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

MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

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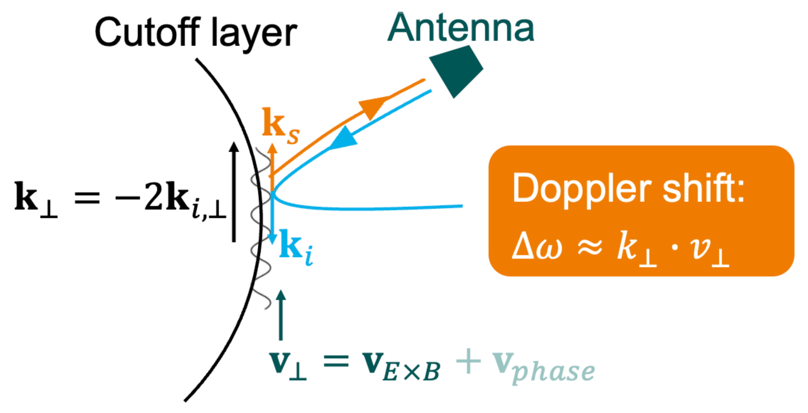
1. Abstract

- The Quasi-Continuous Exhaust (QCE) regime [1] is an ELM-free regime that maintains H-mode-level confinement.
- It is characterized by high-frequency, low-amplitude filaments rather than large ELMs.
- The Quasi-Coherent Mode (QCM) is a characteristic edge fluctuation and is thought to regulate edge transport.
- Here, a single DBS diagnostic is used to localize the QCM, observe filament propagation, and measure E_r profile, enabling an unambiguous determination of the QCM position relative to the E_r well.

2. Doppler Back Scattering (DBS)

- Microwave beams are launched obliquely into the plasma.
- Reflection occurs near the cut off layer.
- Backscattering is produced by density fluctuations satisfying the Bragg condition, $\mathbf{k}_f = -2\mathbf{k}_i$.
- Motion of the fluctuations causes a Doppler shift, $\Delta\omega = \mathbf{v} \cdot \mathbf{k} \approx v_\perp \cdot k_\perp$.
- $v_\perp = v_{E\times B} + v_{phase} \approx v_{E\times B}$, so DBS mainly measures the local $E\times B$ flow.



From Beam Tracing:
- Radial location (ρ_p)
- Scattering wavenumber ($k_\perp$)

From Spectrum:
- Doppler shift (Δf)

$$v_\perp = \frac{2\pi\Delta f}{k_\perp}$$

We get:
- $v_\perp$ plasma rotation profile

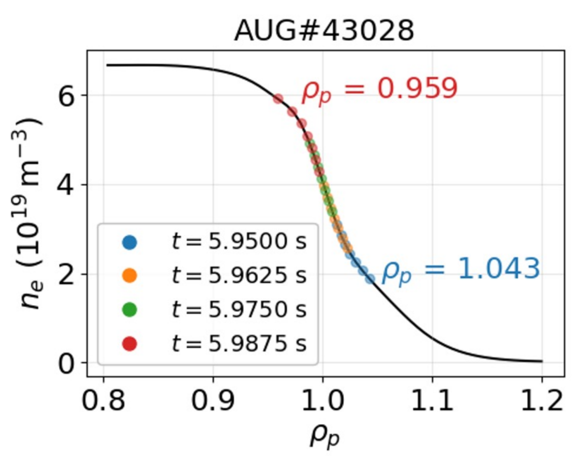
If we assume $v_\perp \approx v_{E\times B}$:
- E_r profile

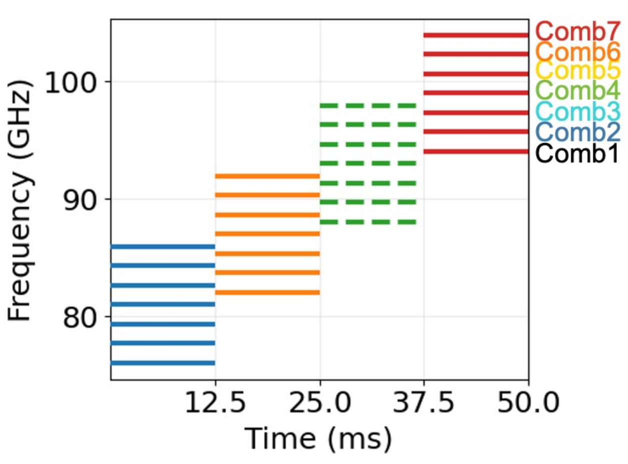
W-band comb DBS on AUG [2]

- W-band (75-110 GHz) comb DBS on ASDEX Upgrade measures intermediate-wavenumber ($k_\perp$ = 3-15 cm^{-1}) density fluctuations.
- 7 frequencies are launched simultaneously as a frequency comb.
- Both the comb center frequency and the inter-frequency spacing can be changed remotely without any hardware changes.

DBS reflection points distribution

- The following analysis is based on data from AUG plasma pulse #43028 at around 5.95 s.
- W-band DBS covers most of the pedestal region.
- 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.

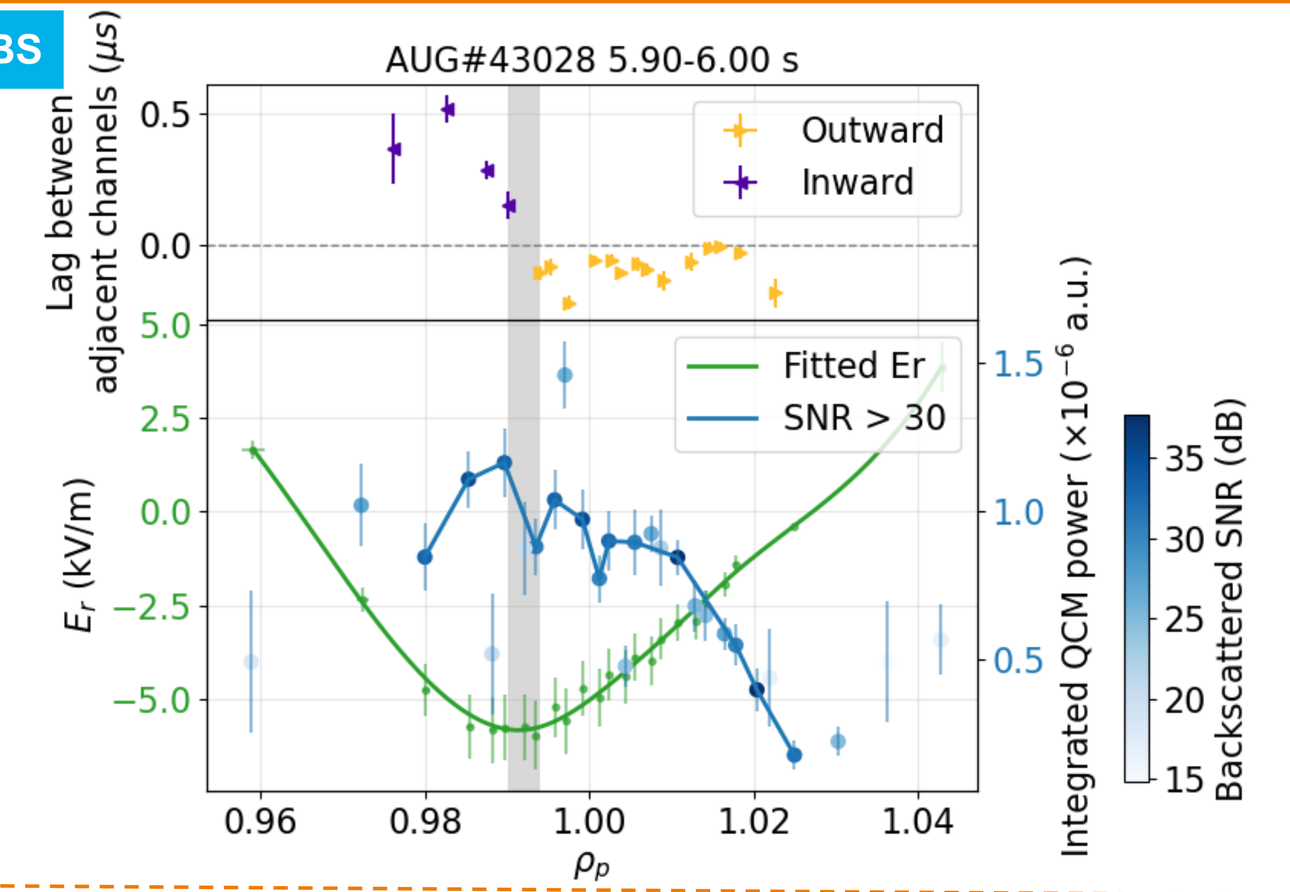




[1] Faitsch M et al., Nucl. Mater. Energy (2025)
[2] Molina Cabrera P A et al., Rev. Sci. Instrum. (2023)
[3] Zhang K et al., Phys. Rev. Lett. (2026)
[4] Donoghue T et al., Nat. Neurosci. (2020)

Comparison between experimental observations and simulation results

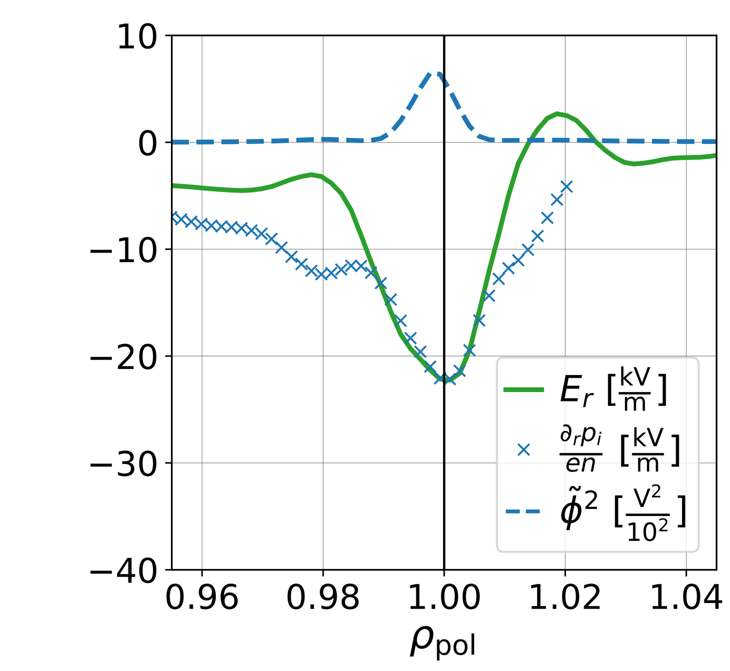
DBS

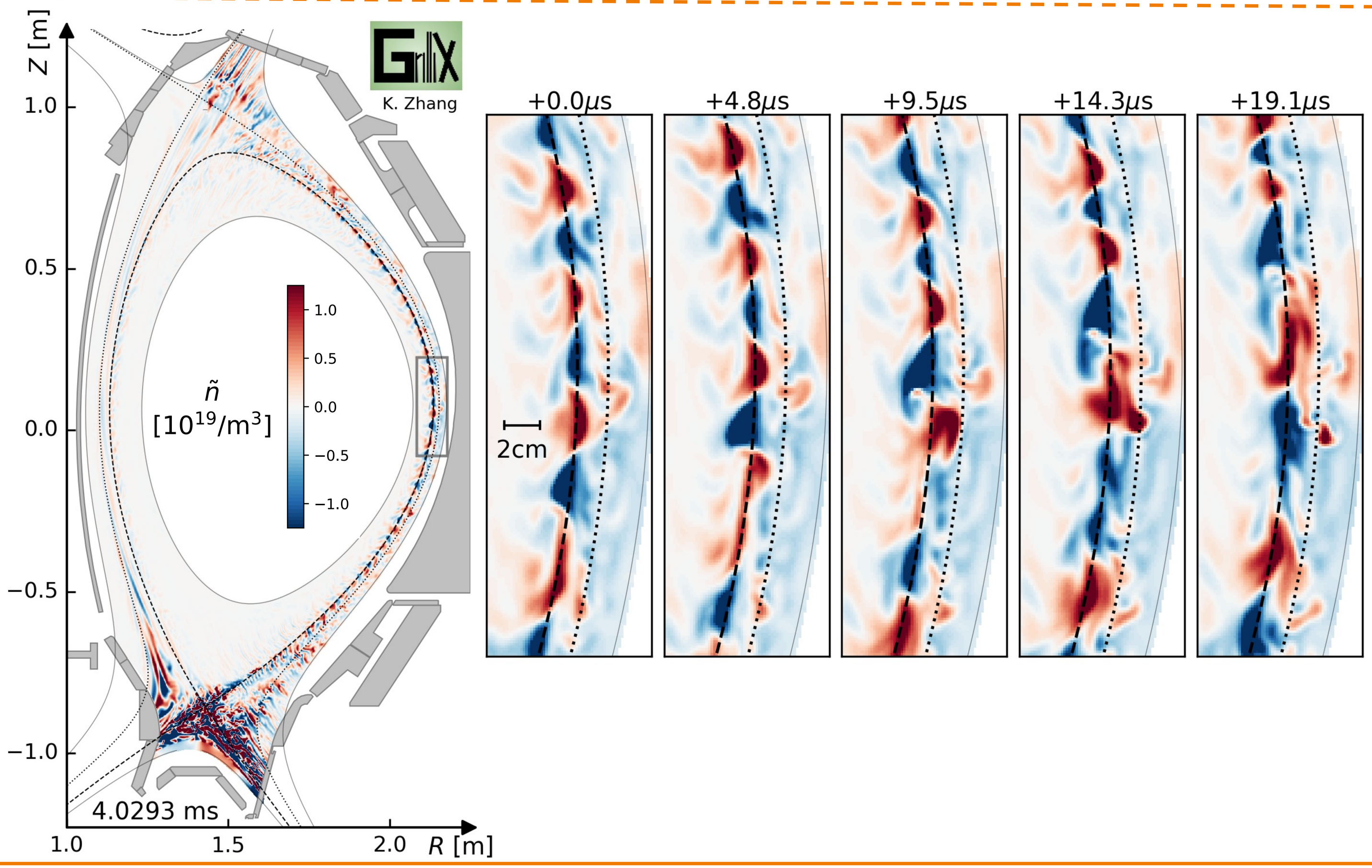


Discussion

- Our analysis indicates that the QCM is located within the E_r well which is consistent with GRILLIX simulation.
- Peaks in the amplitude 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.

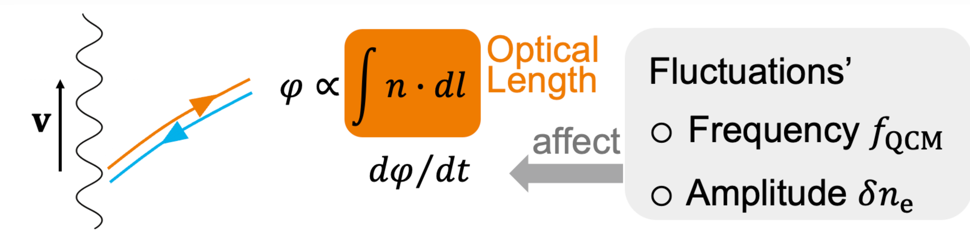
GRILLIX [3]





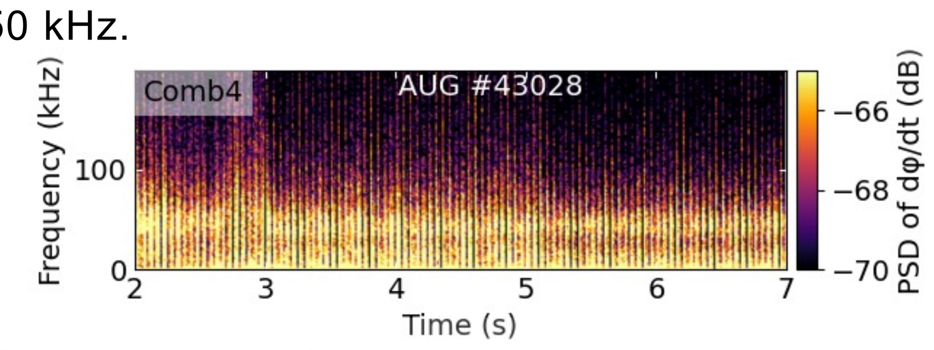
3. Localization of QCM

QCM is observed in the spectrogram of $d\varphi/dt$ (φ is the unwrapped phase of I and Q signals).

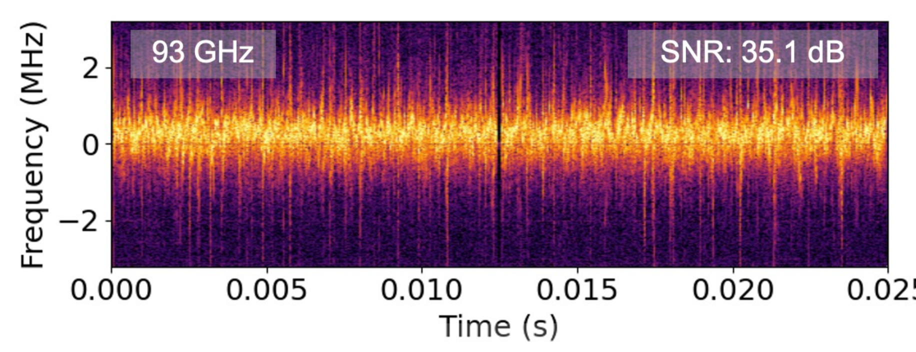


Quantification of QCM strength

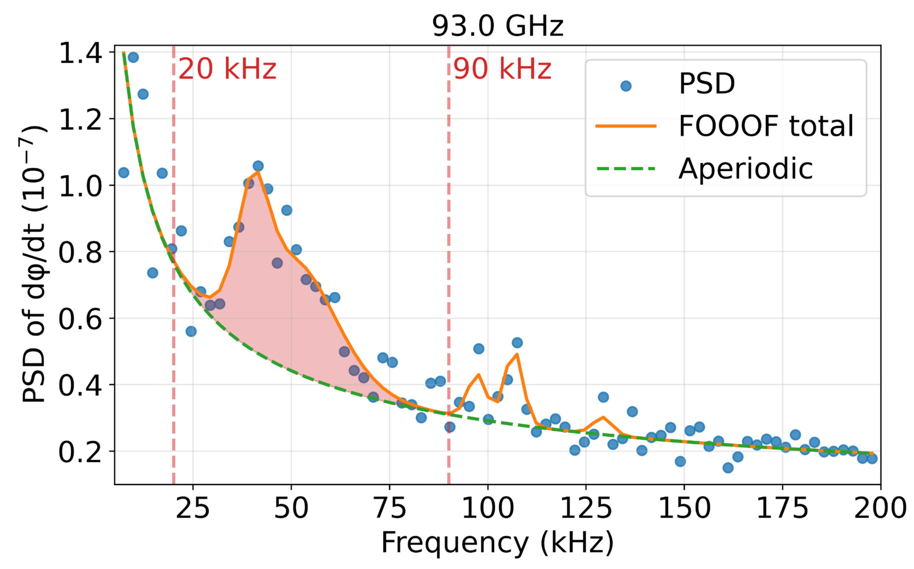
- The spectrogram of $d\varphi/dt$ of Channel 4 is shown as an example below, which shows QCM centered at around 50 kHz.



- The raw signals are segmented and grouped by frequency. For example, within 5.9–6.0 s, the segments corresponding to 93 GHz add up to 0.025 s, with a backscattered SNR of 35.1 dB.

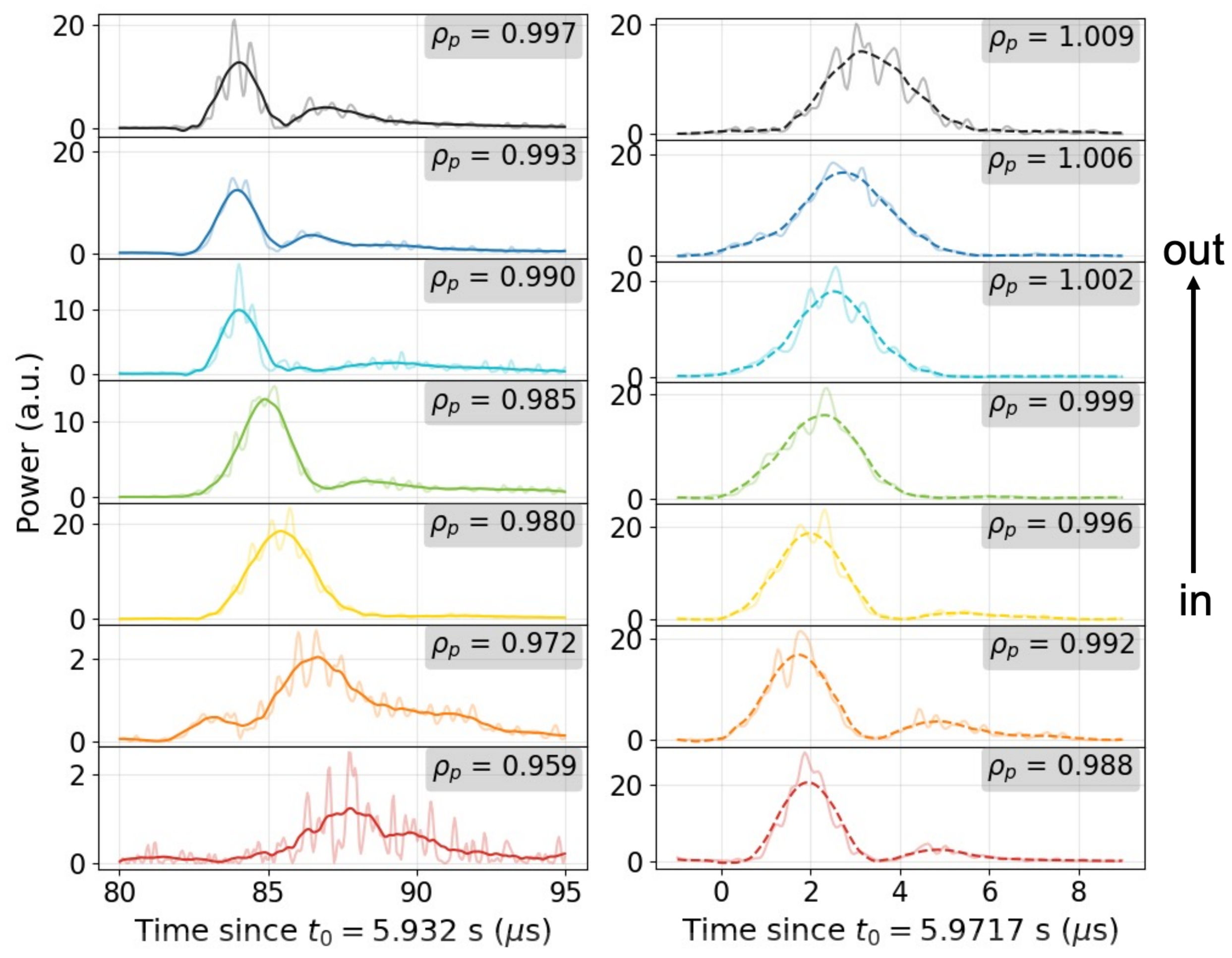


- QCM strength is quantified by integrating the background-subtracted spectrum. (FOOOF method [4])

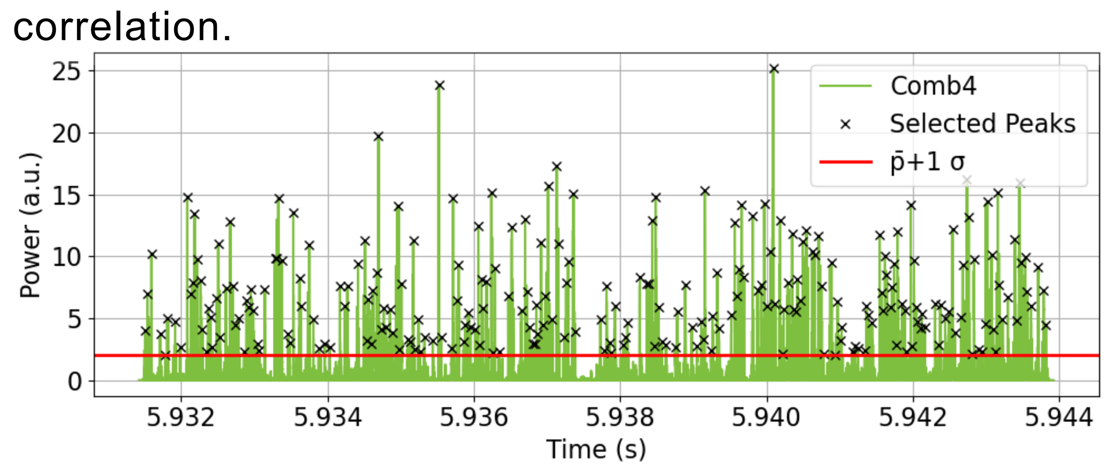


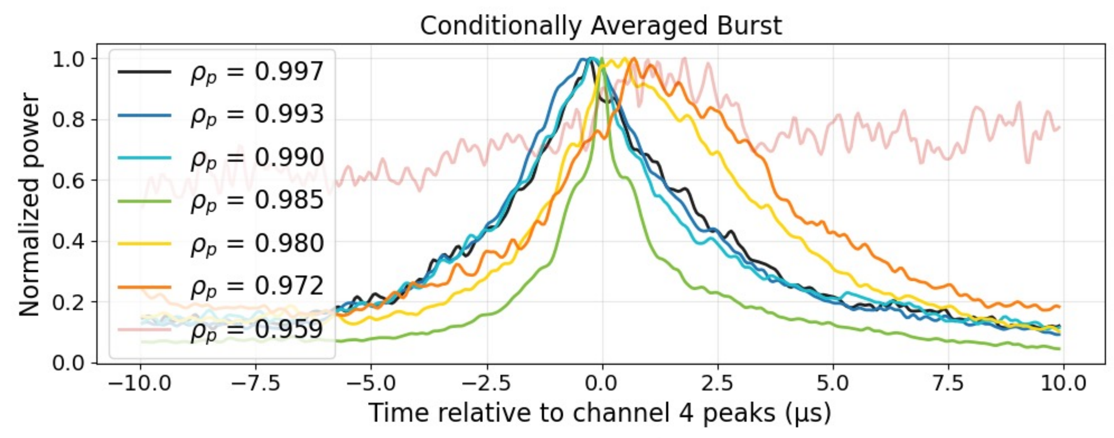
4. Filament-like spikes

- Both outward and inward propagating peaks are observed in bandpass-filtered (0.5-3.0 MHz) DBS power signals ($I^2 + Q^2$).



- Peaks are conditionally averaged based on channel 4 (highest SNR), and then the peak-time lag between adjacent channels are estimated using cross-correlation.





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