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Unveiling the structure and dynamics of peeling mode in quiescent high-confinement tokamak plasmas

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Quiescent high-confinement mode plasmas with edge-harmonic oscillations do not exhibit the explosive instabilities associated with edge-localized modes. Instead, an additional means of enhanced transport is considered to maintain the plasma edge under conditions just below the boundary of the peeling mode instability. Although the potential of the peeling mode has been widely recognized in plasma physics, no direct evidence for this mode has been revealed previously because decisive diagnostics were lacking. Herein, we report evidence of the structure and dynamical steady state of peeling mode in quiescent high-confinement mode. Edge-harmonic oscillations are dominated by fundamental mode at both the low- and highfield sides. Edge perturbations are confirmed to have kink parity and exhibit the frozen-incondition predicted by linear stability analysis. The envelope signal of the fundamental mode exhibits repeated cycles of growth and damping in association with minor changes in the edge gradient. Results from this study are quantitatively consistent with limit-cycleoscillation model.

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he quiescent high-confinement-mode (QH-mode) regime was first discovered in the DIII-D tokamak¹ and was subsequently reproduced in the JT-60U² and ASDEX-Upgrade/JET³ tokamaks. In QH-mode plasmas, edge-localized modes $(ELMs)^{4-6}$ are replaced by continuous magnetohydrodynamic (MHD) oscillations (the so-called edge-harmonic oscillations (EHOs)). Theoretical models and experimental results indicate that the QH-mode edge condition is always near the toroidal mode in a small number (e.g., $n \le 5$) boundary of the peeling mode instability⁷⁻¹⁰. However, no direct evidence of the structure of the peeling mode has been reported previously because of a lack of decisive diagnostics. Especially, fluctuation measurements at the high-field side (HFS) of the tokamak edge region have not been collected. Previous measurements were limited solely to the low-field side (LFS). The magnetic fluctuation data from both the LFS and HFS is available from other tokamaks for the QH-mode. However, the global modes should also appear on the HFS. An important remaining issue is building a consistent story with the other diagnostics to provide meaningful physical explanations of the observed EHO features to understand the peeling mode.

Studies of explosive dynamical events in controlled-nuclearfusion devices display many similarities to solar-flare events on the sun. This observation reveals an additional connection between laboratory plasma physics and astronomy¹¹⁻¹⁴. Improved understanding of the common physics of ELMs and solar/stellar flares contributes to our intellectual understanding of plasma physics and can improve the controllability of burning plasmas in self-regulating, combined/complex next-step devices, such as ITER^{15,16} and DEMO^{17,18}. In particular, highconfinement mode with large ELMs (ELMy H-mode) operation (which has a high pedestal pressure) may be impossible without a proper physics understanding of the "peeling" mode (or coupled peeling-ballooning modes). This seems essential for predicting the ELM stability limit because the instability is driven by the pressure gradient and the parallel current (i.e., the so-called bootstrap current)¹⁹⁻²².

To identify the peeling mode, we propose the following five criteria^{4,23-26} for the associated EHOs: The EHOs must (1) be lower-*n* modes ($\leq 1, 2, 3...$), (2) have a mode structure that extends to all of the plasma surfaces (i.e., not just localized at the LFS), (3) result in perturbation structures that are close to the edge current or corresponding eigenmode, (4) have "kink" parity (rather than "tearing" parity), and (5) be EHOs that are sustained for long times (i.e., times comparable to the current-diffusion time in the edge region). The dynamical steady state during the QH-mode is also reported. The envelope signal of the dominant fundamental mode of the EHOs exhibits repeated growth-damping cycles on the order of a few milliseconds. These cycles are associated with small changes in the pedestal gradient, and the results are quantitatively consistent with a limit-cycleoscillation model.

Results

The JT-60U tokamak is a single null divertor tokamak device with a plasma major and minor radii of 3-3.5 m and 0.6-1.1 m, respectively, and the maximum toroidal magnetic field of ≤ 4 T at a plasma major radius of 3.32 m. The QH-mode plasma on JT- $60U^2$ can be reproduced in the low electron density regime (e.g., Greenwald density fraction of up to ~0.4) under a specific cross-sectional shape of the plasma with an elongation of 1.47 and a triangularity of 0.27. The total plasma volume is 60 m^3 . The plasma current is 1.0 MA, the toroidal magnetic field is ~2.6-2.7 T, and the safety factor at 95% flux surface is ~4. In the observed fluctuation measurements of EHOs in the QH-mode, the

temporal evolution of the multimode fast Fourier transform spectra during a stationary, long-sustained QH-mode is obtained from the electron-cyclotron emission (ECE) radiometer used for local electron-temperature measurements at the LFS and from the far-infrared (FIR) laser interferometers used to obtain lineintegrated electron density measurements along two vertical chords. The two vertical chords pass through the peripheral region of the HFS plasma (FIR-U1) and from top to bottom of the plasma center (FIR-U2), respectively. The radial profiles of the density, temperature, and poloidal/toroidal plasma flows of the fully stripped carbon impurity ions were measured using the charge-exchange recombination spectroscopy diagnostic method with a time resolution of up to 60 Hz. Measurements were performed at 59 spatial points (i.e., 23 toroidal and 36 poloidal viewing chords). We measured the pressure gradient and plasma velocity perpendicular to the magnetic field and evaluated the radial electric field value using the radial force balance in the pedestal region. The radial profiles of electron density and temperature were measured at 15 spatial points using the Thomson scattering diagnostic method with a time resolution of up to 50 Hz.

Observation of low-*n* **EHOs at both the LFS and HFS**. As shown in Fig. 1a–d, the dominant fundamental mode of the EHOs (1f_{EHO}) (obtained from various diagnostics measured at different poloidal (toroidal) angles) occurs at ~10 kHz during a stationary QH-mode phase without large ELMs, keeping the plasma density constant. The magnetic diagnostics identified this 1f_{EHO} mode as n = 2. This QH-mode phase with continuous EHOs ($\tau_{EHOs} \ge 3$ s) was sustained by neutral-beam-injection power of 14 MW (4 MW counter-tangential, 5 MW co-perpendicular, and 5 MW counter-perpendicular injections) for t = 4.5-7.5 s (Fig. 1d), which is significantly longer than the current-diffusion time in the edge region of **O**(1 s).

As illustrated in Fig. 1a–c and e–f, the spectra for the ECE, FIR-U1, and -U2 show that they manifest high coherence among them at the frequency $1f_{\rm EHO} \sim 10 \,\rm kHz$ (n = 2). This observation suggests that the $1f_{\rm EHO}$ mode has a uniform mode structure over the entire circumference of the peripheral region of the plasma (Fig. 1g), and hence it is more likely to be a peeling mode (i.e., nonballooning at the LFS). Conversely, the power (and coherence) for the second-harmonic component that exists at the frequency $2f_{\rm EHO} \sim 20 \,\rm kHz$ ($n \sim 4$) becomes weaker than that of the $1f_{\rm EHO}$ mode, and there are no higher-order modes. Notably, the power spectrum of the EHOs observed in the QH-mode phase at JT-60U is characterized by a dominant fundamental MHD mode rather than containing strong higher-order harmonics (as seen in other devices^{1,3}) which suggests weak nonlinearity (i.e., quasi-linear mode).

Effects of the inner and outer gaps on ELMy/QH operational regimes. The gap width is one of the control knobs that accesses the QH-mode¹⁻³. Therefore, the gap widths on both the LFS and HFS are explored in more detail. In addition, the GAPOUT value (defined by the distance between the last closed flux surface and the wall at the outboard mid-plane) needed to access the stationary QH-mode regime in E042870 was determined by sweeping the edge plasma slowly in another discharge (i.e., E042868), with the cross-sectional shape of the plasma remaining fixed. Therefore, the GAPIN value (defined by the distance between the last closed flux surface and the wall at the inboard mid-plane) is inversely correlated with the GAPOUT value.

Figure 2 (discharge E042868 is shown by solid red lines) demonstrates an extensive gap-scan experiment. For comparison, the equivalent results of a gap-fixed discharge E042870 (as



Fig. 1 Quiescent high-confinement mode (QH-mode) shot (discharge E042870). Fourier analysis of signals (normalized at t = 6.0 s) (**a**) from the electron-cyclotron emission (ECE) at the low-field-side (LFS), together with its measurement position relative to the separatrix (R-R_{SEP}), and from the far-infrared (FIR) laser interferometers for (**b**) the Top/Bottom (FIR-U2) and (**c**) the high-field-side (HFS) (FIR-U1) chords. **d** The total neutral-beam-injection power (black dash-dot line), D_{α} emission from the divertor (solid red line), and line-averaged electron density normalized by the Greenwald density (blue dashed line). The frequency dependences of (**e**) the normalized power spectra for the ECE and FIR-U1 and -U2 and (**f**) their respective coherences evaluated at t = 5.9-6.1 s. **g** Diagnostic locations and magnetohydrodynamic equilibrium reconstruction (from the FBEQU-code) at t = 6.0 s, in which hatched area denotes the peripheral plasma region of the normalized poloidal-flux value of $0.9 \le \psi_N \le 1$.

demonstrated in Fig. 1) are shown in Fig. 2 (blue dotted lines). The main control parameters (e.g., the magnetic field, plasma current, neutral-beam-injection heating power, and plasma crosssectional shape) were almost identical in both discharges, but the GAPOUT/GAPIN values differed. In the configuration with a wider GAPOUT and narrower GAPIN value (~38 and ~33 cm, respectively), small and frequent ELMs (f_{ELM} \sim 100–300 Hz) were observed before the gap scan ($t \le 6.0$ s). During the gap scan toward narrower GAPOUT values (i.e., broader GAPIN values), the frequencies of the ELMs decreased to $f_{ELM} \approx 10 \text{ Hz}$ or less while accessing the QH-mode regime. Note that the GAPOUT/ GAPIN values at t = 6.5 s for discharge E042868 almost matched those of discharge E042870 (Fig. 2a and b). Moreover, changing the gap widths alters the beam deposition profile, fast ion pressure, and fast ion losses at the LFS due to changes in the toroidal-field ripple. We estimate the increase in the total loss power due to orbit-, ripple-, and charge-exchange-losses to be ~10% due to the scan.

This observation does not provide a theoretical understanding of the necessary and sufficient conditions for accessing the QHmode regime; instead, it suggests that the condition of a locally wide gap only at the LFS is insufficient for accessing the stationary QH-mode regime. In any case, this condition is necessary (known as one of the "control knobs" for accessing the QH-regime¹). Compared with other devices, the GAPOUT value seems to be wide enough for this ELMy phase to occur in the pre-QH phase ($t \le 6.4$ s). However, the ELMs reappear in the post-QH phase ($t \ge 6.7$ s) as the GAPOUT value becomes narrower (wider than other devices). This is a known effect, as documented in ref.², which discussed the role of an optimized GAPOUT condition. Further, the conditions of nonlocal gaps at both the LFS and the HFS seem to be more important for the local excitation of EHOs. In future research, these observations will be examined in terms of the wall-stabilizing effect on a peeling mode structure.

As shown in Fig. 3a and b, the edge electron density gradient became slightly weaker in the QH phase than in the ELMy phase. However, the edge electron-temperature gradient exhibited the opposite trend. Thus, the edge electron pressure gradient remained almost unchanged during the transition from the ELMy phase to the QH-mode. The discussion is valid only for the time-averaged profile data; further details regarding the dynamics are presented in the discussion section. Furthermore, the radial structures of the toroidal flow and radial electric field in the QHmode phase in the pedestal region became slightly weaker than those in the ELMy phase (Fig. 3c and d). This observation suggests that a strong shear of the radial electric field is required for QH-mode access, but a moderately large shear may be



Fig. 2 Effects of the inner and outer gaps on the operational regimes of high-confinement mode. Transition from the high-confinement mode with edge-localized mode (ELMy H-mode) to quiescent-mode (QH-mode) was observed in a gap scan during discharge EO42868 (solid red lines), while a gap-fixed discharge (EO42870 shown in blue dashed lines) exhibited a stationary high-confinement mode without edge-localized-mode. **a** GAPIN (defined by the distance between the last closed flux surface and the wall at the inboard mid-plane), **b** GAPOUT (defined by the distance between the last closed flux surface and the wall at the outboard mid-plane), (**c**), and (**d**) D_{α} emission from the divertor, in which hatched area denotes the time at which the GAPOUT/GAPIN values for discharge EO42868 almost matched those of discharge EO42870.

sufficient. Instead, the appearance of EHOs seems to be strongly influenced by the gap optimization, as described above. Indeed, the phase transition from the ELMy to QH-mode was solely induced by changes in the gaps because the other external parameters (e.g., cross-sectional shape, the density of the plasma, and external input torque) were fixed.

The theory of the stability of peeling–ballooning (kink) modes at the plasma edge allows us to confirm one of the peeling mode features for the EHOs in the QH-mode. As illustrated in Fig. 4, the QH-mode data from JT-60U are consistent with the theoretical stability predictions, which have been discussed in previous publications from DIII-D^{27–29}. Consequently, the operating points for the QH (or ELMy) phase are on or below (up to) the low-*n* peeling boundary to within the experimental error bars. However, the dependence of the marginal-stability boundary on the pressure gradient for JT-60U is stronger than that for DIII-D, suggesting that these two devices have different mechanisms for accessing the QH-mode regime.

Radial structure of the peeling mode. Electron-temperature fluctuations measured through ECE within the pedestal region are used to localize the n = 2 mode observed in the magnetics. These are also compared with the expected position using the MHD code. Figure 5 illustrates another important feature of the peeling mode structure for the EHOs in the QH-mode. Fluctuations in



Fig. 3 Pedestal structures during the transition from the ELMy (highconfinement mode with edge-localized mode) to QH (quiescent highconfinement mode) phase in E042868. a Electron density, **b** electron temperature, **c** toroidal flow, and **d** radial electric field. The ELMy and QHphases are evaluated at t = 6.0 s (blue dashed line) and 6.5 s (solid red line), respectively. When fitting the tanh-like functions to the data, the period of the time-averaging was approximated as ±100 ms.

the normalized electron-temperature of the 1f_{EHO} mode (as measured by the ECE with a bandpass filter ($9 \le f_{BPF} \le 10 \text{ kHz}$) are observed to reach a local maximum value at the radial position with respect to the separatrix of $R-R_{SEP} \sim -1$ cm) at which the pressure and current profiles have their steep gradients at the pedestal (Fig. 5a-c). The envelope of the poloidal Fourier components (n = 2) of the linear eigenfunction, $R_e(\xi_r)$ (obtained with the ideal MHD code MARG2 D^{30}), exhibits multiple peak values, which decrease in amplitude from the separatrix to the core region. It is essential that the product of the linear eigenfunction times the inverse gradient scale length $\left| R_{e}(\xi_{r}) \times L_{T_{e}}^{-1} \right| \equiv -\frac{\nabla T_{e}}{T_{e}}$ seems to be reasonably consistent with the radial structure of the 1f_{EHO} mode, exhibiting the so-called "frozen-in" condition of the MHD mode (i.e., the field lines are frozen into the plasma and have to move along with it) 31,32 . This is one of the criteria for identifying the peeling mode. Furthermore, the radial structure of the relative phase difference between the ECE and the magnetic diagnostics (i.e., the saddle coil located on the vacuum vessel) is observed to be almost constant radially, exhibiting a nontearing type of kink parity of the mode, as illustrated in Fig. 5d.

Dynamical steady state of the peeling mode. Examining Fig. 5c in more detail, we note that the reconstructed radial structure of the $1f_{EHO}$ mode is not smooth, unlike a Gaussian shape. Indeed, the envelope of the $1f_{EHO}$ mode seen in the ECE data ($\tilde{T}_e^{Env.}$), at which a narrow bandpass filter ($f_{BPF} = 9.53 - 9.65$ kHz) was applied for the raw data (i.e., calibrated and verified data), exhibits repeated growth and damping cycles in the span of a few milliseconds (the corresponding frequency is about $f_{envelope} \sim 170$ Hz) at a fixed measurement position (e.g., $R-R_{SEP} \sim -1$ cm), as



Fig. 4 MHD stability diagrams of the ELMy (high-confinement mode with edge-localized-mode evaluated at t = 6.0 s) and QH (quiescent high-confinement mode evaluated at t = 6.5 s) phases in E042868. The stability analysis was performed for ideal MHD modes with toroidal mode numbers ranging from 1 to 50. When setting the boundary conditions, the JT-60U vacuum vessel was assumed as an ideal conducting wall. Here, the normalized pedestal current (j_{ped} .^{max}/<j>) is plotted against the normalized pressure gradient (α_{ped} .^{max}) at the pedestal, showing the MHD equilibria. The small numbers associated with the curves correspond to the toroidal mode number of the most unstable kink, peeling, or ballooning modes for several locations in the normalized pedestal current ($(j_{ped}^{max})/(j)$) and pressure-gradient (α_{ped}^{max}) space. The error bars for ELMy (blue star)/QH (red filled star) operation points represent compound errors that result from propagation of the uncertainties in estimating the pedestal current and pressure gradient.

illustrated in Fig. 6a. The oscillation amplitude is the same as that of $\tilde{T}_e^{Env.}$ at the LFS, as can be seen in the $1f_{EHO}$ envelope signals from both the FIR-U1 (HFS) and the FIR-U2 (Top/Bottom) data at almost the same frequency (~ $f_{envelope}$), as shown in Fig. 6b and d. The most crucial point is that the same oscillation at the frequency ~ $f_e^{nvelope}$ can be seen in the "mean" temperature gradient, $\nabla \tilde{T}_e^{Mean} \equiv \Delta \tilde{T}_e^{ECE} / \Delta R^{ECE}$, as shown in Fig. 6c and d. Here, the values of $\Delta \tilde{T}_e^{ECE}$ are obtained by subtracting the ECE data at R $-R_{SEP} \sim -1$ cm from that at $R-R_{SEP} \sim -4$ cm ($\Delta R^{ECE} = 3$ cm) and applying a bandpass filter over the frequency range $f_{BPF} = 100{-}300$ Hz.

Note that the experimental identification described above was made possible because the EHOs were in a state close to that of a linear mode, with almost no higher harmonics. However, the observation of a QH-mode phase remaining stationary longer than its MHD instability growth rate seems strange from a common-sense point of view. Thus, there must be a mechanism to keep the peeling mode from growing explosively. Furthermore, this mechanism is provided by a "dynamical" stationary phase that has a timescale of variation of a few ms ($\sim 1/f_{envelope}$), which is a much longer period than the peeling mode: $1/f_{EHOs} \sim O(0.1 \text{ ms})$. As a result, we conclude that the peeling mode (which has almost no higher-harmonic components) has been identified as a "dynamical" steady state of a QH-mode phase that does not have any large ELMs.

This dynamical steady state is realized as a limit-cycle oscillation, as shown by the relationship between ∇T_e^{Mean} (the mean temperature gradient) and $\tilde{T}_e^{Env.}$ (the envelope of the $1f_{EHO}$ mode). Figure 6e illustrates that the change in ∇T_e^{Mean} follows the change in $\tilde{T}_e^{Env.}$. Once the peeling mode grows (observed as increments of $\tilde{T}_e^{Env.}$), the mean gradient becomes small. The



Fig. 5 Radial profiles of the QH-mode phase. a Pressure and safety factor, **b** pedestal current and linear eigenfunction of the unstable peeling-ballooning mode obtained with the MARG2D code, **c** normalized electron-temperature fluctuations measured by the electron-cyclotron-emission (ECE) diagnostic for the fundamental component of edge-harmonic oscillations (1f_{EHO}) and the product of the poloidal Fourier components (n = 2) of the linear eigenfunction, R_e (ξ_r) (obtained with the ideal MHD code MARG2D) times the inverse gradient scale length, $L_{T_e}^{-1} \left(\equiv -\frac{\nabla T_e}{T_e} \right)$, and **d** the frequency spectrum of the relative phase difference between the ECE and the magnetic diagnostics (saddle coil). These radial structures were obtained during the gap scan shown in Fig. 2 for discharge E042868 (t = 6.325-6.565 s), mapped onto the single-time equilibrium at t = 6.5 s as a function of distance from the separatrix (R-R_{SEP}) at the low-field mid-plane of the plasma.

decrease in the mean gradient suppresses the peeling mode growth (seen in the decrease in $\tilde{T}_e^{Env.}$), which results in the recovery of the pedestal structure toward the original state. Then, the peeling mode starts to grow again, and the cycle repeats.

Discussion

This limit-cycle was modeled in ref. ³³. Noting that the oscillation period [e.g., $1/f_{envelope} \sim O(1 \text{ ms})$] is much shorter than the current-diffusion time [e.g., O(1 ss)], the coupled dynamics between the peeling mode amplitude and the edge pressure gradient assumes that the magnetic structure (edge current and magnetic-shear parameter) is constant during this oscillation. We found that a limit-cycle oscillation of the paired mode amplitude and edge gradient can emerge if the stability boundary has a form like that shown in Fig. 4 (i.e., the peeling mode is unstable in the higher-gradient domains across the stability boundary). In the stability diagram, we determine the stability boundary by associating the unstable equilibrium to a single-*n* MHD mode. Therefore, the condition γ (most unstable mode) $\gg \gamma$ (others) = 0 is satisfied on the boundary, where γ is the growth rate. It should be noted that the spectrum of the growth rate peaked near the stability boundary.

We estimate the incremental loss rate of the edge gradient due to the peeling mode as $\tau_{peel} \sim d^2/\Gamma\xi^2$, where *d* is the scale length of the gradient of the edge pedestal. Moreover, Γ and ξ are the decorrelation rate and the radial-oscillation length of the peeling



Fig. 6 Dynamical steady state of the peeling mode in the quiescent high-confinement (QH) mode (discharge E042870). Temporal behavior of the fluctuations **a** of the temperature measured by the electron-cyclotron-emission (ECE), **b** of the density measured by the far-infrared (FIR) laser interferometers, FIR-U1 (green) and FIR-U2 (blue), and **c** of the mean temperature gradient (discharge E042870). A bandpass filter ($f_{BPF} = 9.53-9.65$ kHz) around the fundamental component of edge-harmonic oscillations ($1f_{EHO}$) was applied to the raw data in (**a**) and (**b**), while a bandpass filter with $f_{BPF} = 0.1-0.3$ kHz was applied in (**c**). Frequency spectra (**d**) for the envelope of the data (ECE: solid red line, FIR-U2: blue dash-dot line, and FIR-U1: green dashed line) shown in (**a**)–(**b**), and for the mean temperature gradient data (black dotted line) shown in (**c**). **e** The relationship between fluctuations of the mean temperature gradient (Fig. 6c) and the envelope signal of the $1f_{EHO}$ mode (Fig. 6a) from the ECE data after applying an additional bandpass filter around $f_{envelope} = 170 \pm 15$ Hz traces a Lissajous figure. The time-window for (**d**)–(**e**) is t = 6.01-6.07 s. The clockwise arrows of the peeling-growth (-decay) in (**e**) denote the temporal evolution of the increment (decrease) of the envelope of the $1f_{EHO}$ mode as the mean gradient becomes small (large).

mode, respectively. The characteristic timescale of the limit-cycle oscillation is $2\pi f_{LCO}^{Cal} \sim (\gamma_0/\tau_{peel})^{1/2}$, where γ_0 is the characteristic growth rate of the linear peeling mode. If one chooses $\xi \sim \mathbf{O}$ (1 mm) (which needs further experimental verification), $d \sim 2$ cm, and $\Gamma/2\pi \sim 0.5$ kHz as characteristic estimates from the observations, one obtains $1/\tau_{peel} \sim \mathbf{O}(10 \text{ s}^{-1})$. Using a typical value, say, $\gamma_0 \sim 10^5 \text{ s}^{-1}$, one finds $(\gamma_0/\tau_{peel})^{1/2} \sim \mathbf{O}(10^3 \text{ s}^{-1})$ and $f_{LCO}^{Cal} \sim \mathbf{O}$ (200 Hz). The observations are quantitatively consistent with this new model of limit-cycle oscillations, especially for the expected order of magnitude of the timescale, $\mathbf{O}(f_{LCO}^{Cal.}) \sim f_{envelope}$. The effect of strong $\mathbf{E} \times \mathbf{B}$ shear flow^{34–37} was also discussed in ref. ³³, and the result is qualitatively unchanged.

In conclusion, we have presented an evidence of the peeling mode for EHOs seen in the peripheral region of the plasma for the QH-mode in JT-60U. This evidence meets the five criteria described above. Furthermore, the saturation mechanism that enables the EHOs to peel off the pedestal (without the effect growing explosively) is presented. In particular, the dominant fundamental mode of the EHOs is observed to repeat cycles of growth and damping, in association with changes in the mean temperature gradient, on the order of a few 100 Hz. This observation is quantitatively consistent with the new dynamical quasilinear steady-state model of limit-cycle oscillations independent of the existence of a strong $\mathbf{E} \times \mathbf{B}$ shear flow exists. This finding further sheds light on the "peeling nature" of laboratory and astronomical plasmas (e.g., ELM events in magneticconfinement-fusion plasmas and solar/stellar flares).

Methods

QH-mode operation on JT-60U². The QH-mode plasma on JT-60U can be reproduced in the low electron density regime of $\sim 2 \times 10^{19}$ m⁻³ without additional gas-puffing. With regard to the momentum injection, a tangential neutral-beam-power injection (~4 MW) in the direction counter-parallel to the plasma current is likely to access the QH-mode regime with stationary EHOs with an additional perpendicular neutral-beam-power injection (~10 MW). Moreover, the QH-mode operation with a tangential neutral-beam-power injection (~4 MW) in the direction co-parallel to the plasma current is possible. The appearance of EHOs and their stationary sustainment was strongly influenced by the optimization of the GAPOUT value (defined by the distance between the last closed flux surface and the wall at the outboard mid-plane) as well as the GAPIN value (defined by the distance between the last closed mid-plane). The typical GAPOUT and GAPOUT values are ~36–37 and ~32–33 cm, respectively, which were determined by sweeping the edge plasma slowly, with the cross-sectional shape of the plasma remaining fixed.

MHD stability analysis. The stability analysis was conducted under the following conditions. The ideal MHD modes with toroidal mode numbers from 1 to 50 were analyzed in the JT-60U vacuum vessel, assuming the ideal- conducting boundary conditions at the vessel walls. The plasma surface was positioned at $\bar{\psi} = 0.995$, and the stability threshold was assumed to be $\gamma - 0.5\omega_{*i}$, where $\bar{\psi}$ is the poloidal flux normalized to 0 (1) on the axis (surface), γ is the growth rate, and ω_{*i} is the effective ion diamagnetic drift frequency, calculated as $\xi |\omega_{*i}| \xi / \xi | \xi$. Here, ξ is the eigenfunction of the MHD mode, and $\langle A \rangle$ is the volume integral of A in the system. Notably, a purely ideal peeling mode is usually stabilized under the ion diamagnetic drift effect even when the toroidal mode number is low (≤ 3) due to the small growth rate of the mode.

Data availability

Any relevant data are available from the authors upon reasonable request after proper procedure at JT-60 Data Analysis Server (nakasvr17), http://nakasvr17.naka.qst.go.jp/index-en.html.

Code availability

Any relevant codes developed for this study can be accessed from the authors, and a report of its use should cite this paper.

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Author contributions

K.K. analyzed the data. K.I. provided the theoretical models. N.A. and M.H. analyzed the MHD stability. K.K., K.I., and N.A. discussed the model validation. K.K., N.O., and A.I. discussed the diagnostics accuracy for the fluctuation measurements. K.K. and K.I. wrote the main manuscript text, and all the authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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