Progress towards a quiescent, high confinement regime for the all-metal ASDEX Upgrade tokamak

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Introduction

Future magnetic fusion devices foresee the high confinement (H-mode) as the baseline operational scenario. However, the steep edge pressure gradient of the H-mode comes with a drawback – edge localized modes (ELMs) that expel particles and energy from the plasma, causing erosion and unacceptable power loads onto the divertor target plates. Several mitigation or even full suppression techniques are currently being developed across all machines to ensure high confinement without the transient degradation of the pedestal caused by ELMs. The quiescent H-mode (QH-mode) [1] is one of the considered alternative scenarios as it is naturally ELM-free. The onset of the QH-mode is characterized by the edge harmonic oscillation (EHO), which is thought to increase the edge particle transport to allow natural stability against ELMs. Originally discovered at DIII-D [1], it was later also observed on ASDEX Upgrade (AUG) [2], JET [3] (both still equipped with a carbon wall) and JT-60U [4]. In a metal machine, a sustained QH-mode proved to be more difficult to obtain.

Experiments dedicated to the development of the QH-mode were carried out in the all-metal AUG tokamak and are presented here. For the first time, the appearance of the EHO was observed during transient QH-modes that lasted several confinement times (up to 500 ms).

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Access conditions

The QH-mode is typically accessed at low density and low collisionality, conditions that are usually obtained right after a fresh boronization. Stationarity has been achieved over a wide operational space [1], including pedestal collisionality, shaping, edge safety factor (q_{95}), poloidal beta (β_{pol}) and Greenwald fraction [5]. However, steady operation at high Greenwald fraction and ITER relevant q_{95} as well as the compatibility with a metal wall have not been demonstrated yet and are current research targets.

For a long time, a counter-current torque was believed to be a necessary ingredient for QH-mode access as the first QH-modes [6] were achieved with counter neutral beam injection (NBI). In 2009, DIII-D carried out dedicated experiments with co- and counter-injection and achieved the QH-mode also with pure co-NBI [6]. This demonstrated that the counter edge rotation is not a necessary condition, but rather the magnitude of the shear in the edge rotation needs to be sufficiently large. While pure co-NBI QH-modes were observed in the past at DIII-D, they are far more challenging to achieve and often some level of counter-injection is applied. At AUG, the counter-current NBI geometry can only be achieved in the reversed I_p/B_t configuration. In fact, when AUG was equipped with a carbon wall, the QH-mode was only achieved with counter-current beams [2].

Experiments in reversed I_p/B_t configuration

Since counter-current beams seem to facilitate the access to the QH-mode, part of the QH-mode development programme at AUG was carried out in reversed I_p/B_t. As increased beam-ion orbit losses are observed in this configuration, beam operation is usually restricted. In order to couple in more beams, the distance of the last closed flux surface to the wall was increased by using a small plasma compared to an edge optimized contour plasma, which is usually used at AUG to obtain high resolved pedestal measurements. A low density scenario at 2.5 T and -800 kA was successfully established with up to 8 MW counter-current beams. The EHO appeared in several discharges, with the most notable phase shown in figure 1. At the switch-on of the fourth beam the ELMs change in size and have a higher frequency (not shown here), until they are replaced by an edge harmonic oscillation (see figure 1(d)), localized to the plasma edge by means of the ECE and soft X-ray diagnostics. Throughout the four-beam phase the radiated power

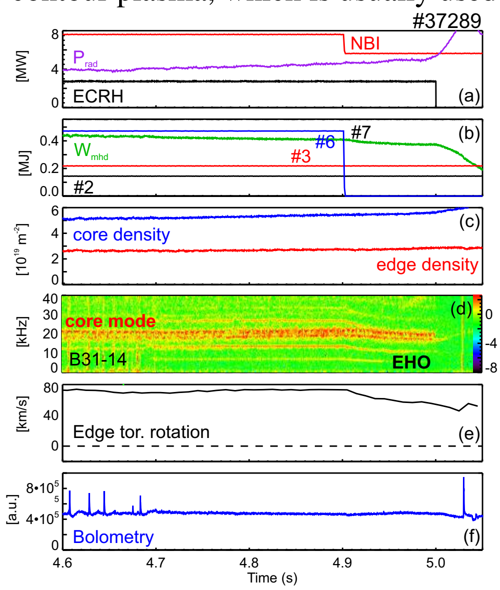

Figure 1: *Overview of discharge #37289.*

and line-averaged density slowly increase, reaching values of 4 MW and 2.5· 10^{19} m^{-2}.

Note that the plasma is ramped down at 5 s, to avoid overheating of the heatshield caused by the NBI in these low density plasmas.

One important difference to the QH-modes in AUG-C is that these plasmas feature a much higher electron temperature (T_e) compared to the ion temperature (T_i), since central electron cyclotron resonance heating (ECRH) is needed to avoid core tungsten accumulation. Figure 2 shows a comparison of the T_e and T_i profiles obtained in AUG-W and in AUG-C [2].

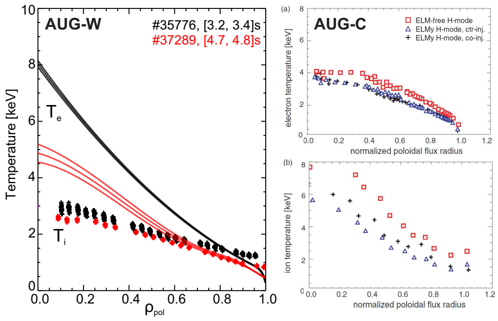

Figure 2: *T_i and T_e profiles during the QH-mode at AUG-W (left) and comparison to AUG-C (right) [2].*

Note that in discharge #37289 the EHO appeared after entering the H-mode regime. Interestingly, in follow-up experiments the EHO also appeared during the early ELM-free phase. An example is given in figure 3. As the plasma transits into a higher confinement regime, two small ELMs appear, and then continues to evolve until, at 1.59s, it arrives into a regime with a higher recycling level, as shown in one of the bolometry channels. At the same time, an EHO appears and the stored energy, plasma density and radiated power stall. The phase with the EHO lasts for 320 ms. At 1.827s the plasma density starts to increase (by 10%) and evolves into a type-I ELMy regime at 1.92s. As shown in figure 3, the EHO appears with 1.8 MW counter-NBI and up to 2.5 MW of ECRH. Future work focusses on extending this phase to stationarity.

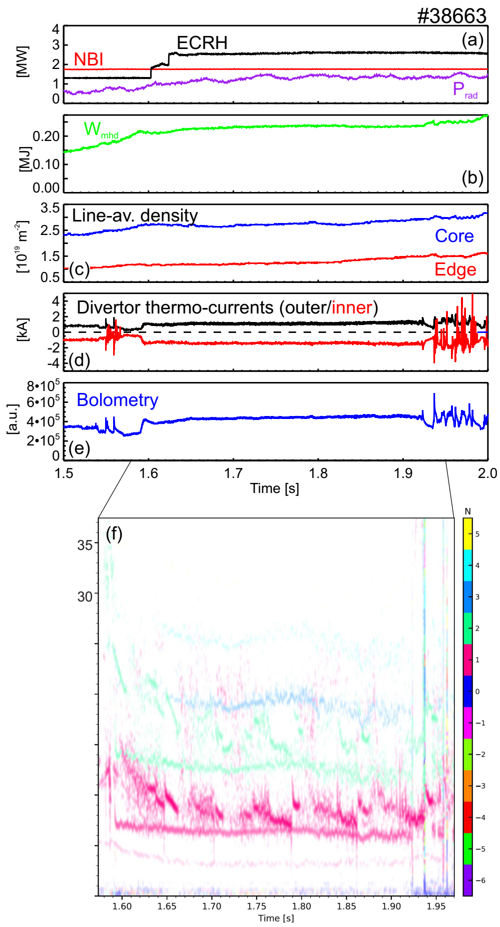

Figure 3: *Overview of discharge #38663.*

Experiments in forward I_p/B_t configuration

In forward I_p/B_t, the most promising phase was identified in an upper single null (USN) discharge, corresponding to the unfavourable ∇B drift configuration. Similar as in reversed I_p/B_t, this provides a higher L-H power threshold and a starting point at low density and higher rotation, as up to two beams (up to 4 MW) of NBI can be coupled into the L-mode phase. Notice that AUG does not feature a pump in the upper divertor, making density control a challenge. Typically, a very small gas puff at the beginning of the discharges or a minimum feedforward gas puff of $0.5 \cdot 10^{21}$ e^{-}/s is applied.

Figure 4 shows an example discharge in USN with up to 6 MW NBI and 0.5 MW ECRH. As soon as the second beam switches on, rotation and stored energy increase. The plasma exhibits 3 small ELMs and as the power ramp on NBI source #6 starts, it enters into a long ELM-free phase (about 500 ms) exhibiting an EHO which is then replaced by an $n = 3$ mode. Both modes are localized in the pedestal region. During this phase a toroidal rotation up to 150 km/s is reached at the plasma edge (see figure 4(g)). The density increases and at 3.76 s the plasma transits into an H-mode regime with compound ELMs [7]. At 4 s, a shape-change transition to lower single null (LSN) is programmed, which brings the plasma into a type-I ELMy regime. Notice the lower density in LSN, as the pump in the lower divertor is active. During this QH-mode phase (3.25 - 3.76 s) an energy confinement factor up to $H_{98}(y,2) \approx 1.4$ is achieved. However, notice the evolution of the density, making this phase a transient. The installation of the upper divertor (and a cryo-pump) foreseen for 2022/23 at AUG may help to get a better control of the density and get a sustained QH-mode in USN.

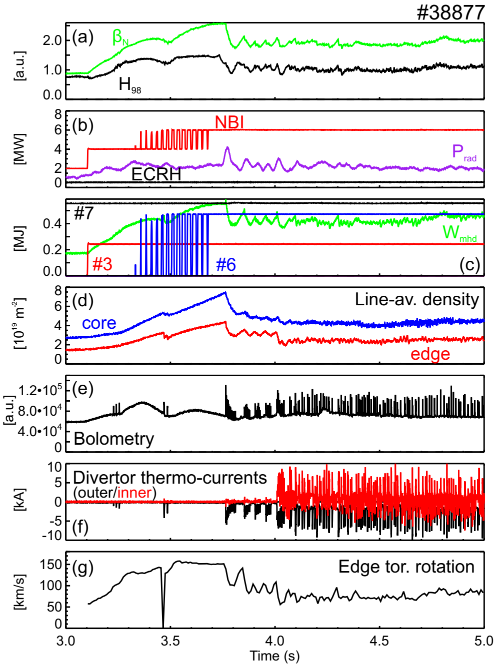

Figure 4: *Overview of discharge #38877.*

Summary

Transient QH-modes up to 500 ms were observed for the first time in the all-W tokamak ASDEX Upgrade. The signatures of the EHO were observed in several diagnostics. The QH-mode appears at the low density, high temperature branch, with the pedestal close to the kink-peeling boundary. Future work focusses on extending the QH-mode to stationarity.

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References

[1] K. H. Burrell et al., Phys. Plasmas **8**, 2153 (2001)
[2] W. Suttrop et al., Plasma Phys. Control. Fusion **45**, 1399 (2003)
[3] E. R. Solano et al., Phys. Rev. Lett. **104**, 185003 (2010)
[4] Y. Sakamoto et al., Plasma Phys. Control. Fusion **46**, A299 (2004)
[5] E. Viezzer, Nucl. Fusion **58**, 115002 (2018)
[6] K. H. Burrell et al., Phys. Rev. Lett. **102**, 155003 (2009)
[7] H. Zohm, Plasma Phys. Control. Fusion **38**, 105 (1996)