Radial structure of quasi-coherent mode in ohmic plasma of the T-10 tokamak

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Abstract. The paper presents the recent results from the quasi-coherent (QC) mode studies performed in the ohmic plasma of the T-10 tokamak (R = 1.5 m, a = 0.3 m, B₀ = 2.2 T, Iₚ₀ = 230 kA, and nₑ ≈ 1∙10¹⁹ m⁻³) using Heavy Ion Beam Probe diagnostics (HIBP). The radial distribution of the amplitude of the density perturbations caused by the QC-mode has two pronounced peaks (approximately 5 and 1.5 % at radii of 25–30 and 8–14 cm, respectively) with an intermediate zone of lower amplitude in between them (<1% at radii of 16–21 cm). The mean QC-mode frequency remains nearly constant within the studied region (75–80 kHz). For the edge plasma, the HIBP observations were confirmed by the Langmuir probe measurements.

1. Introduction
One of the most important problems in the fusion physics is the abnormally high level of the energy and particle losses caused by the plasma turbulence. It has been recently shown that, at the T-10 tokamak, the major contribution to the turbulent particle flux is given by the density oscillations in the 50–150 kHz frequency range [1] corresponding to Low Frequency Quasi-Coherent mode (LFQC) [2]. The QC mode was first observed using the correlation reflectometry technique at the T-10 tokamak [3, 4]; its low- and high-frequency branches were attributed to the Ion Temperature Gradient (ITG) and Trapped Electron (TEM) modes, respectively. Further, the similar observations were performed at the EAST [5] and KSTAR tokamaks [6]. Later on, the LFQC mode with almost similar characteristics [7, 8] was observed at the T-10 tokamak using the HIBP diagnostics [9–11]. Here and after the QC abbreviation is used to specify the LFQC mode. The QC mean frequency f is of the same order as its frequency range Δf: f ≈ Δf. The earlier studies on T-10 have shown that QC mode has both density and plasma potential components [12] and it tends to rotate poloidally to the electron diamagnetic drift direction with the ExB velocity [13, 14]. It was also shown that QC mode experiences the three-wave interaction with Geodesic Acoustic Mode [15, 8], which is the global plasma eigenmode in T-10 [16, 17].
This paper presents the first measurements of the radial structure of the QC mode power spectral density and amplitude performed using the HIBP diagnostics in a wide radial range of $r = 8$–$30$ cm as well as the data provided by the Langmuir probe (LP) at the plasma edge.

2. Experimental set-up

The HIBP measurements were carried out in the steady-state OH stage (400–750 ms long) of the reproducible shots with a magnetic field of $B_0 = 2.2$ T on the axis, a plasma current of $I_{pl} = 230$ kA and a plasma density of $n_e \approx 1 \cdot 10^{19}$ m$^{-3}$. Comparison with the LP data was performed under the similar plasma conditions but at the higher plasma density ($n_e \approx 2.2 \cdot 10^{19}$ m$^{-3}$). Typical shot scenario is shown in figure 1. In each shot, the HIBP provides data in the radial range of 3–8 cm (radial scan). In the next shot, by varying the sample volume (SV) radial position (by varying the beam energy [18]), the data from other radial interval can be obtained. The total radial range of the HIBP measurements is from 8 to 30 cm ($0.25 < r/a < 1$); data in the entire radial range were obtained shot by shot (see figure 2).

![Figure 1](image1.png)

**Figure 1.** The typical T-10 discharge scenario: green line marks plasma current $I_{pl}$, blue line – plasma electron temperature $T_e$, yellow line – plasma density $n_e$, red line – ECRH performance and magenta line – stored plasma energy $W_{dia}$.

![Figure 2](image2.png)

**Figure 2.** The method of radial stitching: a) power spectrogram (PSD) of plasma density fluctuations during periodical radial scanning; b) time evolution of the HIBP sample volume radial position; c) set of spectrograms transformed to radial distributions of PSD.
3. Data processing

Studies were performed in the quasi-stationary stage of the discharge (600–750 ms). Duration of a single HIBP radial scan was 30–100 ms at a signal time resolution of 1 µs. The QC mode power spectrograms were obtained using the fast Fourier transform (FFT) with sliding Hann windows (number of points for the FFT was 1024 or 2048, and number of points for the Hann window was 512 or 1024). During one radial scan, 30–100 spectra can be obtained. Since the radial range of one scan is about 3–8 cm, the SV shift during the time of measuring one spectrum is equal to a fraction of a millimeter, which is considerably less than the SV size (about 1 cm). So we can neglect the SV motion during the FFT time and assume that the Fourier power spectra are obtained at the same SV position.

The plasma density oscillations in the QC mode were studied by studying the secondary probing beam current oscillations. The time-dependent power spectrograms were transformed into the radial distributions of the power spectral density (see figure 2) and stitched into the unified radial distribution (see figure 3).

4. Results

4.1. QC mode radial distributions

The final joint PSD radial distribution demonstrates the constancy of the QC mode mean frequency (see figure 3a). By integrating the plasma density PSD in the QC mode frequency range, we obtain the QC mode amplitude radial distribution (see figure 3b). The QC mode amplitude distribution has two pronounced peaks: 5% at radii of 25–30 cm and ~1.5% at radii of 8–14 cm. There is a minimum of ~1% of the QC mode amplitude between these two peaks.

![Figure 3](image_url)

**Figure 3.** a) Radial distribution of plasma density PSD; b) radial distribution of QC mode amplitude: colored lines correspond to the QC amplitudes (different shots are marked by different colors), grey lines show the noise level.
4.2. QC mode at the plasma edge

For the same T-10 scenario ($B_0 = 2.2$ T, $I_{pl} = 230$ kA), but at a higher density of $n_e \approx 2.2 \cdot 10^{19}$ m$^{-3}$, the LP measurements were performed. The QC mode is more pronounced when analyzing the PSD of the floating potential (see figure 4a). In the PSD of the ion saturation current, the QC mode is less pronounced but still visible (see figure 4b).

Figure 4. Power spectrograms of LP signals: a) the floating potential; and b) the ion saturation current. Red line marks time of comparison with the data of HIBP diagnostics.

The comparison between the HIBP and LP data was performed at the time $t = 843$ ms (marked by red line in figure 5b), when the radial position of the HIBP SV ($r = 27.8$ cm) was the closest to the LP position ($r = 28.5$ cm). The LP data was averaged over the time interval of 840–845 ms. The HIBP and LP power spectra of density perturbations are remarkably similar, as can be seen in figure 5b.

Figure 5. a) PSD of the HIBP signal of density perturbations; red line marks the time of the outermost SV position ($r = 27.8$ cm, $t = 843$ ms); b) density perturbations spectra measured by the HIBP (green line, $t = 843$ ms) and LP (red line, $t = 840–845$ ms).

5. Summary

The radial distribution of the density perturbation amplitude, associated with low frequency quasi-coherent (LFQC) mode was measured by the HIBP diagnostics in the wide radial range of $0.25 < r/a < 1$ for the low-density ($n_e \approx 1 \cdot 10^{19}$ m$^{-3}$) ohmic plasma of the T–10 tokamak. The amplitude of the LFQC mode considerably varies along the radius: it is about 5% at radii of 25–30 cm, <1% at radii of 16–21 cm and about 1.5% at radii of 8–14 cm. The LFQC mode mean frequency is 75–80 kHz, and it remains constant within the entire measurement range.

In the similar OH scenario with higher density ($n_e \approx 2.2 \cdot 10^{19}$ m$^{-3}$), the HIBP and Langmuir probe spectra were measured at the plasma edge during the same discharge. PSDs of the density perturbations measured at the same time and at close radial positions by the HIBP and LP shows remarkable similarity between each other.
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