New insights on the quasicoherent mode in EDA high confinement discharges

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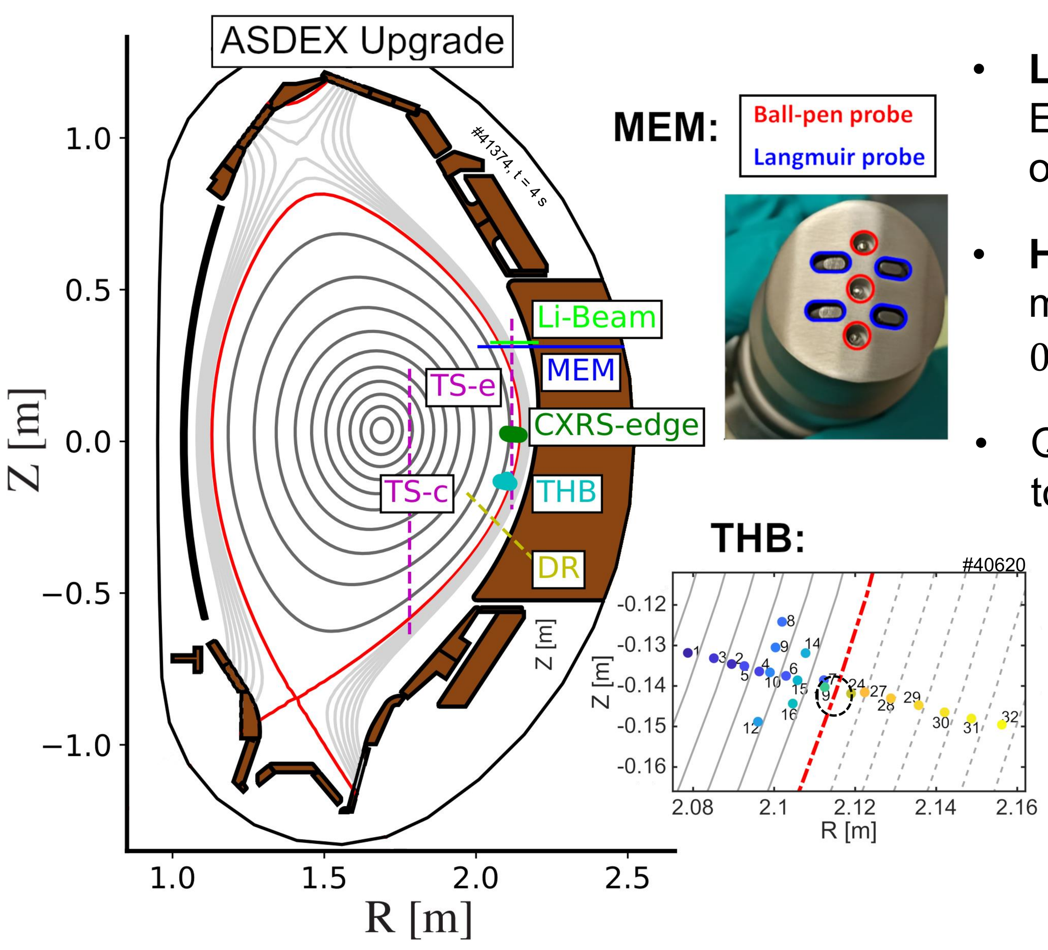
INTRODUCTION

- The **enhanced D-Alpha (EDA) H-mode** is a promising ELM-free regime for ITER and a DEMO reactor [1,2];
- A **quasi-coherent mode (QCM)** around the separatrix enhances radially outward transport [3], likely preventing the pressure gradient from overcoming the peeling-ballooning limit;
- Characterizing the QCM drive instability is key to reliably extrapolating the EDA H-mode to future fusion devices.

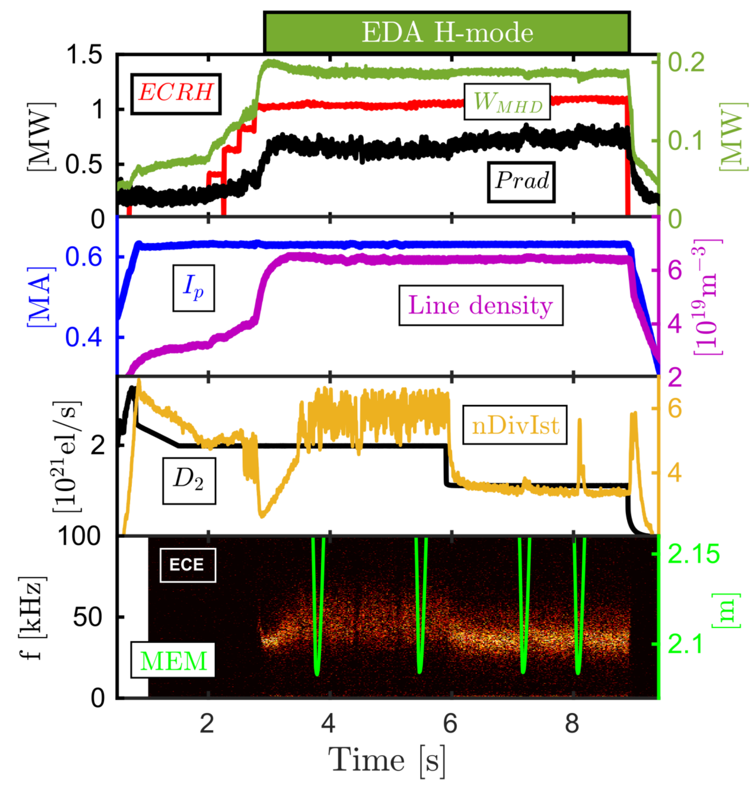
GOAL

- Compare QCM experimental fingerprints with linear gyrokinetic simulations to identify potential QCM drivers.

1. LOW POWER EDA H-MODE

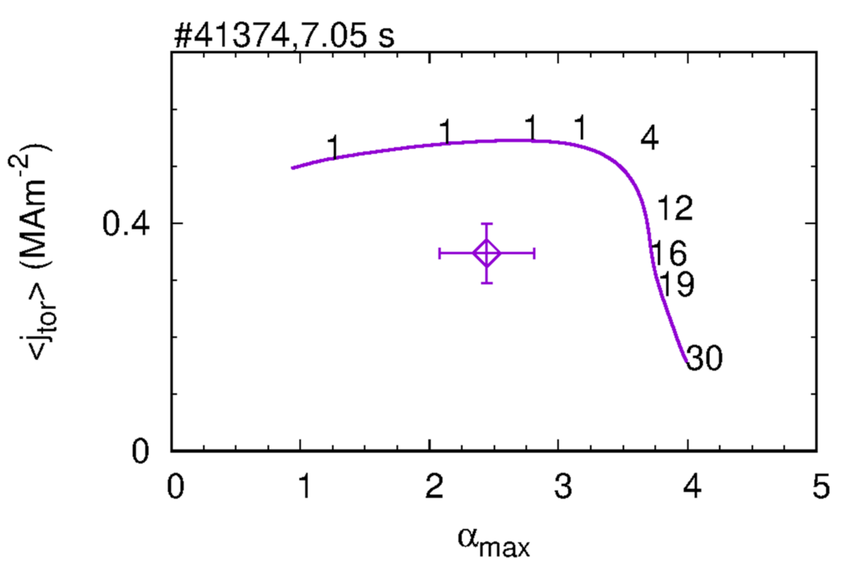


- **Low power EDA H-mode** (B_t = -2.5 T, plasma current 0.6 MA, and ECRH up to 1 MW) to maximize the number of experimental observables;
- **High shaping** favors EDA H-mode: $\kappa = 1.63$ and $\delta_{avg} = 0.39$;
- QCM is visible after the transition to EDA H-mode around 3 s;
- **Main diagnostics to measure the QCM here:**
  - Midplane reciprocating probe (MEM) [4];
  - Thermal helium beam (THB) [5].



2. MHD STABILITY ANALYSIS

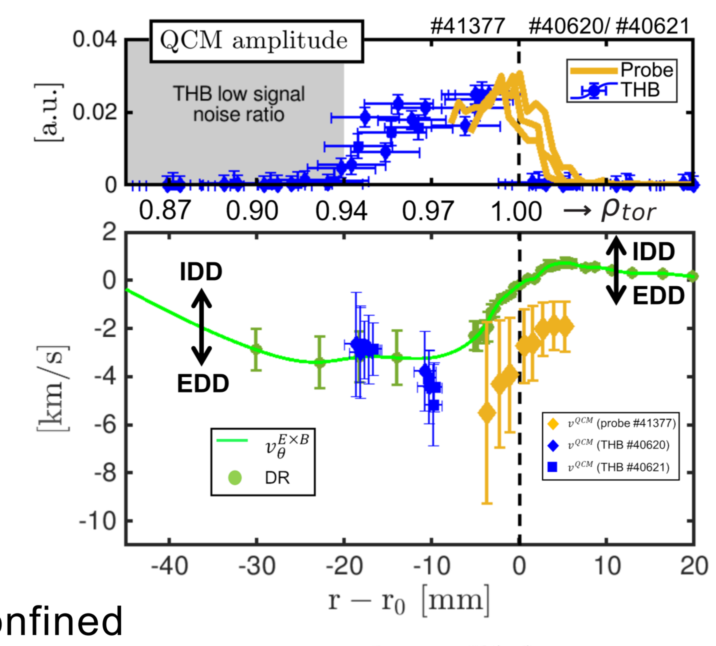
- MHD stability analyses with the MISHKA code [6];
- The low-power EDA H-mode is stable against peeling ballooning stability → enhanced pedestal transport by the QCM [3] likely clamps the pressure gradient below the limit.

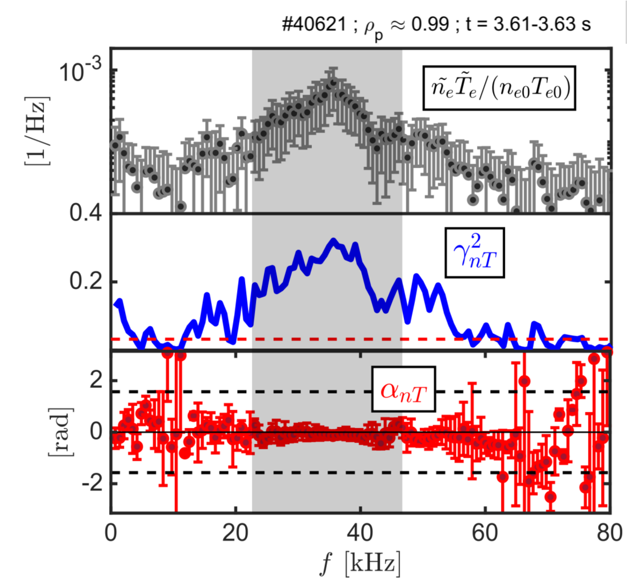


3. QCM TURBULENT FINGERPRINTS

❖ **Radial localization, wavenumber, and phase velocity:**

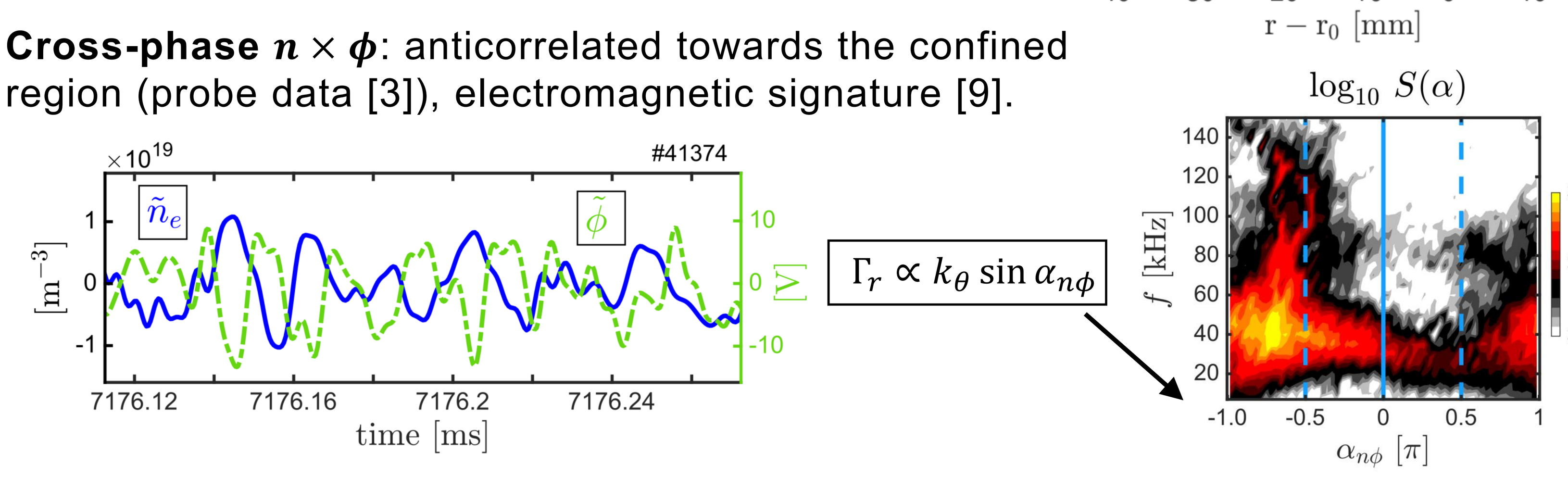
- QCM is radially localized in the pedestal foot and center, spreading to the SOL;
- Poloidal wavenumber: $k_\theta \rho_s = 0.02 - 0.05$ ($\rho_s = \sqrt{m_i T_e}/eB$) [3,7];
- In the plasma frame, QCM propagation varies radially from the electron diamagnetic direction (EDD) to the ion diamagnetic direction (IDD) (within the error bars).





❖ **Cross-phase $n \times T_e$**: near zero (THB linearized spectrum correlation analysis [8]);

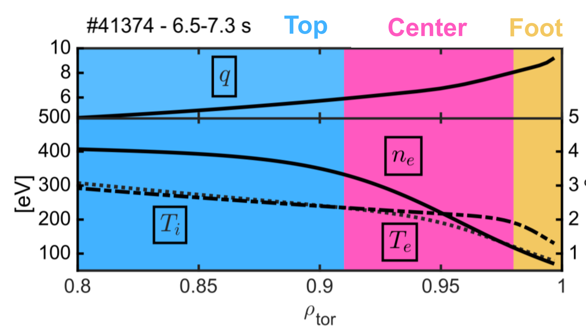
❖ **Cross-phase $n \times \phi$**: anticorrelated towards the confined region (probe data [3]), electromagnetic signature [9].

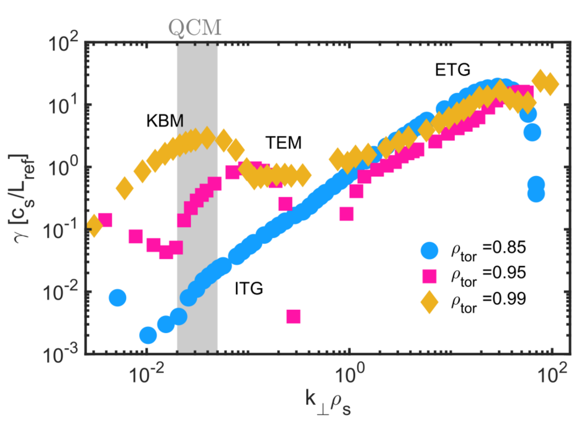


4. LINEAR GYROKINETIC SIMULATIONS

- Linear gyrokinetic simulations with the code GENE [10,11]:
- Maximum growth rate over the ballooning angles. Pedestal divided in **Top**, **Center**, and **Foot**;
  - Dominant instabilities in each region:

Top: ITG and ETG
Center: TEM and ETG
Foot: KBM, TEM, and ETG



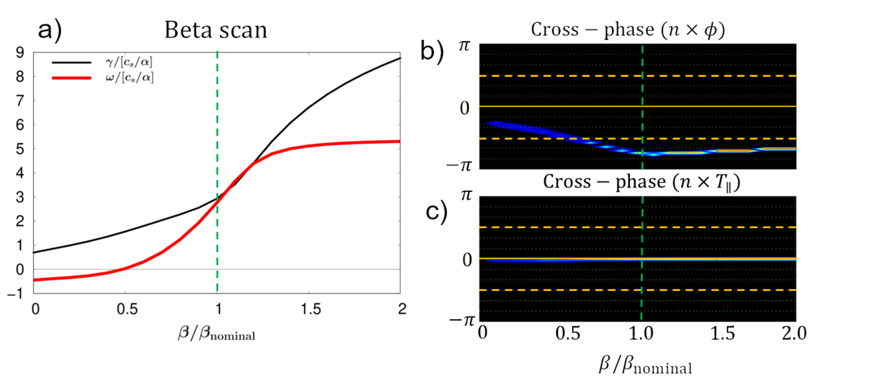


ITG: ion temperature gradient; **ETG**: electron temperature gradient; **TEM**: trapped electron mode; **KBM**: kinetic ballooning mode

6. BETA AND COLLISIONALITY SCAN ($\rho_{tor} = 0.99$)

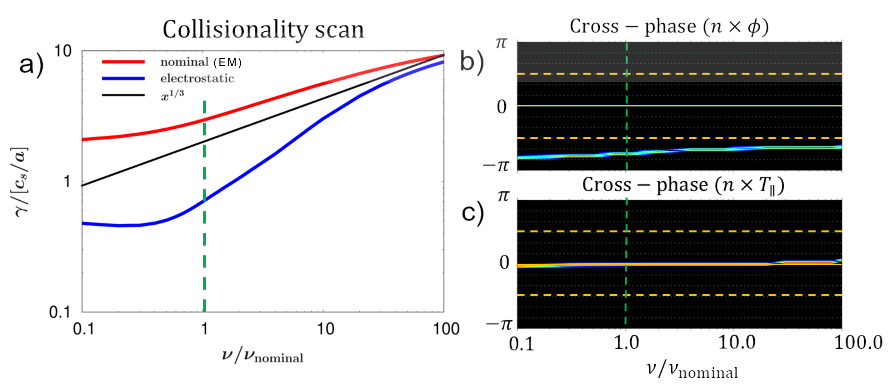
❖ **Sensitivity scan in beta:**

- Mode growth rate (γ) and frequency (ω) change rapidly with β: KBM signature [12];
- **Cross-phase $n - \phi$**: close to $-\pi$ at high β and zero at low, i.e., drift-wave like [9];
- **Cross-phase $n - T_{e,\parallel}$**: around zero.



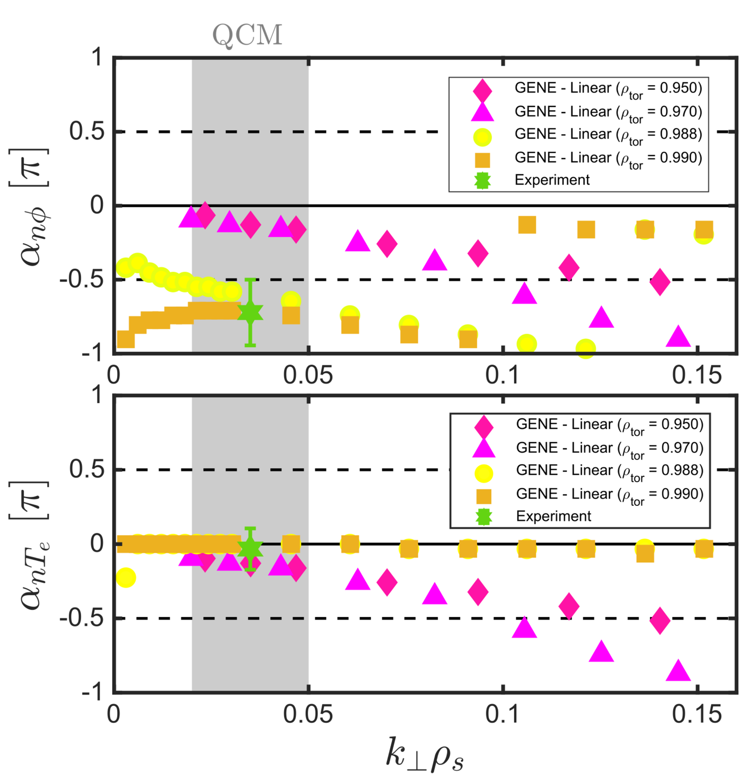
❖ **Sensitivity scan collisionality:**

- Growth rate (γ) strongly depends on ν above nominal: for higher values, RBM scale [13];
- **Cross-phase $n - \phi$**: closer to $-\pi$ for lowν and $-\pi/2$ for high ν;
- **Cross-phase $n - T_{e,\parallel}$**: remains around zero.



5. COMPARISON WITH EXPERIMENT

- QCM is radially localized in the pedestal center and foot. At first glance, TEM and KBM are the main candidate;
- KBM growth rate is larger within QCM $k_\perp \rho_s$ range. TEM peaks at higher $k_\perp \rho_s$;
- QCM velocity in the co-moving (plasma) frame: KBM → IDD; TEM → EDD. However, significant uncertainties;
- Comparing the cross-phases → experimental α_{nT_e} and $\alpha_{n\phi}$ have good agreement with KBM linear fingerprint at the pedestal foot.



CONCLUSION

- A **kinetic ballooning mode (KBM)** in the pedestal foot is identified as the main candidate for the QCM drive instability (based on comparisons between experimental fingerprints and **local linear gyrokinetic simulations;**
- **Global linear gyrokinetic simulations** with the nominal E_r also observed a KBM in the pedestal foot/center that shares similarities with the QCM (e.g., radial location and $\alpha_{n\phi}$);
- The good agreement with the linear simulations suggests that the linear character of the mode is preserved to some extent. Next step: non-linear gyrokinetic and global flux-driven simulations.

[1] M. Greenwald et al., PoP 6, 1943 (1999)
[2] L. Gil et al. NF 60, 054003 (2020)
[3] G. Grenfell et al. NF 64 104002 (2024)
[4] G. Grenfell et al., RSI, 023507 (2022)
[5] M. Griener et al., RSI, 89, 10D102 (2018)
[6] A. Mikhailovskii et al. PPR (1997)
[7] T. J. Kalis et al. NF 64 016038 (2023)
[8] T. Nishizawa et al., RSI, 92, 103501 (2021)
[9] B. Scott. Book. Vol. 1 (2022)
[10] F. Jenko et al. PoP 7 1904 (2000)
[11] T. Görler et al. JCP 230(18), 7053-7071 (2011)
[12] H. Doerk et al. PPCF (2016)
[13] C. Bourdelle et al. PPCF 54 115003 (2012)

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