moment of the ion velocity distributions are defined as

\[ M_0 = \int f(v) \, dv \]
\[ M_1 = \frac{1}{M_0} \int v f(v) \, dv \]
\[ M_2 = \frac{1}{M_0} \int (v - M_1)^2 f(v) \, dv \]
\[ M_3 = \frac{1}{M_0 M_2^{3/2}} \int (v - M_1)^3 f(v) \, dv \]
\[ M_4 = \frac{1}{M_0 M_2^{5/2}} \int (v - M_1)^4 f(v) \, dv. \]  

When the ion velocity distribution has a Maxwell–Boltzmann distribution, \( M_1 = V_{\text{eff}}, \) \( M_2 = V_{\text{eff}}^2, \) \( M_3 = 0, \) and \( M_4 - 3 = 0, \) where \( V_{\text{eff}} \) is the ion thermal velocity. When the ion velocity distribution is distorted from the Maxwell–Boltzmann distribution, \( M_3 \) and \( M_4 - 1 \) become nonzero.

The time evolutions of the 1st moment \((M_1),\) the square root of the 2nd moment \((M_2),\) the 3rd moment skewness \((M_3),\) and the 4th moment kurtosis \((M_4 - 3)\) of the ion velocity distribution of carbon at \( r_{\text{eff}}/\delta_{\text{pp}} = 0.8, \) at the tongue event. Here \( \tau \) is the relative time of the event with respect to the time of the sharp increase of RF intensity in the LHD (Reprinted from [9], with the permission of AIP Publishing).

The radial profile of the poloidal rotation velocity and the radial electric field shows the large negative electric field well at \( r_{\text{eff}}/\delta_{\text{pp}} = 0.9, \) while the radial electric field before the tongue collapse is positive as seen in figures 11(d)–(e). The change in radial electric field near the plasma edge \((r_{\text{eff}}/\delta_{\text{pp}} > 0.8)\) is mainly contributed by the change in poloidal flow in the electron diamagnetic direction, while the change in radial electric field further inside the plasma is contributed by the increase of toroidal flow in the counter-direction. The radial electric field outside the plasma boundary \((r_{\text{eff}}/\delta_{\text{pp}} = 1)\) is almost unchanged. The change of the radial profile of the radial electric field to a more negative value clearly shows the loss of bulk ions associated with the tongue collapse.

3.3. Turbulence exhaust driven by MHD collapse

It is interesting to investigate the impact of MHD collapse on turbulence. The Doppler reflectometer is a useful tool for measuring the density fluctuation near the plasma boundary.
Frequency-hopping Doppler reflectometers have been installed in the LHD and the frequency is set to 30 GHz in this experiment [62, 63]. The location of the measurement (reflection point) can be scanned from the edge stochastic region to the nested region inside during the discharge where the edge density gradually decreases in time. The analysis technique of the radial scan of the reflection point of the Doppler reflectometer using the density ramp up/down in time has been applied in the LHD experiments. This method is recognized to be a useful technique to measure the radial profile of the density fluctuation amplitude and perpendicular velocity near the plasma edge [64].

Figure 12 shows the time evolution of the perpendicular velocity at the edge stochastic region ($r_{eff}/a_{99} > 0.95$) and inside the plasma ($r_{eff}/a_{99} < 0.95$). The contour of the fluctuation level integrated low-frequency (30–150 kHz) turbulence and high-frequency (150–490 kHz) turbulence are also plotted. When the reflection point is in the edge stochastic region, the positive spikes of the intensity of high frequency ($f = 150–490$ kHz) micro-turbulence are observed at the tongue collapse event. In contrast, the slight decrease of high-frequency micro-turbulence is observed at the nested flux region inside the plasma ($r_{eff}/a_{99} < 0.95$). It should be pointed out that there is no change in turbulence intensity at a lower frequency range ($f = 30–150$ kHz).

The time evolution of the perpendicular velocity of the stochastic region and the nested region inside shows the change of perpendicular velocity in the electron diamagnetic direction. This data indicates the formation of negative radial electric field consistent with the negative poloidal flow measured with charge exchange spectroscopy. The formation of a negative electric field is transient and lasts only 2 ms. As seen in the spectrum in the stochastic region ($r_{eff}/a_{99} > 0.95$) plotted in figures 12(d)–(e), only the micro-turbulences in the frequency region above 150 kHz increase rapidly within 0.15 ms after the collapse. This rapid increase of turbulence observed is due to the rapid avalanche-like radial propagation process [65–68] into the SOL rather than the change in locally driven turbulence associated with changes in the temperature or density gradients in the SOL.

4. Discussion

As an example of interplay between the turbulence and the topology, the following experimental evidence has been reported in a toroidal plasma. Turbulence spreading from the X-point to the O-point of the magnetic island is identified from the phase delay between the heat pulse and the turbulence response. The bifurcation of magnetic island states can...
be explained by the interplay between turbulence spreading and stochastization at the X-point of the magnetic island. The radial propagation of the stochastic magnetic field towards the magnetic axis of the helical plasma can also be explained by the interplay between the plasma flow and stochastization of the magnetic field.

The experimental evidence for two states of a magnetic island provides a new insight into understanding the radial flux of (surface-averaged) heat transport in the presence of magnetic islands during RMP experiments. This understanding can be further improved and it may be possible to achieve better control of the heat transport in discharges with RMP fields by using the heat pulse propagation technique as a tool to identify the state of the magnetic island. Turbulence spreading observed in the magnetic island also gives a new insight into turbulence spreading physics, which is necessary for better understanding of the turbulence in the SOL, where the spreading turbulence dominates locally driven turbulence. Because the turbulence in the SOL is beneficial for the broadening of the power decay length, deeper understanding of SOL turbulence is essential for better control of the SOL decay length in future devices. Exploration of the impact of magnetic field stochastization on turbulence spreading and flow damping is a new research field. The former is important in understanding the complicated plasma response of particle and heat transport to the RMP field and the latter is indispensable to understand the response of plasma flow to RMP fields, where partial stochastization is expected. Better understanding of the impact of RMP fields on plasma flow is essential for more reliable predictions of the power threshold of the L- to H-mode transition in future devices.

The strong impact of energetic-particle-driven MHD instability has been observed. MHD bursts are triggered by tongue formation and collapse. This tongue collapse has an impact on ion velocity distribution and causes distortion from the Maxwell–Boltzmann distribution. The distortion has been found in experiments with a significant transient change in skewness and kurtosis of the ion velocity distribution. The tongue collapse also enhances the loss of the bulk ions of epithermal ions and produces a negative radial electric field, exciting the MHD instability at the plasma edge. The turbulence exhaust by the tongue collapse is also observed in the Doppler reflectometer. This interplay between MHD and turbulence is essential for integrated understanding for various phenomena in toroidal plasma.

Understanding the impact of MHD instabilities driven by energetic particles on plasma flow and turbulence becomes more important for future devices, because an increased fraction of energetic particles is expected in burning plasmas. Because of the strong coupling between plasma rotation and the plasma potential in toroidal plasma, the plasma rotation can be driven by energetic ion losses triggered by MHD instabilities. Once the plasma starts to rotate, another MHD instability can be excited by the resonance between the mode frequency and the precession frequency of the trapped particles. This is an example of where an MHD instability drives another MHD instability through the plasma flow which is determined by the momentum transport. Therefore, the interplay between MHD and transport is key physics in understanding the situation where various MHD modes appear one after the other during the discharge in the plasma when the fraction of the beam beta is high [16, 69].

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References

[1] Shibata K and Tanuma S 2001 Earth Planets Space 53 473
[2] Nishizuka N and Shibata K 2013 Phys. Rev. Lett. 110 051101
[3] Biancalani A et al 2019 Interaction of Alfvenic modes and turbulence, investigated in a self-consistent gyrokinetic framework XLVI EPS Conf. on Plasma Physics (8–12 July) (Milano, Italy)
[4] Ida K et al 2018 Phys. Rev. Lett. 120 245001
[5] Ida K et al 2015 Sci. Rep. 5 16165
[6] Ida K et al 2015 Nat. Commun. 6 5816
[7] Ida K et al 2018 Sci. Rep. 8 2804
[8] Ida K et al 2016 Sci. Rep. 6 36217
[9] Ida K et al 2017 Phys. Plasmas 24 122502
[10] Ida K et al 2018 Nucl. Fusion 58 112008
[11] Yun G S et al 2011 Phys. Rev. Lett. 107 045004
[12] Lee J E et al 2017 Sci. Rep. 7 45075
[13] Evans T E et al 2018 arXiv:1805.10394v2
[14] Wu W et al 2019 Nucl. Fusion 59 066010
[15] Ida K et al 2015 Nucl. Fusion 55 013022
[16] Ida K 2019 Nucl. Fusion 59 117001
[17] Happr T et al 2019 J. Nucl. Mat. 483 159
[18] Harrison J R et al 2019 Nucl. Fusion 59 112011
[19] Harrison J R et al 2015 Phys. Plasmas 22 092508
[20] Scotti F et al 2018 Nucl. Fusion 58 126028
[21] Kaye S M et al 2019 Nucl. Fusion 59 112007
[22] Grafen G et al 2019 Nucl. Fusion 59 016018
[23] Snape J et al 2012 Plasma Phys. Control. Fusion. 54 085001
[24] Inagaki S et al 2004 Phys. Rev. Lett. 92 055002
[25] Bardocz L et al 2017 Phys. Plasmas 24 062503
[26] T Hahm S et al 2004 Plasma Phys. Control. Fusion. 46 A323
[27] Diamond P H and Hahm T S 2018 J. Korean Phys. Soc. 73 747
[28] Fonck R J et al 1990 Rev. Sci. Instrum. 61 3487
[29] McKee G R et al 2007 Plasma Fusion Res. 2 s1025
[30] Evans T E, Moyer R A and Monat P 2002 Phys. Plasmas 9 4957
[31] Ida K et al 2016 Nucl. Fusion 56 092001
[32] Diamond P H, Dupree T H and Tetreault D J 1980 Phys. Rev. Lett. 45 562
[33] Lichtenberg A J, Itoh K, Itoh S-I and Fukuyama A 1992 Nucl. Fusion 32 495
[34] Itoh K, Itoh S-I, Fukuyama A and Lichtenberg A J 1992 Nucl. Fusion 32 1851
[35] Liang Y et al 2007 Nucl. Fusion 47 L21
[36] Wang W X, Hahm T S, Lee W W, Rewoldt G, Manickam J and Tang W M 2007 Phys. Plasmas 14 072306
[37] Yi S, Kwon J M, Diamond P H and Hahm T S 2015 Nucl. Fusion 55 092002
[38] Wang W X, Hahm T S, Lee W W, Rewoldt G, Manickam J and Tang W M 2007 Phys. Plasmas 14 072306
[39] Yi S, Kwon J M, Diamond P H and Hahm T S 2015 Nucl. Fusion 55 092002
[40] Wang W X, Hahm T S, Lee W W, Rewoldt G, Manickam J and Tang W M 2007 Phys. Plasmas 14 072306
[41] Yi S, Kwon J M, Diamond P H and Hahm T S 2015 Nucl. Fusion 55 092002
[42] Ida K et al 2008 Phys. Rev. Lett. 100 045003
[43] Ida K et al 2013 New J. Phys. 15 013061
[44] Ida K et al 2015 Plasma Phys. Control. Fusion. 57 014036
[45] Terry P W et al 1996 Phys. Plasmas 3 1999
[46] Ida K et al 2017 Nucl. Fusion 57 076032
[47] Cheng C Z and Chance M S 1986 Phys. Fluids 29 3695
[48] Heidbrink W W 2008 Phys. Plasmas 15 055501
[49] Tii K et al 2000 Nucl. Fusion 40 1349–62
[50] Yamamoto S et al 2005 Nucl. Fusion 45 326–36
[51] Nagaoka K et al 2008 Phys. Rev. Lett. 100 065005
[52] Ogawa K et al 2010 Nucl. Fusion 50 084005
[53] Ogawa K et al 2018 Nucl. Fusion 58 044001
[54] Ogawa K et al 2018 Plasma Phys. Control. Fusion. 60 044005
[55] Ogawa K et al 2013 Nucl. Fusion 53 053012
[56] Sakakibara S et al 2010 Fusion Sci. Technol. 58 471–81
[57] Voermans S et al 2019 Nucl. Fusion 59 106041
[58] Yoshinuma M et al 2010 Fusion Sci. Technol. 58 375
[59] Heidbrink W W et al 2011 Plasma Phys. Control. Fusion. 53 085028
[60] Schild P, Cottrell G A and Dendy R O 1989 Nucl. Fusion 29 834
[61] Dendy R O et al 1994 Phys. Plasmas 1 1918
[62] Tokuzawa T, Ejiri A and Kawahata K 2010 Rev. Sci. Instrum. 81 10D906
[63] Tokuzawa T et al 2012 Rev. Sci. Instrum. 83 10E322
[64] Creely A J et al 2017 Rev. Sci. Instrum. 88 073509
[65] Diamond P H and Hahm T S 1995 Phys. Plasmas 2 3640
[66] Carreras B A, Newman D, Lynch V E and Diamond P H 1996 Phys. Plasmas 3 2903
[67] Newman D E, Carreras B A, Diamond P H and Hahm T S 1996 Phys. Plasmas 3 1858
[68] Garbet X and Waltz R E 1998 Phys. Plasmas 5 2836
[69] Lauber P H et al 2018 Strongly non-linear energetic particle dynamics in ASDEX Upgrade scenarios with core impurity accumulation Preprint: 2018 IAEA Fusion Energy Conf. 22–27 October) (Gandhinagar, India/[EX/1-1]. https://iaea. org/events/fec-2018.