New insights on the quasicoherent mode in EDA high confinement discharges

G. Grenfell[1], T. Görler[1], J. Kalis[1], L. Gil[2], P. Manz[3], J. Adamek[4], G. Birkenmeier[1,5], D. Brida[1], J. Cavalier[4], G. D. Conway[1], M. Faitsch[1], M. Griener[1], T. Happel[1], M. Spolaore[6], C. Silva[2], U. Stroth[1,5], B. Vanovac[7], E. Wolfrum[1], the ASDEX Upgrade Team[a], and the EUROfusion Tokamak Exploitation Team[b]

[1]*Max-Planck-Institut für Plasmaphysik, Boltzmannstr.2, 85748 Garching, Germany*
[2]*Instituto de Plasmas e Fusao Nuclear, Instituto Superior Técnico, Universidade de Lisboa, 1049-001 Lisboa, Portugal*
[3]*Institute of Physics, University of Greifswald, Greifswald, Germany*
[4]*Institute of Plasma Physics of the Czech Academy of Sciences U Slovanky 2525/1a 182 00 Praha 8*
[5]*Physics Department, TUM School of Natural Sciences, Technical University of Munich, 85748 Garching, Germany*
[6]*Consorzio RFX, 35127, Padova, Italy*
[7]*Massachusetts Institute of Technology, Plasma Science and Fusion Center, Cambridge, MA 02139, USA*
[a]*See author list of Hartmut Zohm 2024 Nucl. Fusion in press and*
[b]*See author list of E. Joffrin et al. Nucl. Fusion to be published)*

Email: gustavo.grenfell@ipp.mpg.de

Intrinsic ELM-free regimes that effectively combine a high-performance fusion core with a robust power exhaust solution are crucial for a fusion reactor [1]. The enhanced D-Alpha (EDA) H-mode is a promising ELM-free regime that fulfills several requirements for ITER and a DEMO reactor [2,3], such as low impurity content, high normalized energy confinement, compatibility with a highly radiative edge and divertor region, and high Greenwald density fraction. Nevertheless, the instability that triggers the quasicoherent mode (QCM) [4,5], an edge oscillation that prevents the pressure gradient from exceeding the peeling-ballooning limit, is poorly understood, making it difficult to extrapolate this regime to future devices. In this contribution, several turbulence fingerprints associated with the QCM are measured [5] and compared to linear gyrokinetic simulations. The result indicates that the QCM is driven by a marginally unstable kinetic ballooning mode (KBM) in the pedestal foot.

A stationary low-power EDA H-mode was developed in ASDEX Upgrade [5] in order to maximize the number of experimental observables to compare with simulations. Fluctuations associated with the QCM are measured with a reciprocating electrostatic probe and with the thermal helium beam (THB) diagnostics at the outer midplane. Fig. 1 a) shows the mode amplitude in arbitrary units. The two diagnostics combined cover well the mode's radial extension of about 2 cm, spanning from the pedestal region into the near scrape-off layer (SOL). The maximum amplitude is just inside the separatrix at the pedestal foot. In the laboratory frame, the QCM frequency is constant $f^{QCM} \approx 45$ kHz across its radial extension [5], even though the background $E \times B$ velocity ($v_\theta^{E\times B}$) varies (Fig. 1 b) in the same interval. The mode velocity ($v^{QCM} = 2\pi f^{QCM}/k_\theta$) is in the electron diamagnetic direction (EDD) in the lab frame. The poloidal wavenumber of the mode is found in the range $k_\theta \rho_s \approx 0.02 - 0.05$ (where ρ_s is the ion gyroradius) [5,6], increasing slightly towards the SOL [5]. In the co-

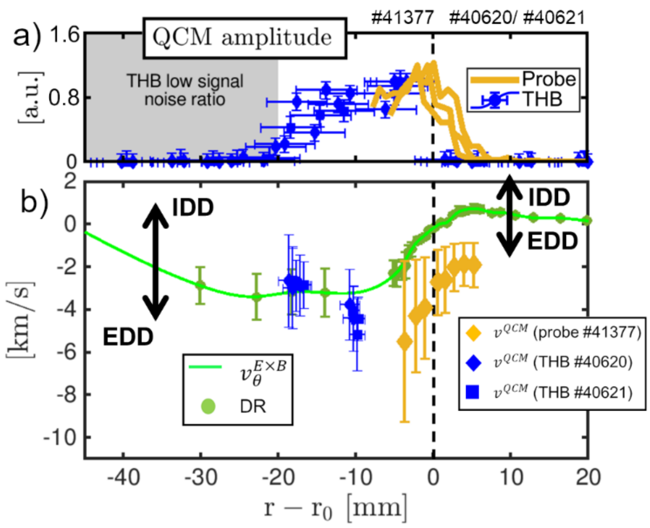

Fig. 1 a) QCM normalized amplitude measured with the reciprocating probe and the thermal helium beam (THB); b) background $\boldsymbol{E} \times \boldsymbol{B}$ velocity measured with the Doppler reflectometry (DR) is compared to the QCM phase velocity. Here, EDD/IDD = electron/ion diamagnetic direction.

moving frame (i.e., plasma frame rotating with $v_\theta^{E\times B}$), the QCM velocity direction depends on the radial location. While in the confined region, the mode propagates somewhere between the EDD and the ion diamagnetic direction (IDD), in the SOL, the propagation is mainly in the EDD (within the errorbars). Such variation in the velocity keeps the mode frequency in the laboratory frame constant, and it is connected with changes in the mode characteristic that becomes more drift-wave-like in the SOL [5]. For a larger database of EDA H-mode and QCE discharges, the QCM was estimated to propagate in the IDD at its maximum amplitude [6].

Focusing on the confined region where the QCM is likely generated, we have performed linear gyrokinetic simulations with the code GENE [7]. The result shows that the pedestal top is dominated by electron and ion temperature gradient modes (ITG and ETG, respectively), the pedestal center is mostly dominated by trapped electron modes (TEM) and ETG, and the pedestal foot is governed by TEM and a marginally unstable KBM. However, based on the mode radial location and wavenumber, the KBM at the pedestal foot initially appears to be the main drive of the QCM. To assess this result further, we compare the simulations with the experimental turbulence cross-phases between density and electron temperature (α_{nT_e}, measured with the THB diagnostic [8]), as well as between the plasma potential and density ($\alpha_{n\phi}$, measured with the probe [5]). Note that the latter is associated with the radial particle flux, $\Gamma_r \propto \sin\alpha_{n\phi}$ [5]. Fig. 2 shows that the experiment is in line with the simulation in the QCM perpendicular wavenumber range (gray area), where the KBM is dominant. While temperature and density fluctuations are in phase, density and potential fluctuations are closer to π. The latter is a fingerprint of electromagnetic instabilities such as the KBM [5,9,10].

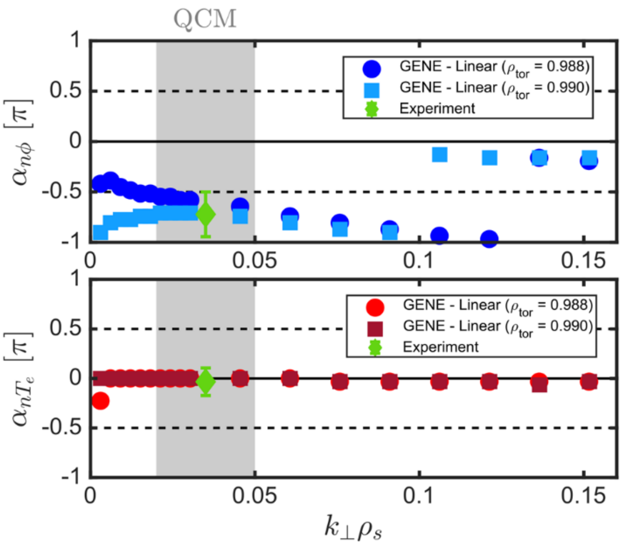

Fig. 2 Cross-phase between density and plasma potential ($\boldsymbol{\alpha_{n\phi}}$) and density and electron temperature ($\boldsymbol{\alpha_{nT_e}}$) from the experiment and from linear simulations with GENE at two locations at the pedestal foot where KBM is dominant.

In short, new experimental evidence indicates that a marginally unstable KBM in the pedestal foot drives the QCM in the EDA H-mode in ASDEX Upgrade. Linear gyrokinetic simulations with the code GENE support this conclusion. Non-linear gyrokinetic and global flux-driven simulations are planned for the future, which will be important to check the consistency of the linear analysis and to understand pedestal-SOL coupling. Nevertheless, the good agreement already suggests that the linear characteristics of the driven instability are likely preserved. The extrapolability of this result to future fusion reactors is not straightforward, but the implications of an unstable KBM in the pedestal foot of future reactors need to be better addressed, especially if the EDA H-mode (or variants of this regime) becomes the route pursued for a fusion reactor.

Acknowledgment: *This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No. 101052200 - EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.*

[1] H. Zohm et al 2021 Fusion Eng. Des. 166 112307
[2] L. Gil et al 2020 Nucl. Fusion 60 054003
[3] A. Kallenbach et al 2020 Nucl. Fusion 61 016002
[4] B. LaBombard et al. 2014 Phys. Plasmas 21, 056108
[5] G. Grenfell et al 2024 Nucl. Fusion 64 104002
[6] J. Kalis et al 2023 Nucl. Fusion 64 016038
[7] F. Jenko et al 2000 Phys. Plasmas 7 1904
[8] T. Nishizawa et al 2021 Rev. Sci. Instrum. 92, 103501
[9] B. Scott B 2021 Book, Volume 1
[10] W. Zholobenko et al 2024 Nucl. Fusion 64 106066