Quasi-coherent mode evolution in discharges with positive radial electric field at the T-10 tokamak

M A Drabinskiy1,4, A V Melnikov1,2, L G Eliseev1, P O Khabanov1, N K Kharchev1,3 and S E Lysenko1

1 National Research Centre 'Kurchatov Institute', 123182 Moscow, Russia
2 National Research Nuclear University ‘MEPhI’, 115409 Moscow, Russia
3 Prokhorov General Physics Institute, 119991 Moscow, Russia
4 E-mail: Drabinsky_ma@phystech.edu

Abstract. The effect of the high-power ECRH on the quasi-coherent (QC) mode in the plasma of the T-10 tokamak with the magnetic field \( B_t = 2.2 \) T, plasma current \( I_{pl} = 230 \) kA and chord-averaged electron density \( <n_e> \approx 1 \cdot 10^{19} \) m\(^{-3}\) is discussed. The most pronounced changes appear in the core plasma region with \( r < 0.5a \). For the ECRH power \( P_{ECRH} = 2.2 \) MW causing the appearance of the positive radial electric field \( E_r^{EC} = +20 \) V/cm (in the OH stage, the occurring field is \( E_r^{OH} = -75 \) V/cm), the mean frequency of the QC-mode gradually decreases from \( f_{QC}^{OH} = 80-100 \) kHz (in the OH stage) to \( f_{QC}^{EC} = 20 \) kHz, and its frequency spread \( \Delta f_{QC} \) decreases from \( \Delta f_{QC}^{OH} = \pm 50 \) kHz to \( \Delta f_{QC}^{EC} = \pm 10 \) kHz. For the ECRH power \( P_{ECRH} = 1.7 \) MW and weak negative radial electric field (\( E_r^{EC} = -20 \) V/cm), the mean frequency decreases to \( f_{QC}^{EC} = 40 \) kHz, and the frequency spread becomes \( \Delta f_{QC}^{EC} = \pm 30 \) kHz. After the ECRH-induced drop, the QC-mode mean frequency increases with increasing line-averaged density.

1. Introduction

The quasi-coherent mode (QC) is an oscillation with the mean frequency \( f_{QC} \) comparable with its frequency spread \( \Delta f_{QC} \), i.e., \( f_{QC} \approx \Delta f_{QC} \). The QC-mode was discovered at the T-10 tokamak (\( R = 1.5 \) m, \( a = 0.3 \) m, \( B_t \leq 2.5 \) T, \( I_{pl} = 350 \) kA) using the correlation reflectometry diagnostics [1]. Two branches of the QC-mode can be distinguished in plasma of the T-10 tokamak: the high frequency branch HFQC (\( f \approx 200-400 \) kHz) and low frequency one LFQC (\( f \approx 50-150 \) kHz) [2]. In this study, the low frequency branch is considered and the QC abbreviation is used to specify LFQC.

Previously, the QC-mode was also detected at the T-10 using the Heavy Ion Beam Probe (HIBP) diagnostics [3]. The modes with similar distinctive features were also discovered at the ASDEX [4], KSTAR [5], Alcator C-mod [6], Tore Supra and TEXTOR tokamaks [7].

In different studies, the QC-mode is associated with both the trapped electron modes (TEM) [8] and ion temperature gradient modes (ITG) [2]. In [9], it was shown that the most part of the turbulent particle flux is associated with the QC-mode frequency range. The radial distribution of the QC-mode was measured at the T-10 [2] and Tore Supra [8] tokamaks using the correlation reflectometry technique (CR). Recently the QC-mode radial distribution was measured in the ohmic plasma of the T-10 tokamak using the HIBP diagnostics [10]. All measurements show the two-peak radial structure of the QC-mode with the dominant peak at the periphery of the plasma column (\( r \approx 0.9a \)) and the lower peak in the vicinity of \( r \approx 0.3a \).
The evolution of the QC-mode into the coherent mode with the same mean frequency $f_{QC}$ was reported at the T-10 tokamak [11]. At the KSTAR tokamak, the gradual or abrupt evolutions from the coherent mode to the QC-mode were observed; the nature of such evolution was associated with the collisionality dynamics [12]. In this study, we discuss the phenomenon of a considerable decrease in the QC-mode mean frequency down to $f_{QC}^{EC} = 20$ kHz and a decrease in its frequency spread down to $\Delta f_{QC}^{EC} = \pm 10$ kHz measured using the HIBP diagnostics in the core region of the tokamak plasma ($r < 0.5a$) under conditions of the high-power ECR heating ($P_{ECRH} = 2.2$ MW).

2. Discharge scenario
In the quasi-stationary ohmic stage of the typical T-10 shot, the toroidal magnetic field is $B_t = 2.2$ T, the plasma current is $I_{pl} = 230$ kA and the chord-averaged plasma density is $<n_e> \approx 1 \cdot 10^{19}$ m$^{-3}$. In the present study, two scenarios of the auxiliary ECR heating are considered: (1) the combined on- and off-axis ECRH with the total power $P_{ECRH} = 2.2$ MW and (2) the off-axis ECRH with the power $P_{ECRH} = 1.7$ MW. Waveforms of the basic parameters are shown in Figure 1. In the combined ECRH stage (1), the radial electric field becomes positive, as discussed in [13]. In the shots considered in this paper (nos. 73137, 73138, 73197, 73200), the HIBP measurements were performed in the radial range $r \approx 0.25$–$0.5a$ during the quasi-stationary OH and ECRH stages of the discharge.

Figure 1. Typical discharge scenarios: (a) with combined on- and off-axis ECRH; and (b) with off-axis ECRH. 1 – combined ECRH stage with $P_{ECRH} = 2.2$ MW, 2 – off-axis ECRH stage with $P_{ECRH} = 1.7$ MW [13]

3. Results
Power spectrograms (PSDs) of the plasma density and potential fluctuations were obtained using the fast Fourier transform (FFT) with the sliding Hann windows (the number of points for the FFT is 4096; the numbers of points for the Hann window of the PSD and the coherence spectrograms are 1024 and 512, respectively). The time evolution of the QC-mode was judged by the PSD of the plasma density fluctuations $\delta n$ (proportional to relative fluctuations of the total beam current measured by the HIBP detector $\delta I_{tot}/I_{tot}$ [14–16]) and the spectrograms of the coefficient of coherence between two signals of the density fluctuations measured at the spatially spaced points.

The Sample Volumes (SV) of the HIBP diagnostics changed the radial position periodically during the shot (spatial scan [17, 18]). The experiments have shown that the radial distribution of the QC-mode amplitude in the plasma region under consideration ($r \approx 0.3a$) remains constant; it can be seen on the PSDs of the plasma density fluctuations and the spectrograms the coefficient of coherence during the steady-state OH stage (see Figure 2). These results are in good agreement with the results for the OH plasma obtained previously [10].

In the OH discharge stage, the mean frequency of the QC-mode is approximately $f_{QC} \approx 90$–100 kHz. It can be clearly seen both on the PSDs and the coherence spectrograms in Figures 2 and 3. In the ECRH stage of the discharge, the density turbulence spectra change considerably. The QC-mode can no longer be clearly distinguished on the PSDs of the plasma density fluctuations (see Figures 2a and 2d). In the frequency range of 50–150 kHz, the QC-mode amplitude remains approximately constant, while in the low frequency range (15–35 kHz), it considerably increases.
(by one order of magnitude). To distinguish the QC-mode in the ECRH stage of the discharge, it is necessary to involve the coherence spectrogram of the plasma density fluctuations (see the following subsections).

3.1. Combined ECRH stage (2.2 MW)

Time evolution of the mean frequency \( f_{QC} \) in the core plasma in two shots with close beam energies after switching-on the ECRH is presented in Figure 2. Although the gradual evolution of the mean frequency \( f_{QC} \) during the transition from the OH stage to the ECRH one can’t be clearly traced by analyzing the PSDs of the plasma density fluctuations (see Figures 2a and 2d), one can see a pronounced peak in the frequency range 30–50 kHz in the coherence spectrograms of the plasma density fluctuations (see Figures 2b and 2e). In 10–15 ms after switching-on the ECRH pulse, the gradual decrease in the mean frequency \( f_{QC} \) is observed. It is important that in the ECRH stage, the mean frequency \( f_{QC} \) is in the GAM frequency range \([3, 19, 20]\). Previously, the three-wave interaction between the GAM and QC-mode was observed in the T-10 tokamak plasma \([21]\). The difference between the mean frequencies of the QC-modes in these two shots corresponds to the 20%-difference between the corresponding line-averaged plasma densities: \(<n_e> \approx (0.9 \text{ and } 1.1) \times 10^{19} \text{ m}^{-3} \) in shot nos. 73138 and 73197, respectively. Due to the scanning regime of the HIBP measurements, the HIBP signal becomes too weak during certain time intervals (at some SV radial positions, the beam attenuation is strong). Red rectangles in Figures 2c and 2f correspond to such time intervals.

We note that during the ECRH stage, rather high “background” coherence \( \gamma^2 = 0.5–0.6 \) is observed between the neighboring density signals in the frequency range 50–150 kHz, which corresponds to the ohmic QC-mode. This high coherence can be considered as a manifestation of the broadband turbulence.

3.2. Off-axis ECRH stage (1.7 MW)

In the off-axis ECRH stage of the discharge, the mean frequency \( f_{QC} \) decreases to 45-50 kHz. It can be clearly seen in Figures 3b and 3e. After switching-on the ECRH pulse, the line-averaged density begins to increase (see Figureb). With increasing line-averaged density, the mean frequency \( f_{QC} \) also increases (see Figure b and Figure c).
Figure 3. QC-mode time evolution in the core plasma region caused by off-axis ECRH, shot nos. 73200 (\(E_b = 330\) keV) and 73137 (\(E_b = 300\) keV): (a), (d) PSDs of plasma density fluctuations, red line corresponds to line-averaged density multiplied by arbitrary factor; (b), (e) coherence spectrograms of plasma density fluctuations, and (c), (f) time evolutions of the radial positions of the HIBP SVs, red rectangles show idle time intervals.

4. Discussion and conclusions

As affirmed in [12], the QC-mode dynamics (the evolution from the coherent mode to the quasi-coherent one and then to the broadband turbulence) is associated with the collisionality. The results of the present study agree with this statement. Indeed, in the off-axis ECRH stage, a decrease in the collisionality causes a decrease in the mean frequency \(f_{QC}\) in the core plasma region to 45–50 kHz, while in the combined ECRH stage, further decrease in the collisionality causes a further decrease in the mean frequency \(f_{QC}\) in the core plasma region to the GAM frequency range 15–35 kHz. In addition, the density (collisionality) rise during the ECRH phase causes the corresponding rise of the mean frequency \(f_{QC}\). Moreover, a decrease in the QC-mode frequency just after the beginning of the ECRH pulse may be associated with a change in the velocity of the \(E \times B\) poloidal rotation caused by changes in the radial electric field, presumably, affected by the collisionality dynamics as well [13]. It was found in [13] that the direction of the poloidal rotation of the QC-mode remains the same despite a change in the sign of the radial electric field. The reason for this phenomenon is unknown so far and should be discovered in the future research.

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