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Plasma Physics and Controlled Fusion

PAPER

Characterization of the quasi-coherent mode in QCE in experiment and simulation

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Abstract

The quasi-coherent mode (QCM) observed in the type-I edge-localized mode free quasi-continuous exhaust (QCE) regime of ASDEX Upgrade is studied through a detailed comparison of experimental measurements and linear gyrokinetic simulations using the GENE code. The QCM, detected by the thermal helium beam diagnostic near the separatrix, i.e. at $\rho_{\text{pol}} \approx 0.99$, exhibits a frequency of approximately 30 kHz and a normalized poloidal wavenumber in the range $0.02 < k_{\theta} \rho_s < 0.08$. It propagates in the ion diamagnetic direction with roughly half the ion diamagnetic velocity in the plasma frame and shows electromagnetic characteristics. Cross-phase analyses reveal in-phase density and temperature fluctuations, i.e. $\alpha_{n_e, T_e} \approx 0$, while an interchange-like cross-phase between density and potential fluctuation, i.e. $\alpha_{n_e, \phi} \approx -0.7\pi$ is observed, indicating a pressure-driven nature. Linear local GENE simulations quantitatively reproduce its location at $\rho_{\text{pol}} = 0.991$, wavenumbers, propagation direction, and cross-phase behavior. Parameter scans demonstrate a strong dependence of the growth rate on the normalized electron pressure β_e , confirming the electromagnetic character of the instability, and negligible sensitivity to collisionality ν_c . The combined experimental and simulation results consistently identify the underlying QCM instability as a kinetic ballooning mode.

1. Introduction

For future tokamak fusion reactors, such as ITER [1], operating in high confinement regimes [2] without type-I edge localized modes (ELMs) is preferred. Type-I ELMs are generally caused by the peeling-ballooning instability, appearing at sufficiently high pressure gradients and current densities at the plasma edge [3]. This limit is reached in classical ELMy H-modes, and the resulting type-I ELMs generate a heat load that would be too large for large future fusion machines to tolerate [4]. Type-I ELM-free regimes provide a remedy. It can be shown that an edge fluctuation, or edge mode, caused by an edge instability occurs in almost all type-I ELM-free regimes [5]. Typically, the edge mode causes sufficient radial transport at the plasma edge to flatten the pressure gradient, thereby avoiding type-I ELMs.

In this work, we focus on the quasi-coherent mode (QCM), which appears in the enhanced D_{α} high confinement mode (EDA H-mode) [6] and quasi-continuous exhaust scenario (QCE) regime [7, 8] at the tokamak experiment ASDEX Upgrade [9–11]. Generally, the QCM is a well-documented phenomenon that occurs in several tokamaks, including TCV [12], DIII-D [13, 14], EAST [15] and Alcator

C-Mod [16, 17]. The EDA H-mode and QCE are quite similar from an operational standpoint and are achieved through high plasma shaping, i.e. high triangularity δ and elongation κ_{geo} . From a mode perspective, Harrer *et al* [18] found that EDA H-modes have one ballooning unstable radial region, whereas QCE has two, with a small stable region separating them radially. In addition, the QCM frequency in QCE discharges has been observed to be higher than in EDA H-modes [19]. Additionally, QCE is characterized by filaments that dominate transport in the scrape-off layer.

Because the edge mode is thought to be responsible for the absence of type-I ELMs, whether such an ELM-free regime can be achieved in the future depends on whether the corresponding edge mode appears. However, to answer this question, we must first determine the nature of the edge mode, which is the subject of this work. Some mode fingerprints can be determined experimentally and compared with those of theoretically derived linear edge instabilities [20]. These include the poloidal wavenumber, $k_\theta \rho_s$, which must be normalized to the hybrid gyroradius $\rho_s = \sqrt{m_i T_e / (qB)}$, including the ion mass m_i and charge q , electron temperature T_e and the magnetic field strength B . Furthermore, the poloidal phase velocity of the mode in the plasma frame is of great interest $v_{\text{ph}} = v_{\text{lab}} - v_{E \times B}$, for which one must determine the externally measured laboratory velocity of the mode v_{lab} , composed of k_θ and the measured frequency f_{QCM} , i.e. $v_{\text{lab}} = 2\pi f_{\text{QCM}} / k_\theta$ and the $E \times B$ background velocity of the plasma $v_{E \times B}$, for which ion data or data from Doppler back-scattering [21] are required. Furthermore, identifying the nature of the QCM involves understanding of the cross phases between different fluctuating quantities. The focus is on the cross phase between electron density and temperature α_{n_e, T_e} and between electron density and potential $\alpha_{n_e, \phi}$.

The thermal helium beam diagnostic (THB) [22, 23] is used as the main diagnostic tool due its excellent temporal (900 kHz) and spatial (3 mm) resolution. The measurements are sensitive to electron temperature and density and they are performed locally, near the separatrix at the outer mid-plane of the plasma. The exact methodology used for data analysis can be found in reference [24].

This paper presents and compares the experimental results of the QCM in EDA H-modes and QCEs at ASDEX Upgrade using the THB diagnostic with linear simulations of the gyrokinetic turbulence code GENE [25]. The results are discussed at the end of the paper, along with an outlook.

2. Characterization of the QCM

The following section compares experimentally determined mode properties, largely taken from previous work [19] and partly extended, and compares them with the results of a linear simulations from GENE.

This study focuses on discharge #39 605, which has a toroidal magnetic field strength of $B_t = -1.9$ T and a plasma current of $I_p = 1.1$ MA in a lower single null configuration. An overview of the discharge is presented in figure 1, which comprehensively captures the temporal evolution of key plasma parameters and diagnostic signals. Figure 1(a) displays time traces of the various heating sources, including electron cyclotron resonance heating (P_{ECRH} , green), Ohmic heating (P_{Ohmic} , purple), neutral beam injection (P_{NBI} , black), and ion cyclotron resonance heating (P_{ICRH} , blue) as well as the total radiated power (P_{rad} , red). Further insight into the plasma behavior is provided by the temporal evolution of the line-integrated electron densities $\bar{n}_e$, measured via interferometry [26] in the plasma core and edge, together with the plasma stored energy W_{MHD} . Notably, these traces reveal a clear transition from the low-confinement (L-mode) phase to the QCE regime, which occurs approximately after $t \approx 3$ s. To evaluate the reactor relevance and confinement quality of the scenario, several dimensionless plasma parameters are presented in figure 1(c). These include the energy confinement enhancement factor (H_{98y2}) [27], the normalized plasma beta (β_N) [28], and the Greenwald density fraction (f_{GW}) [29]. Figure 1(d) shows divertor currents, which act as proxies for the particle and energy fluxes arriving at the divertor targets. The plasma is mostly free of type-I ELMs except for a short phase at around $t \approx 5$ s, in line with the requirements for possible future steady-state fusion scenarios. Below (figure 1(e)), a spectrogram from the THB diagnostic, which measures electron temperature and density fluctuations near the separatrix (here at $\rho_{\text{pol}} = 0.99$), illustrates the presence of a fluctuation, i.e. the QCM at a frequency of approximately $f_{\text{QCM}} \approx 30$ kHz during the QCE phase. The dark blue vertical stripes in the THB spectrogram indicate the beam-off phases, i.e. the times when He is not actively puffed into the plasma. ρ_{pol} is defined as $\rho_{\text{pol}} = \sqrt{(\Psi - \Psi_a) / (\Psi_{\text{sep}} - \Psi_a)}$, where Ψ is the poloidal magnetic flux and Ψ_a the corresponding magnetic flux at the magnetic axis and Ψ_{sep} at the separatrix. The QCM can also be observed by the measurement of magnetic field coils (see figure 1(f)), measuring deviations of the radial field

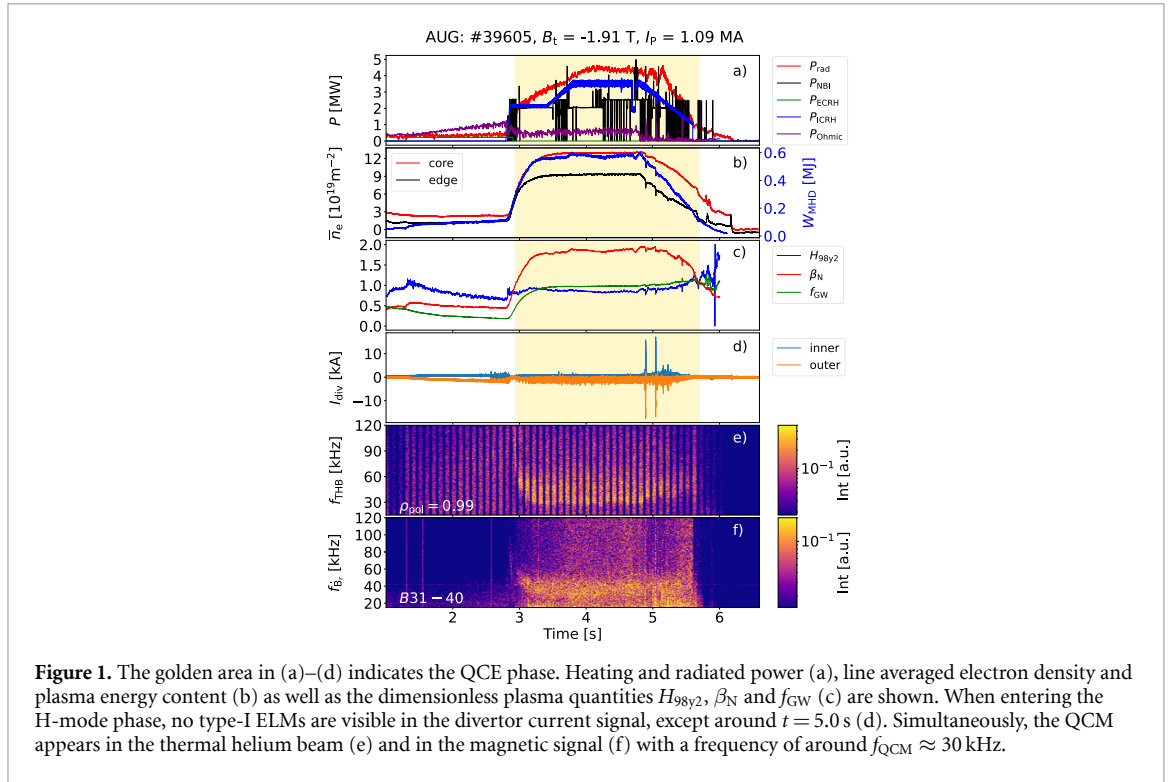


Figure 1. The golden area in (a)–(d) indicates the QCE phase. Heating and radiated power (a), line averaged electron density and plasma energy content (b) as well as the dimensionless plasma quantities H_{98y2} , β_N and f_{GW} (c) are shown. When entering the H-mode phase, no type-I ELMs are visible in the divertor current signal, except around $t = 5.0$ s (d). Simultaneously, the QCM appears in the thermal helium beam (e) and in the magnetic signal (f) with a frequency of around $f_{QCM} \approx 30$ kHz.

component $\tilde{B}_r$, thus indicating the electromagnetic nature of the observed QCM. It is notable that when zooming in on figure 1(d), the divertor current reflects mainly the filaments, that are typical for QCE discharges. This finding is discussed in more detail in appendix A.

2.1. Experimental results

The QCM was radially located in the confined region, just inside the separatrix at $\rho_{pol} = 0.99$. The radial position was identified as the position of the mode with the highest Fourier amplitude after subtracting the background measured with the THB. Figure 2(a) shows an example localization for a 30 ms time interval in an R - z diagram. The light gray dots represent the THB measurement positions, and the yellow line represents the separatrix. The color map reflects the measured Fourier amplitude at each measurement channel: light colors represent high values, dark colors represent low values. The mode is located along the lime green line, i.e. at $\rho_{pol} = 0.99$.

Experiments have shown that the QCM has a normalized poloidal wavenumber that falls between the ranges of $0.025 < k_\theta \rho_s < 0.075$. In our classification, this is in the mesoscale between classical MHD instabilities and microinstabilities [20]. Further insights are gained by examining the propagation velocity of the QCM in the poloidal direction within the plasma frame. To get this quantity, we measured first the velocity of the QCM in the poloidal direction in the laboratory frame, which was found to be between -1 km s^{-1} and -6 km s^{-1} . The negative sign indicates that the mode propagates in the electron diamagnetic direction in the laboratory frame, which is consistent with the rotation direction of the background plasma. However, it could be shown that the background $E \times B$ velocity is larger in absolute values, i.e. $v_{E \times B}$ is between $(-5 \pm 3) \text{ km s}^{-1}$ and $(-12 \pm 2) \text{ km s}^{-1}$, indicating that the mode propagates in ion diamagnetic direction (IDD) in the plasma frame. On average, the QCM moves at approximately $v_{ph} = (1/2) v_{i,dia}$ in the plasma frame, where $v_{i,dia} \sim (-10 \pm 2) \text{ km s}^{-1}$ is the ion diamagnetic velocity. The ion data is measured by edge charge exchange recombination spectroscopy [30]. All values and profiles can be found in reference [19]. This means that only ballooning-like modes or ion temperature gradient driven modes (ITG) [31] can be considered as the underlying QCM nature. However, since we operate in the high electromagnetic range (high plasma beta), and ITGs are stabilized in this range [32], electromagnetic ballooning modes are particularly favored as candidates for the QCM, i.e. ideal (IBM) [33], resistive (RBM) [34] or kinetic ballooning modes (KBM) [32].

Next, we will discuss two other interesting quantities: the cross phase between electron density and temperature fluctuations α_{n_e, T_e} , which can be measured with the THB and the cross phase between density and potential fluctuations $\alpha_{n_e, \phi}$, which can be measured with the ball-pen probe (BPP) [35]. These quantities are important for identifying the mode and will be useful for later comparison with the simulation.

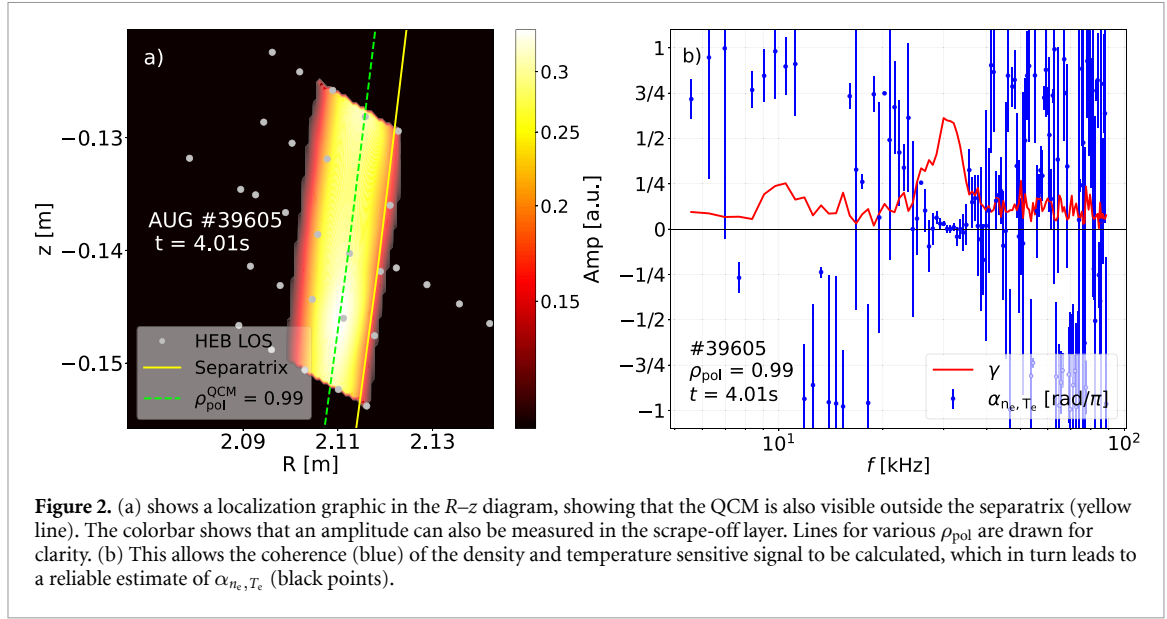


Figure 2. (a) shows a localization graphic in the R - z diagram, showing that the QCM is also visible outside the separatrix (yellow line). The colorbar shows that an amplitude can also be measured in the scrape-off layer. Lines for various ρ_{pol} are drawn for clarity. (b) This allows the coherence (blue) of the density and temperature sensitive signal to be calculated, which in turn leads to a reliable estimate of α_{n_e, T_e} (black points).

For the calculation of α_{n_e, T_e} with the THB we follow the work by Nishizawa *et al* [36]. The basic idea is to combine the individual light intensities measured by the THB so that a n_e —sensitive quantity and a T_e —sensitive quantity is obtained. These quantities are labeled $R_I^{n_e}$ and $R_I^{T_e}$, respectively. Then, the cross phase α_{n_e, T_e} can easily be determined from the cross spectrum of these two quantities (details in reference [36]). Although this quantity is rarely used in theoretical considerations, it provides another indication of the underlying instability of the QCM, as this quantity can be validated by simulation results later on. To determine α_{n_e, T_e} (blue dots in figure 2(b)), it is necessary that the coherence γ (blue) of the density sensitive $R_I^{n_e}$ and temperature sensitive signal $R_I^{T_e}$, is sufficiently large. The coherence is defined as

$$\gamma = \frac{\left| \left\langle R_I^{n_e}(f) \left(R_I^{T_e} \right)^*(f) \right\rangle \right|^2}{\sqrt{\left\langle \left(R_I^{n_e}(f) \right)^2 \right\rangle \left\langle \left(R_I^{T_e}(f) \right)^2 \right\rangle}}. \quad (1)$$

A value of one indicates a strong correlation and a value of zero indicates that they are completely uncorrelated. Figure 2(b) shows a γ of 50% which is sufficiently large at the QCM frequency. It is observable, that the density $\tilde{n}_e$ and temperature fluctuations $\tilde{T}_e$ are in-phase, i.e. $\alpha_{n_e, T_e}^{\text{QCM}} \approx 0$, indicating that the QCM amplitude is a pressure perturbation without separate dynamics for n_e and T_e .

Furthermore, a high-flux BPP head at the outer mid-plane is used to obtain the cross-phase between potential and density fluctuations [35]. The apparatus under consideration consists of four Langmuir and three ball-pen pins. These instruments are designed to facilitate the study of fluctuations in plasma potential (ϕ^{BPP}), electron density (n_e), and electron temperature (T_e). Hence, the cross-phase between density and potential fluctuations, denoted by $\alpha_{n_e, \phi}$, which is instrumental for mode characterization, can be ascertained. Unfortunately, no BPP data was available in the proposed discharge. Since it has been shown that the QCM in EDA H-modes and QCE plasmas is very similar [19], we will use the cross phase measured for a QCM in a classic EDA H-mode as a point of comparison, which is $\alpha_{n_e, \phi} \approx -0.7\pi$ [37]. It must be noted that this measurement was performed slightly further out than the mode position, at approximately $\rho_{\text{pol}} = 0.997$. Nonetheless, this once again shows that electromagnetic ballooning modes are the favored candidates for the QCM.

Now, it is interesting to know which type of ballooning instability, i.e. kinetic or resistive, is more likely to be linked to the QCM. Generally, these are almost impossible to distinguish in experiments and therefore, the use of simulations will be employed henceforth.

2.2. Simulation results

To compare with the experimental results we performed local (flux tube) linear gyrokinetic simulations with the GENE code, which has already been extensively validated in core plasmas [38]. Additionally, GENE was used to perform validated runs for the plasma edge [31]. This allows us to characterize the

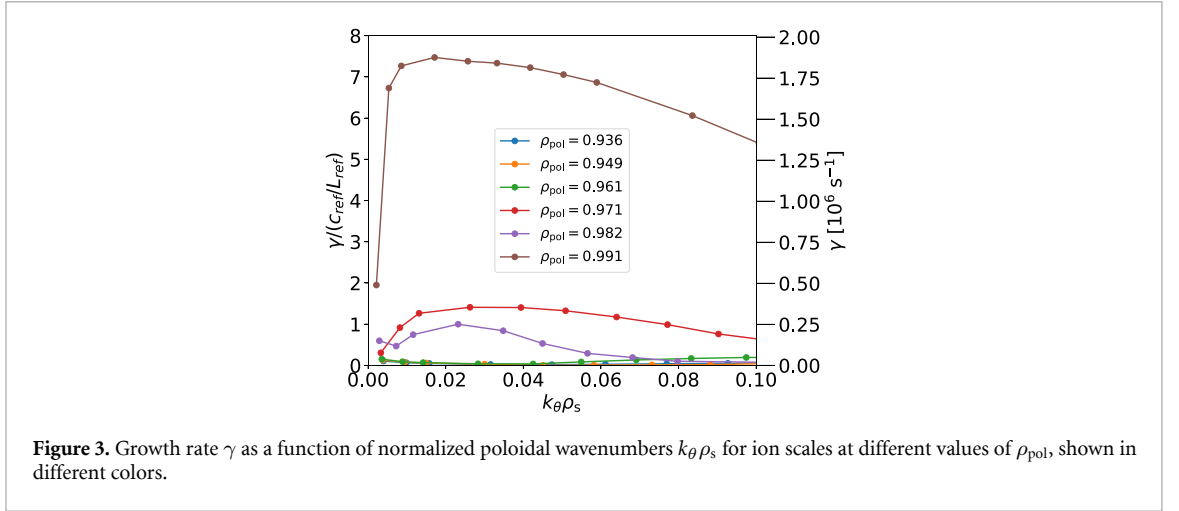


Figure 3. Growth rate γ as a function of normalized poloidal wavenumbers $k_\theta \rho_s$ for ion scales at different values of ρ_{pol} , shown in different colors.

dominant modes in the system by studying their trends and dependencies with other plasma parameters at moderate computational costs.

All simulations are electromagnetic with deuterium ions and electrons as the main species. The effect of impurities is considered through the effective charge Z_{eff} in the collision operator. The typical grid resolution at a given toroidal mode number is $(n_{kx}, n_z, n_{v_{||}}, n_\mu) = (15, 64, 48, 16)$, with n_{kx} the number of radial modes in Fourier representation, n_z the points in the parallel coordinate, and $n_{v_{||}} \times n_\mu$ the total points of the velocity space. Higher resolution tests were also performed using a grid of $(n_{kx}, n_z, n_{v_{||}}, n_\mu) = (31, 96, 64, 32)$.

We begin with a scan over the poloidal wavenumber across different radial positions, as shown in figure 3. Initially, scans were performed up to electron scales ($k_\theta \rho_s \gg 1$), which revealed dominant electron temperature gradient mode activity. However, since our goal is to compare the simulation results with the QCM, which can be found on the ion scale as shown above, we will not examine the electron scales further. On the corresponding ion scale, two prominent modes with ballooning parity are present at $\rho_{\text{pol}} = 0.971$ and $\rho_{\text{pol}} = 0.991$, with the latter agreeing with the radial position of the QCM (cf figure 2(a)). We observe that the mode that is radially furthest out exists across nearly the entire $k_\theta \rho_s$ scale, and it generally agrees well with the $k_\theta \rho_s$ from the experiment (see section 2.1).

Focusing on this mode with $k_\theta \rho_s = 0.03$, a phase velocity of approximately $v_{\text{ph}}^{\text{GENE}} = 0.43 v_{i, \text{dia}}$ was found in the ion diamagnetic propagation direction. Moreover, the electron density and temperature fluctuations remained in phase, i.e. $\alpha_{n_e, T_e}^{\text{GENE}} = 0$, while the cross phase between density and potential was determined to be $\alpha_{n_e, \phi}^{\text{GENE}} \approx -0.77\pi$. All three simulation variables match the experimentally measured values (cf section 2.1).

Furthermore, we carry out scans over the normalized collisionality $\nu_c = \pi \ln \Lambda e^4 n_{\text{ref}} L_{\text{ref}} / 2^{3/2} T_{\text{ref}}^2$ corresponding to the common factor between the species-dependent collisionalities, and electron beta $\beta_e = 8\pi n_{\text{ref}} T_{\text{ref}} / B_{\text{ref}}^2$ in figure 4, where $\ln \Lambda$ is the Coulomb logarithm and n_{ref} , T_{ref} , and B_{ref} are the reference values of density, temperature and magnetic field, respectively. L_{ref} is set to 0.66m. The rest are extracted from the experimental profiles at the radial position considered. For both scans we take advantage of the theoretical model to identify the impact of collisionality and β_e independently of other parameters, elucidating their direct dependence on the mode of interest.

Based on the strong dependence of the growth rate with β_e (black curve in figure 4) it is clear that the mode has an electromagnetic character, which in addition to having ballooning parity suggest either KBM or RBM activity. However, RBMs have a marked dependency with collisionality [34], which is not observed in our ν_c scan (purple in figure 4), except for the highest collisionality value, that lies far beyond the experimentally determined values and is therefore not assigned any significance. In addition to the expected dependence of the growth rate on ν_c , one would expect the mode to disappear as $\nu_c \rightarrow 0$ in the case of an RBM, since collisionality (or resistivity) is necessary for RBMs. However, since the growth rate remains constant as ν_c decreases, we do not favor an RBM in our simulation setup.

The QCE operation window is often associated with a fixed collisionality (or turbulence parameter α_T value [39]), and the presented results seem to contradict this, as the GENE runs show a dominant dependence on β_e . However, QCE was originally defined through the onset of a ballooning mode at the pedestal foot [18], and this mode is indeed recovered in the simulation. Notably, the mode itself does not need to have a collisionality dependence. The additional filament structures—potentially originating

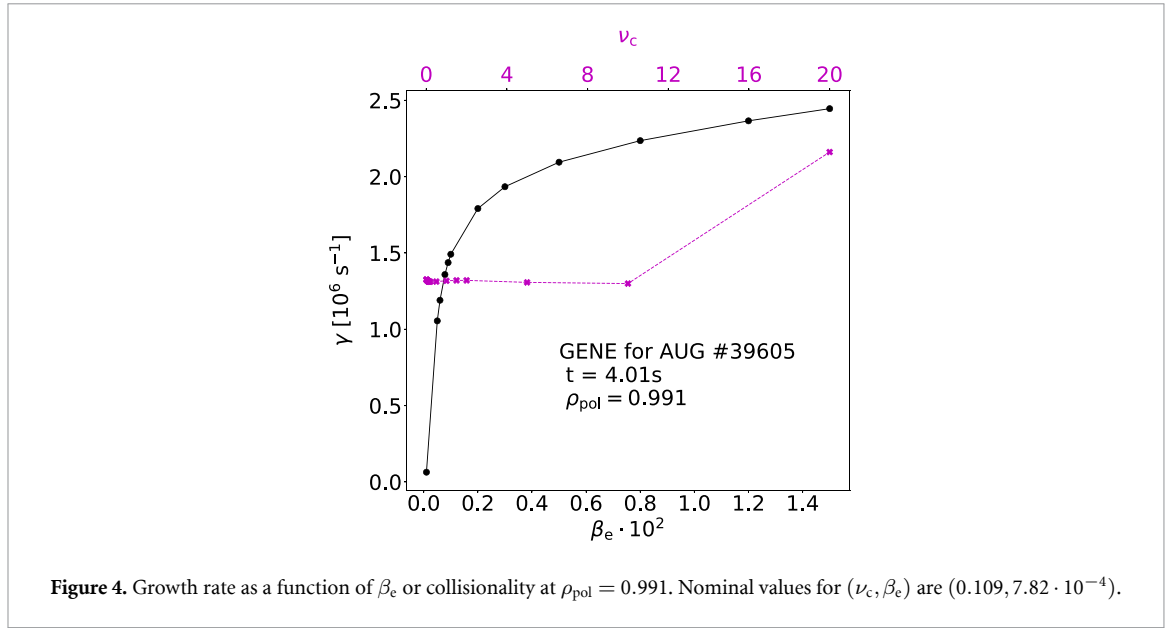


Figure 4. Growth rate as a function of β_e or collisionality at $\rho_{\text{pol}} = 0.991$. Nominal values for (ν_c, β_e) are $(0.109, 7.82 \cdot 10^{-4})$.

at the separatrix or further out—which are likewise characteristic of the QCE, may exhibit a collisionality dependence. Such structures are located outside the radial domain presently accessible to GENE and are therefore not captured in the simulations discussed here. Consequently, it cannot be determined on the basis of the present results whether the filaments are generated by the QCM or are associated with a distinct instability. A definitive clarification of this issue requires dedicated investigations in future work. The scans were repeated for the modes found further inside (at $\rho_{\text{pol}} = 0.971$ and $\rho_{\text{pol}} = 0.982$), shown in appendix B. An increase in growth rate with higher collisionality was found there. However, the main argument that the mode remains when collisionality disappears still holds. This behavior was confirmed in the linear GENE simulation for a pure EDA H-mode case [40]. The nominal electron beta appears to be the decisive parameter for the appearance of the mode, which is why the KBM is favored. Furthermore, it should be noted that nonlinear simulations of this case could adjust these findings, and collisionality dependence could still be identified. Additionally, analyses of EDA H-modes (and QCEs) at Alcator C-Mod require a beta limit rather than a collisionality limit to access these regimes [41]. In summary, it can be said that the presented results do not necessarily contradict those of reference [10].

Another variable to consider for this scenario is the value of the normalized parallel electric field, given by $\hat{E}_{\parallel} = (\int |-\partial_z \phi_1 + \partial_t A_1| dz) / (\int |\partial_z \phi_1| dz + \int |\partial_t A_1| dz)$. For modes largely driven by ideal MHD, one would expect a value of $\hat{E}_{\parallel} \lesssim 0.1$ [42, 43]. In this case, the value of $\hat{E}_{\parallel}$ ranged from 0.05 to 0.15 (depending on the specific wavenumber considered), which aligns well with the dominant mode being a KBM.

We note that impurity checks, such as Z_{eff} scans and the inclusion of a gyrokinetic impurity species were performed. However, only minor changes, and no qualitative changes in behavior, were found.

Overall, these results point to KBM activity as the primary drive of transport on this case at the plasma edge. The presence of this mode can therefore lead to the absence of type-I ELMs as mentioned above.

3. Summary

This paper presents a comparison of the experimental and simulated results of the QCM that appears at the plasma edge in QCE discharges. Results from the experiment, determined using the THB diagnostic and the BPP at ASDEX Upgrade, showed excellent agreement with local, linear GENE simulation results for the key parameters. Experiment and simulation both exhibited a mode that:

- (i) exists at the plasma edge at $\rho_{\text{pol}} \approx 0.99$,
- (ii) has a normalized poloidal wavenumber in the range $0.02 < k_{\theta} \rho_s < 0.08$,
- (iii) propagates in the plasma frame in the IDD with nearly half the ion diamagnetic velocity,

- (iv) exhibits a vanishing cross phase between electron temperature and density fluctuations, i.e.
 $\alpha_{n_e, T_e} \sim 0$,
- (v) exhibits an interchange-like cross phase between electron density and potential fluctuations, i.e.
 $\alpha_{n_e, \phi} = -0.7\pi$ (experimental data from an EDA H-mode) and
- (vi) has an electromagnetic character.

Consequently, we can assert that the instability observed in the GENE simulation corresponds to the QCM present in the QCE discharge.

Additionally, scans of the normalized collisionality (with almost no change in the mode growth rate) and electron beta β_e (large influence on growth rate) have led us to conclude that we can identify the mode from the simulation as a KBM, which is consistent with the experimental results of the QCM.

As a side note, we were also able to categorize other instabilities with the help of the THB. For instance, the weakly coherent mode in the improved energy confinement mode (I-mode) is attributed to a drift wave-like mode [44]. Similarly, the edge instabilities of the intermediate phase (I-phase) are attributed to a micro-tearing mode [45]. Therefore, it can be concluded that the THB is unbiased and can accurately identify different underlying instabilities. Simulations are currently underway for these scenarios.

Finally, we should note that despite the great agreement with the local linear GENE simulations, further insight could be gained with higher fidelity approaches via nonlinear and/or global gyrokinetic simulations (see for example reference [46]).

Such cases are being considered for future work. However, the results of this paper are highly consistent and represent an important step in the final categorization of the mode. Additionally, simulations for ITER/DEMO/SPARC-type fusion experiments should be carried out to determine if a corresponding KBM appears at the plasma edge and if this prevents type-I ELMs.

Acknowledgments

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Data availability statement

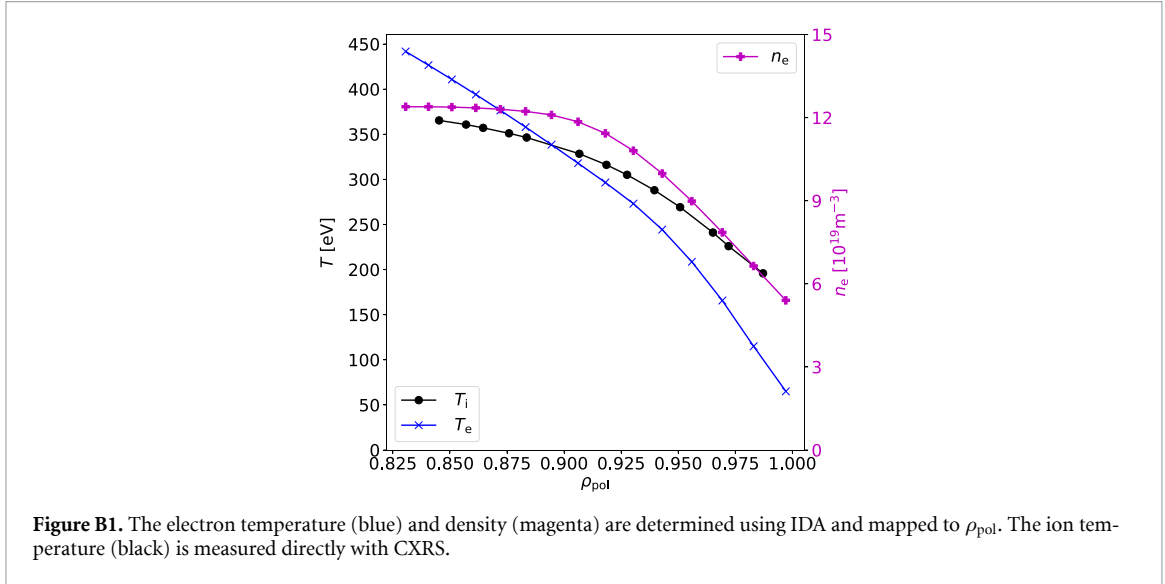
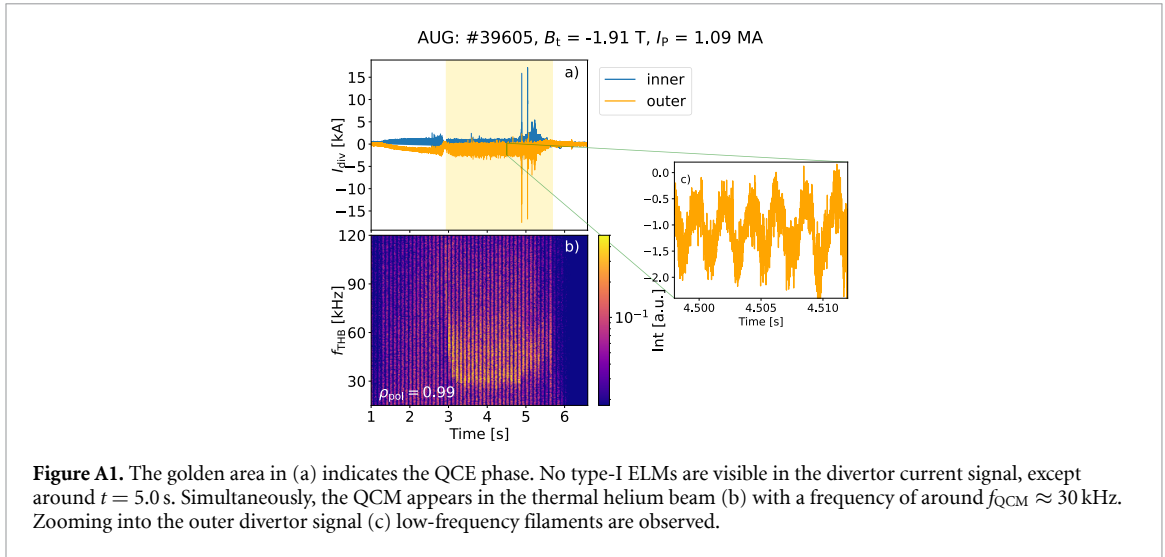
All data that support the findings of this study are included within the article (and any supplementary files).

Appendix A. QCM and divertor saturation current

Figure A1 shows the divertor saturation current (a) I_{div} and the THB spectrogram (b) for the analyzed discharge. As explained in section 1, I_{div} is used as an indicator of the particle and energy fluxes arriving at the divertor targets. Therefore, this quantity can be used to determine what kind of fluctuations cause transport.

Zooming in on figure A1(c), we see that the divertor current is dominated primarily by slow (<1 kHz) fluctuations (filaments), which are typical for QCE discharges.

The transport properties of the QCM cannot be determined directly by I_{div} . However, analyses using Langmuir probes have shown that particle transport must originate from the QCM [37]. This is evident from the non-vanishing cross phase of electron density and potential fluctuations. Nevertheless, determining the transport properties of the QCM requires considerable investment.

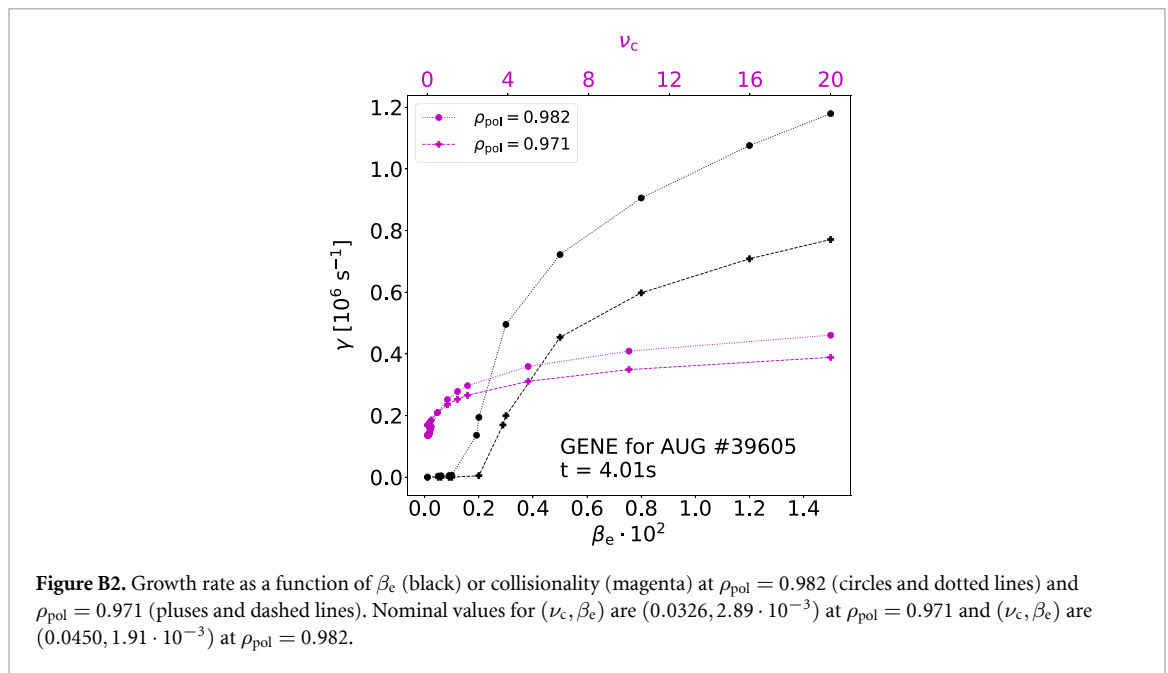


Appendix B. Profiles for GENE simulation and inner position scans

Figure B1 shows the electron and ion profiles that were used in the GENE simulation. The electron data (T_e and n_e) come from integrated data analysis (IDA) [47], a computational tool that combines measurements from various diagnostics with a Bayesian probability approach to obtain reliable n_e and T_e profiles. To achieve this unification, the measurements from the individual diagnostics must be mapped to ρ_{pol} . This requires a reliable equilibrium reconstruction. The ion data are supplied directly via the charge exchange recombination spectroscopy (CXRS) diagnostic [30] and mapped to ρ_{pol} using magnetic equilibrium reconstruction.

The collisionality and beta scans were repeated for the instabilities found further inside at $\rho_{pol} = 0.971$ (dotted lines and circles) and $\rho_{pol} = 0.982$ (dashed lines and pluses). Figure B2 (black lines) shows that, at both radial positions, the beta scan again plays a decisive role. As the beta value decreases, the modes disappear, and the growth rate increases explosively.

In contrast to the strongest mode analyzed in section 2.2, the collisionality scan (magenta lines) shows that the modes increase with increasing collisionality. However, when collisionality disappears, the modes do not disappear, which is why the KBM can still be favored as the underlying mechanism.



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