Localization of QCM and Observation of Filament Birth Location in the QCE Regime Using Comb Doppler Backscattering on ASDEX Upgrade

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The Quasi-Continuous Exhaust (QCE) regime [1] is an ELM-free regime that maintains H-mode-level confinement and is therefore considered a promising candidate for future reactor operation. Instead of large type-I ELMs, QCE is characterized by small, high-frequency filaments and by the presence of a quasi-coherent mode (QCM), which is believed to play an important role in edge transport regulation. In this work, the W-band comb Doppler Backscattering (DBS) on ASDEX Upgrade [2] is used to localize the QCM, observe filament propagation, and measure E_r profile simultaneously, enabling an unambiguous determination of the QCM position relative to the E_r well. The results indicate that the QCM is localized within the E_r well. In addition, peaks in the power signal are observed to propagate both outward and inward, and their crossing point is identified as a candidate filament birth location, also within the E_r well.

Localization of QCM

The following analysis is based on data from AUG plasma pulse #43028 at around 5.95 s. The W-band comb DBS on ASDEX Upgrade launches 7 frequencies simultaneously as a frequency comb. The comb center frequencies step through 81, 87, 93, and 99 GHz, with a fixed spacing of 1.65 GHz between adjacent frequencies. The full set of 28 frequencies probes 28 distinct spatial locations covering most of the pedestal region ($\rho_p = 0.959 \sim 1.043$). The spectrogram of $d\varphi/dt$ reveals the presence of QCM, where φ is the unwrapped phase of I and Q signals. The spectrogram of $d\varphi/dt$ of Channel 4 (Fig. 2) is shown as an example, which shows QCM centered at around 50 kHz.

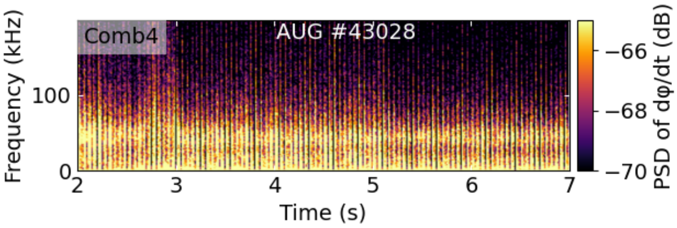

Fig. 1 The spectrogram of $d\varphi/dt$ of Channel 4 of DBS for AUG #43028.

The raw DBS in-phase and quadrature signals are first organized according to probing frequency. Since the comb frequencies step in time, the raw time series are segmented and regrouped so that all intervals corresponding to the same probing frequency are concatenated into a single signal. The backscattered signal to noise ratio (SNR) is also evaluated in this step. The spectrogram of backscattered signal with probing frequency of 93 GHz is shown as an example in Fig. 3.

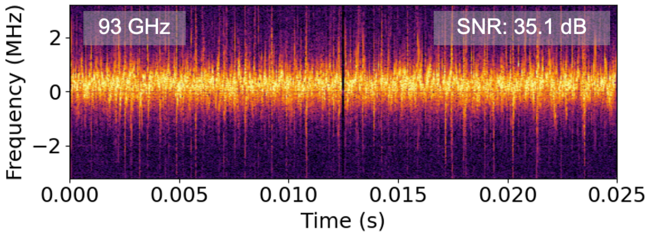

Fig. 2 The spectrogram of backscattered signal with probing frequency of 93 GHz within 5.9-6.0 s for AUG #43028.

For each signal, the spectrum of $d\varphi/dt$ is obtained, with FOOOF [3] fitting method applied. The QCM is characterized by a narrow spectral feature in the spectrum, and the strength of QCM is quantified by integrating the background-subtracted spectrum. The $d\varphi/dt$ spectrum and fitting results for probing frequency of 93 GHz is shown in Fig. 4. After subtracting the background spectrum (green dash line), the remaining spectral power between 20 to 90 kHz is integrated (red area) and taken as the measure of the QCM strength. In this way, the radial distribution of QCM can be obtained, which is presented in the Results section.

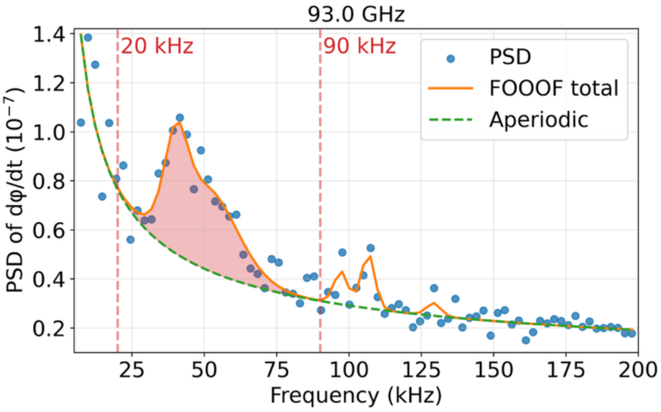

Fig. 3 The dφ/dt spectrum and FOOOF fit for the 93 GHz probing signal. Blue dots indicate the original spectrum, the orange line the total FOOOF fit, and the green dashed line the aperiodic background. The QCM strength is quantified by integrating the background-subtracted spectral power (red area) from 20 to 90 kHz.

Observation of Filament Propagation

In addition to the QCM analysis, transient peaks are observed in the backscattered power signals ($I^2 + Q^2$), which are suspected as filament induced peaks (can be seen in Fig. 3). Because the AUG DBS system launches 7 probing frequencies simultaneously, it can probe 7 different spatial locations at the same time, enabling the study of filament propagation. To isolate the peaks, a band-pass filter (0.5 – 3.0 MHz) is applied to remove the Doppler-shift component and high-frequency noise. The timing of the peak appearance across the radially located channels shows that some peaks propagate outward, while others propagate inward, as shown in Fig. 5. This indicates bidirectional dynamics rather than a purely outward filament motion.

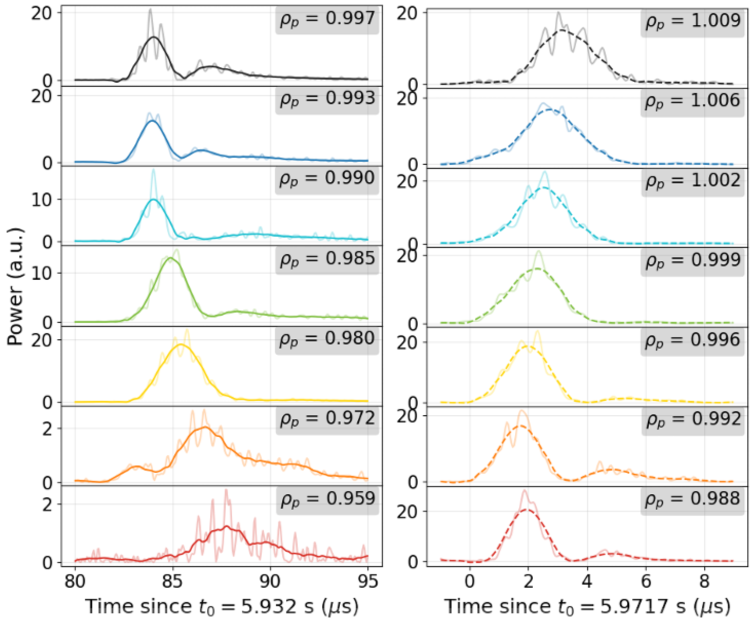

Fig. 4 Power peak propagation at different time points and thus different radial locations. Left: Power peaks are observed to propagate inward from $\rho_p \sim 0.993$. Right: Power peaks are observed to propagate outward from $\rho_p \sim 0.992$.

To obtain a statistical characterization of the filament propagation, peaks are conditionally averaged based on channel 4 (Fig. 6), which serves as the refence channel because it is centrally located and usually has the highest SNR. Peaks higher than one standard deviation are selected, and the time lag between adjacent channels is estimated using cross-correlation.

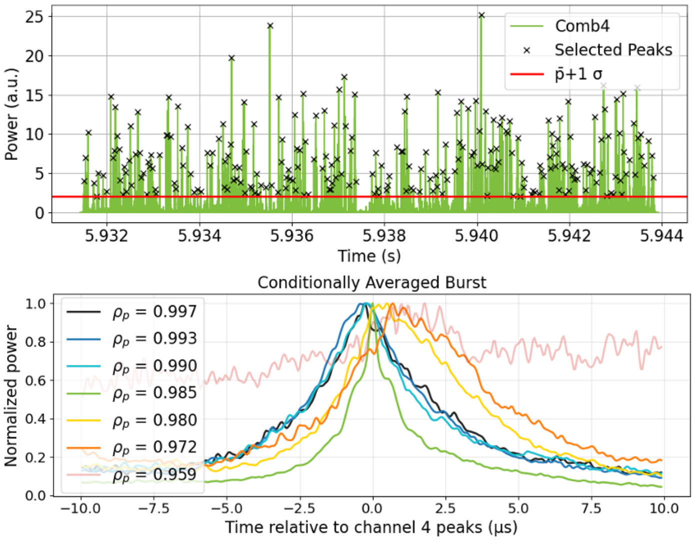

Fig. 5 Top: Selected refence peaks from channel 4. Bottom: The conditionally averaged peaks based on reference peaks, where the peak at $\rho_p = 0.993$ is observed to appear first in time.

Comparison between Experimental Results and GRILLIX [4] Simulation

Fig. 7 shows the experimental results from DBS system. The QCM is found to lie within the E_r well. The grey region is suspected to indicate the filament birth location, from which peaks are observed to propagate both outward and inward, and which also lies within the E_r well.

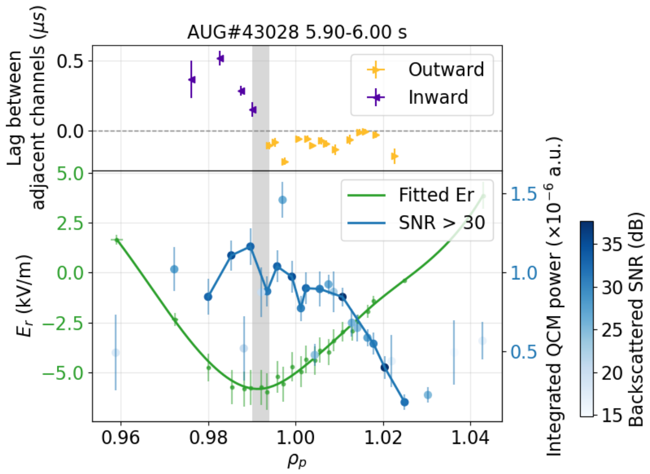

Fig. 6 The experimental results from DBS system. Top: the peak lag time between adjacent channels obtained by cross-correlation. Bottom: the green line is the fitted E_r profile, the blue line is the QCM strength with scattered SNR higher than 30. The grey region is the suspected filament birth location.

Fig. 8 shows the GRILLIX results. the left panel shows that the QCM ($\tilde{\phi}^2$) lies within the E_r well, while the right panel shows the evolution of the density fluctuation, revealing the formation of blobs (outward) and voids (inward).

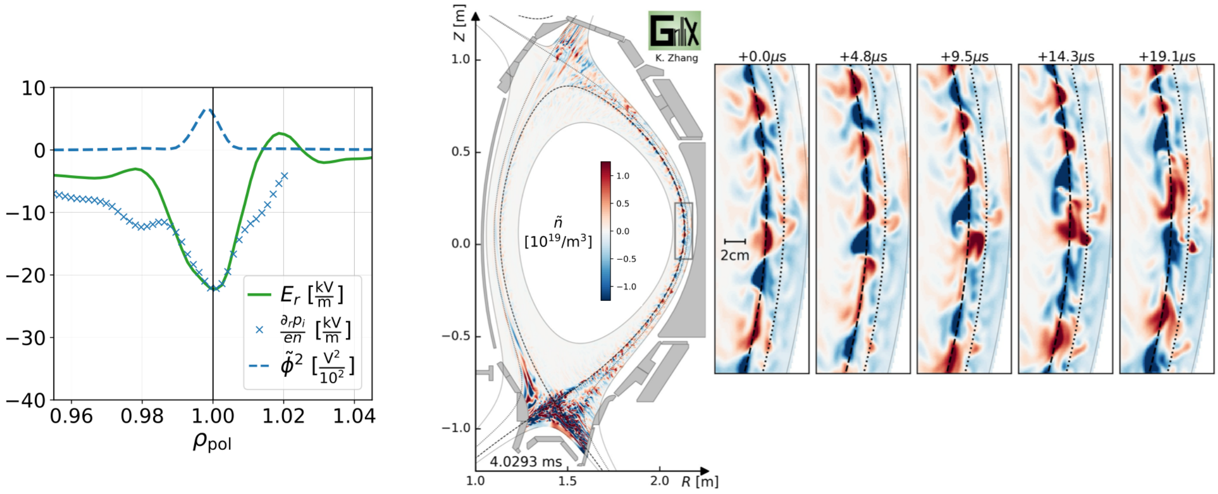

Fig. 7 The GRILLIX simulation results. Left: the green line is the Er profile and the blue dashed line represent QCM. Right: the 2-D presentation of the evolution of the density fluctuation.

Discussion

Our analysis indicates that the QCM is located within the E_r well which is consistent with GRILLIX simulation. Peaks in the power signals are observed to propagate both outward and inward, and their crossing location is suspected to mark the filament birth location, which also lies within the E_r well. It is consistent with the generation and propagation of voids (inward) and blobs (outward) in GRILLIX. Power signal may not be able to distinguish between voids and blobs, further analysis on phase signals may help.

References

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