Corrigendum

Corrigendum: Multiscale interaction between a large scale magnetic island and small scale turbulence (2017 Nucl. Fusion 57 126058)

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In the paper ‘Multiscale interaction between a large scale magnetic island and small scale turbulence (2017 Nucl. Fusion 57 126058)’, the word ‘vortex’ was overused. ‘Vortex’ should have been replaced with ‘reversed’ in descriptions of our observations for more careful understanding, but it was missed during the proofreading process.

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Multiscale interaction between a large scale magnetic island and small scale turbulence

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Abstract
Multiscale interaction between the magnetic island and turbulence has been demonstrated through simultaneous two-dimensional measurements of turbulence and temperature and flow profiles. The magnetic island and turbulence can mutually interact via coupling between the electron temperature \(T_e\) gradient, the \(T_e\) turbulence, and the poloidal flow. The \(T_e\) gradient altered by the magnetic island steepens outside and flattens inside the island. The \(T_e\) turbulence can appear in increased \(T_e\) gradient regions. The combined effects of the \(T_e\) gradient and the poloidal flow shear determines the two-dimensional distribution of the \(T_e\) turbulence. When the poloidal vortex flow forms, it can maintain the steepest \(T_e\) gradient and the magnetic island acts more like an electron heat transport barrier. Interestingly, when the \(T_e\) gradient, the \(T_e\) turbulence, and the vortex flow shear increase beyond critical levels, the magnetic island turns into a fast electron heat transport channel, which directly leads to the minor disruption.

Keywords: magnetic island, turbulence, multiscale interaction

(Some figures may appear in colour only in the online journal)
[17–21], and they found that the flow shear across the island can also be important in multiscale interactions. Recent simulation studies have shown various multiscale interactions between the magnetic island and turbulence via pressure and flow profiles [8, 9, 23, 24, 38, 53]. They made detail observations such as the localized turbulence distribution and the poloidal vortex flow around the magnetic island [22–25, 53]. The turbulence level is expected to be insignificant across the O-point region probably due to small pressure gradient inside the magnetic island and the strong flow shear outside the magnetic island [9, 23, 24, 38, 53]. The turbulent transport inside the magnetic island and turbulence. The two-dimensional flow near the Te are indeed important in multiscale interaction between the magnetic island and turbulence. The two-dimensional turbulence gradient distribution is determined by the combined effect of the Te gradient (turbulence drive) and the poloidal flow (turbulence suppression/convection). In particular, when the poloidal vortex flow forms around the magnetic island, the steepest Te gradient is obtained in the inner region (r < rso) where rso represents the inner separatrix of the magnetic island and the magnetic island acts more like a barrier of the electron heat transport until the transport bifurcation occurs. In section 2, multiscale interaction in the poloidal vortex flow state is described and compared qualitatively with previous studies. In section 3, coupled evolution of the Te gradient, the Tv turbulence, and the poloidal flow towards the poloidal vortex flow state and the transport bifurcation phenomena are discussed. The summary and conclusion are given in section 4.

2. Multiscale interaction in the poloidal vortex flow state

2.1. Experimental set-up

In the Korea superconducting tokamak advanced research (KSTAR; major radius R = 180 cm and minor radius a = 50 cm) experiment #13371, the plasma was heated by 1 MW neutral beam injection and kept in the low confinement mode with the plasma current Ip = 0.7 MA, the safety factor at the 95% magnetic flux surface q95 ~ 4.6, and the Spitzer resistivity η ~ 1.4 × 10−7. The non-rotating m/n = 2/1 magnetic island was induced by an external n = 1 resonant magnetic perturbation (RMP) field. Coil current for the n = 1 RMP field was increased in time as shown in figure 1, and above a critical threshold value the n = 1 field penetrates deep into the plasma. The toroidal flow speed (Vt) near the q = 2 region measured by the charged exchange spectroscopy (CES) [26] dropped to almost zero within the measurement error (±5 km s−1) during the penetration. The core electron temperature from the electron cyclotron emission (ECE) diagnostics indicates that the sawtooth crash became very frequent and small [27]. A slow decrease in the line averaged electron density, often referred to as the density pump-out, was also observed. The major disruption occurs with the continuously increased n = 1 field [28].

For measurements of the Te profile, the Tv turbulence, and the poloidal flow, the 1D ECE diagnostics and the 2D ECE imaging (ECEI) diagnostics [29] were utilized. The ECEI diagnostics was cross-calibrated [30] using the axis-symmetric Te profile from the absolutely calibrated ECE diagnostics and the EFIT reconstructed equilibrium [31] in the period without the magnetic island in figure 1. The poloidal flow velocity could be deduced from the vertical pattern velocity (vpt) [32, 33] estimated using two vertically adjacent ECEI channels. A spatial resolution of the ECEI diagnostics is close to 2 cm in both radial and vertical directions and a temporal resolution is 2 µs. Note that effects of the relativistic shift, the Doppler broadening, and finite poloidal field [34] for the radial channel positions are more or less cancelled out in this plasma condition, and the cold resonance positions could be used. In the outer region (r > rso) where rso means the outer separatrix of the magnetic island), Te measurement is uncertain because the ECE diagnostic capability becomes marginal. In terms of the optical depth (τ) [35], it is close to or less than 1 in the outer region while close to 3 in the inner region and in between 1 and 3 inside the magnetic island.

2.2. The Te profile with the magnetic island

When the m/n = 2/1 magnetic island is induced, the Te profile is altered along the magnetic topology of the island and it is no longer axisymmetric. The radial Te profiles measured by the ECE diagnostics in the high field side and the 2D Te profile by the ECEI diagnostics in the low field side at different toroidal angles are shown in figure 2. The Te profile inside the magnetic island flattens probably due to the fast
parallel transport along the reconnected field line [13] and/or the negligible turbulence spreading [24]. The full width of the magnetic island ($W$) will be close to or larger than 5 cm which is larger than the typical critical width ($W_c \sim 1.0$ cm) for the $T_e$ flattening in the KSTAR L-mode plasmas [36]. Note that the separatrix of the magnetic island in the 2D $T_e$ profile can be roughly estimated by the temporal behavior of the electron temperature. A full 2D electron temperature profile and a proper modeling are needed to estimate the magnetic island full width accurately [36, 54], especially when the localized (not uniform) and dynamic turbulence exists around the magnetic island which can affect the perpendicular electron heat transport characteristics [37].

In contrast to the flattened $T_e$ profile inside the magnetic island, the $T_e$ profile in the inner region ($r < r_a$) becomes more steep with the increase of the core $T_e$ level (figure 2(a)). In particular, the $T_e$ gradient increases towards the O-point region as indicated by the widths of the orange arrows in the 2D $T_e$ profile in figure 2(b). More closely packed magnetic flux surfaces due to the magnetic island may induce some local $T_e$ profile modifications [9, 16]. In order to understand the global $T_e$ profile variation, the electron heat transport around the magnetic island has been studied with measurements of the $T_e$ turbulence and the poloidal flow as follows.

2.3. The $T_e$ turbulence and its characteristics

In order to estimate the electron turbulent heat transport near the magnetic island, the $T_e$ fluctuations measured by the ECEI diagnostics are analyzed. For example, figures 3(a)–(c) are the cross coherence of $\delta T_e / \langle T_e \rangle \equiv (T_e - \langle T_e \rangle) / \langle T_e \rangle$ between two ECEI channels where $\langle \cdot \rangle$ means the time average. It represents the coherent fraction in the total $\delta T_e / \langle T_e \rangle$ fluctuation power. They are calculated using two vertically adjacent ECEI channels for $t = 7.35$–7.40 s in the plasma #13371. One inside the magnetic island does not show a significant coherent fluctuation, but the others show some coherent fluctuation power. In the inner region where the $T_e$ gradient is increased significantly, the fluctuation power over a broad frequency band ($0 \leq f \leq 75$ kHz) is measured clearly. The $T_e$ gradient can be considered as a predominant drive of this turbulent fluctuation. In fact, the coherence increases with the $T_e$ gradient as shown in figure 6. Note that the weak fluctuation power over a narrow frequency band ($0 \leq f \leq 30$ kHz) is measured in the outer region.

A detail 2D distribution of the $T_e$ turbulence level can be investigated by calculating the summed cross coherence image using more ECEI channels. The cross coherence only above a significance level is summed over a 10–75 kHz band to make the summed coherence image. Note that a 0–10 kHz band was neglected because some channels suffer from 4 kHz electronics noise in this experiment. Each dot in the images in figure 3(d), 4(a) and (b) represents the summed coherence estimated using the channel at that position and the one below. Note that one row of the ECEI channels had a low signal-to-noise ratio and reliable coherence calculations in two rows near the midplane are not available. The smooth and continuous 2D $T_e$ profile in figure 2(b) is obtained by interpolations.

The summed coherence image in figure 3(d) shows that the strong $T_e$ turbulence is localized both radially and poloidally in the inner region. It has the maximum close to the inner separatrix of the magnetic island near the X-point. The insignificant ($<2$) summed coherence is observed inside the magnetic island, and weak but meaningful coherence is observed in the outer region.

The $T_e$ turbulence distribution has been further studied in a similar KSTAR plasma #15638 in which the toroidal phase of the applied $n = 1$ field is slowly varying at the frequency of 2 Hz. In that experiment, both the X-point and O-point regions can be captured in the ECEI view frame in different
time periods (20 ms each) and the $\delta T_e/\langle T_e \rangle$ summed coherence images are obtained as shown in figures 4(a) and (b), respectively.

The summed coherence is insignificant everywhere for the O-point period, which implies the small turbulent electron heat transport there [9, 14, 15, 23, 24, 38, 53]. For the X-point period, it is found that the significant coherence is not only localized but also poloidally asymmetric against the X-point. Note that this localized turbulence follows the X-point, which is rotating with the RMP field, with a constant poloidal shift.

The localized asymmetric turbulence near the X-point region strongly suggests that the $T_e$ gradient is not the only control parameter in growth of the $T_e$ turbulence. The poloidal flow can be important as it will be discussed in next section. In fact, the poloidal shift of the turbulence with respect to the X-point coincides with the direction of the local poloidal flow [9, 25, 38]. This locality of the island-associated $T_e$ turbulence is consistently observed in other experiment [39]. Although it is beyond the scope of this work, the radial locality may also imply that the magnetic island itself can be important in driving the turbulence via a direct nonlinear coupling [5, 22, 40].

At this point, it would be helpful to provide some quantitative characteristics of the $T_e$ turbulence such as the rms amplitude, correlation lengths, and the poloidal wavenumber. Firstly, the rms amplitude can be measured by integrating the cross power spectral density between vertically adjacent channels over a 10–75 kHz band, and the maximum turbulence rms amplitude is about $2.5 \pm 0.25\%$ in the plasma #13371. Note that the 2D rms amplitude has the almost same distribution with the summed coherence image in figure 3(d). Next, the summed coherence images in figures 4(c)–(f) are calculated especially for estimation of correlation lengths in the plasma #15638. A pair of a fixed reference channel (indicated by a black cross) and other channel are used to estimate the correlation length defined as a range of the significant summed cross coherence. The correlation length is found to not be uniform and has a finite poloidal (2–6 cm) and radial (2–3 cm) range. Note that it is a little larger than the radial correlation lengths of density fluctuation across the magnetic island in [41]. Lastly, the poloidal wavenumber of the $T_e$ turbulence can be estimated from the cross phase ($\Delta \Theta$) between vertically adjacent ECEI channels. Figures 5(a) and (b) represent the vertical ECEI cross phase measured in the inner and outer regions in the plasma #13371. (c) The 2D $v_{pe}$ profile is measured using the coherent cross phase.
region of the plasma #13371, respectively. Fluctuations in a range of $\Delta z/\rho_i \approx 0.4$ were revealed in most channels in the inner region and in some channels in the outer region where $\rho_i$ is the ion gyroradius. The vertical distance between two adjacent channels ($\Delta z$) was set to be about 2 cm and detectable poloidal wavenumber is roughly limited to $k_0\rho_i \leq 0.4$ in this experiment.

2.4. The poloidal vortex flow

Using the slope of the coherent vertical ECEI cross phase, the vertical phase velocity in the laboratory frame, or the pattern velocity ($v_{pt}$), can be measured [32, 33]. Figure 5(c) shows 2D measurement of the $v_{pt}$ near the magnetic island for $t = 7.35-7.40\,s$ in the plasma #13371. Note that the $v_{pt}$ measured with uncertainty less than 0.8 km s$^{-1}$ is only shown. For the accurate $v_{pt}$ measurement, the ECEI data should have sufficient power of the coherent fluctuation and record length (at least 50 ms).

In this state, the $v_{pt}$ in the inner region is positive (a counter clockwise or the electron diamagnetic direction), and its speed is radially peaked near the separatrix of the magnetic island. More importantly, it is not uniform in the poloidal direction, i.e. it increases toward the O-point region. The positive radial shear of the poloidal flow ($dv_{pt}/dr \geq 10^3\,s^{-1}$) forms in the inner region and it also increases toward the O-point region. This $v_{pt}$ behavior is consistent with the numerical simulation there [9, 23, 24, 53], and can explain the $T_e$ turbulence is not detected and the steep $T_e$ profile is maintained near the O-point region. In addition, the $v_{pt}$ is reversed across the magnetic island and the strong negative radial shear of the poloidal flow ($-dv_{pt}/dr > 10^3\,s^{-1}$) develops across the island. Although it was not possible to measure the flow inside the flat and quiet magnetic island, the poloidal flow around and inside the island is expected to have a vortex structure [18, 21, 23–25, 53]. This 2D poloidal vortex flow can prohibit a turbulent eddy from developing across the magnetic island [42] and from spreading into the island [24].

The origin of the poloidal vortex flow is not clearly understood yet despite its remarkable agreement with the simulation. The toroidal flow decreases significantly after the field penetration and its contribution would be negligible in the $v_{pt}$. The electron diamagnetic drift may serve as a nearly uniform and small background, considering evolution of poloidal flows in figure 6(d). Note that from $t = 7.50\,s$ to $t = 7.55\,s$ the plot E showed a drastic change (+4 km s$^{-1}$) which is hardly explained by the 10% increase of the electron temperature gradient. The $E \times B$ [9, 22–25, 53, 55, 56] or zonal flow driven by the turbulence itself [57] may play an important role in the measured $v_{pt}$.

3. The poloidal vortex flow formation and the transport bifurcation

In previous experiments, the applied RMP field strength keeps increasing in time, and it is not easy to study the temporal coupled evolution between the $T_e$ gradient, the $T_e$ turbulence, and the poloidal flow. In the experiment #16150, the constant and non-rotating $n = 1$ RMP field is applied and the plasma is maintained in the mode-locking state without the major disruption. A repetitive minor disruption is observed as the plasma evolves in time with the constant RMP field, and the coupled evolution is studied for a single minor disruption cycle.

Four distinctive phases are observed during a single minor disruption cycle as illustrated in $T_e$ profiles in figure 6(a). The temporal evolutions of the $T_e$ gradient in the inner region, the $T_e$ turbulence level (the summed cross coherence) at different positions (A, B, C, and D), and the poloidal flow ($v_{pt}$) at different positions (A, B, C, D, and E) are shown in figures 6(b)–(d), respectively. Note that the summed coherence in figure 6(c) and the summed coherence image for the phase 1 (figure 6(e)) and the phase 2 (figure 6(f)) are obtained using pair of vertically adjacent ECEI channels and the cross coherence over a 0–60 kHz band in which there is no electronics noise in this experiment.

In the initial recovery phase 1, the $T_e$ gradient in the inner region is not very steep but increasing in time as shown in figure 6(b). The summed cross coherence image in figure 6(e) shows that the coherent fluctuation power is relatively weak.
but peaked across the X-point of the magnetic island. The negative poloidal flow is sheared across the X-point as shown in the \( v_{\phi} \) measurement at B, D, and E in figure 6(d), but near the X-point, it seems not to be strong enough to affect the turbulence distribution. Although the accurate entire two-dimensional flow measurement was not available in this phase due to the marginal turbulent fluctuation power except the X-point region, the localized turbulence near the X-point implies that the flow shear may be effective beyond the X-point region.

The transition from the phase 1 to the phase 2 involves with a rapid increase of the \( T_e \) gradient, i.e. \( T_e \) increases at the core region and decreases slightly in the \( q \geq 2 \) region, as well as changes of the 2D patterns of the \( T_e \) turbulence level and poloidal flow. Note that the 2D estimated magnetic island geometry (indicated by the dashed purple line) is also perturbed as seen decrease of the summed coherence at D, which might involve change of the island full width. The line averaged density is nearly constant in the transition and decreases by a few percent later in phase 3. The electron density profile measured by the Thomson scattering system [58] becomes a little broader but it is not clear due to the unsatisfactory measurement condition.

In the phase 2, the 2D \( T_e \) turbulence distribution is changed as shown in figure 6(f) as figure 3(d), and the poloidal vortex flow forms as shown in the \( v_{\phi} \) measurement at A, C, and E in figure 6(d) as figure 5(c). Development of the poloidal vortex flow can be originated from change in \( v_{\phi, b} \) around the magnetic island by the nonlinear resonant low \( n \) electrostatic mode [22, 23, 53, 24] or the response potential to the magnetic perturbation in the initial shear flow [25]. The strong vortex flow developed across the magnetic island can prohibit the turbulence growth or convection across the X-point [24, 42] and shift the \( T_e \) turbulence level upwards in the inner region as observed in figures 6(c) and (f), which can explain the \( T_e \) gradient increase in phase 2.

A sudden decrease of electron temperature in the \( q \geq 2 \) region occurs in the phase 3 through some unknown process (possibly related to edge modes), which leads to a jump in the \( T_e \) gradient and the \( T_e \) turbulence in the inner region. In addition, the stronger radial shear of the poloidal flows in the inner region (difference between A and E in figure 6(d)) and across the X-point (difference between A and C in figure 6(d)) are observed.

However, when all the \( T_e \) gradient, the \( T_e \) turbulence, and the vortex flow shear increase significantly, a massive fast (~100 \( \mu \)s) \( T_e \) collapse occurs. Note that the \( T_e \) profile collapses in two steps, i.e. the local \( q = 2 \) collapse and the \( q \leq 1 \) collapse, which is very similar with the large minor disruption in [43] where the RMP field was not applied. The role of the magnetic island has been changed from a barrier of the electron heat transport (from phase 1 to phase 3) to a fast channel (from phase 3 to phase 4). The observed transport bifurcation may be relevant to either the bifurcation observed in [44], secondary instabilities [7, 45], or the vortex flow shear destabilization of the long wavelength fluctuation [25].

4. Summary and conclusion

The 2D profiles of \( T_e \) and poloidal flow and the 2D \( T_e \) turbulence distribution are closely coupled around the magnetic island. The magnetic island and turbulence mutually interact via this coupling and it has a critical effect on the electron heat transport. The magnetic island can play as either a barrier or a fast channel of the electron heat transport.

The magnetic island acts more like an electron heat transport barrier when the poloidal flow is perturbed to have a vortex structure. The speed of the vortex flow is peaked near the separatrix of the magnetic island increasing towards the O-point region. The positive flow shear in the inner region would suppress the \( T_e \) turbulence around the O-point region, and the \( T_e \) turbulence level is only significant in the narrow region close to the X-point region. The negative flow shear across the magnetic island would prevent a turbulent eddy from growing across the X-point and from spreading into the island. In this state, the poloidal flow developed around the magnetic island seems to regulate the electron turbulent heat transport across the magnetic island.

However, when the \( T_e \) gradient, the \( T_e \) turbulence, and the vortex flow shear exceed critical levels, the transport bifurcation occurs and a massive heat transport event follows. The role of the magnetic island on the electron thermal transport is more complicated than a direct thermal loss channel.

This experiment clearly demonstrates multiscale nonlinear interaction between a large scale magnetohydrodynamic instability and small scale turbulence and its importance on the electron thermal transport. It may provide some physical insights to understand the internal transport barrier formation [46–48] or the RMP edge localized mode suppression experiment [49, 50]. More research focused on the validation of experimental observations with the numerical simulations will be done in near future.

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