ELM-free stationary H-mode plasmas in ASDEX Upgrade

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Introduction

High-confinement mode (H-mode) plasmas with best performance are usually accompanied by type I Edge Localised Modes (ELMs), which in a next step fusion device might place an excessive heat load to the divertor target [1]. It is therefore important to study ELMfree or small ELM regimes with high pedestal energy and good confinement. Several such H-mode regimes have been demonstrated in various machines [2]. A recent finding is the Quiescent H-mode (QH mode) in DIII-D [3], a stationary ELM-free regime with high edge pedestal pressure and good confinement, which, unlike most small-ELM regimes, exists at low pedestal collisionality, $v^* < 1$. In 2002, QH mode plasmas have been obtained also in ASDEX Upgrade [4], with essentially the same phenomenology as QH modes in DIII-D. The QH regime has been reproduced during a new campaign in 2003. Here, we report on these experiments with emphasis on the new results, particularly on the specific MHD activity.

Quiescent H-mode plasma behaviour

The conditions for achieving QH mode in ASDEX Upgrade are found to be in agreement with those reported in Ref. [3]: 1. Neutral beam injection opposite to the plasma current (counter-injection), 2. plasma equilibrium with high wall clearance and good pumping, and 3. good wall conditioning. In the 2003 campaign with reversed plasma current for counterinjection, we obtained QH mode in the first pulse with Neutral Beam Injection (NBI) after boronisation. The equilibrium used in these experiments is shown in Fig. 1 (a) together with selected diagnostics sightlines (discussed below). The inboard and outboard gaps at midplane are about 8 cm. The strike points are in a pumping position for ASDEX Upgrade divertor IIb. Shape parameters are: $\kappa = 1.7$, $\delta_l = 0.41$, $\delta_u = 0.05$. A plasma current of 1 MA was used throughout. So far, QH modes have been obtained with toroidal fields from $B_t = 2.0$ to 2.5 T, and corresponding to $q_{95} = 3.5...4.4$.

Figure 1 (b) shows time traces of a discharge in ASDEX Upgrade that shows long Quiescent H-mode (QH) phases. After 5 MW of counter NBI is applied, an initial ELMy Hmode plasma is established which (at ≈ 3 s) begins to develop extended ELM-free phases, during which the main chamber radiation (P_{rad}), central line-averaged electron density (\overline{n}_e) and peripheral line-averaged density ($\overline{n}_{e,edge}$) remain approximately constant. The energy confinement time in the ELMy and QH phases is very similar, here with an H-mode factor $H_{92,y} = 0.95$. In the plasma centre, typically $T_i > T_e$ with $T_i = 6$ keV in the present example. Often pronounced toroidal core plasma rotation is observed in charge exchange recombination measurements, 300 km/s in this example and up to 350 km/s in other shots. Rotation



Figure 1: (a) High clearance configuration for QH mode with diagnostics sightlines for EHO characterisation, (b) Time traces of shot 17686 with long QH phases.



spin-up and spin-down are not directly correlated with the central temperature. The discharge shown in Fig. 1 has a strong m = 1, n = 1 mode and fishbones from the beginning of the H-mode phase and becomes sawteething in the middle of the QH phase, at t = 4.9 s. The Z_{eff} with counter-injection is high compared to co-injection. In the 2002 campaign we found $Z_{\text{eff}} \approx 4$ in ELMy and $Z_{\text{eff}} \leq 5$ in QH phases, dominated by carbon and oxygen. The 2003 QH experiments have been made with fresh boronisation, and Z_{eff} is considerably lower, ranging to well below $Z_{\text{eff}} = 3$ (lowest value $Z_{\text{eff}} = 2.4$).

A scan of the neutral beam injection angle has been performed, using 5 MW power from two NBI sources at a time, selected from the eight installed sources with injection geometry ranging from near radial injection to tangential injection with a tangency point near mid-radius on the inboard side. Although QH mode occurs in all cases, the longest phases are obtained with intermediate injection angle. In several shots the outer midplane wall distance has been lowered from 8 to 5 cm, without losing the QH mode regime. In one shot with radial sources, QH mode has only been obtained with outer gap smaller than 7 cm. This contrasts with a previous gap scan [4] with intermediate injection angle which showed a min-



Figure 2: *T_i* profiles in ELMy and QH phases with and without ICRH.

imum gap of 7.5 cm. It is not clear at present whether the required wall distance depends,

for example, on the neutral beam trapped particle orbit width. In addition to neutral beam heating, we have used up to 1.5 MW centrally deposited Ion Cyclotron Resonance Heating (ICRH), the maximum power coupled into high clearance shape. With ICRH, the central ion temperature for the QH mode conditions described above rises from about 6 to 8 keV (Fig. 2). The pedestal T_i increases by the same ratio and the T_i gradient length is maintained during the shot. T_e is also increasing but with a reduction of gradient length, i.e. the T_e profile appears less stiff. The electron density and Z_{eff} are varying only little, indicating that the pedestal pressure depends more strongly on heating power in QH mode than in ELMy H-mode.

Edge Harmonic Oscillation

The Quiescent H-mode plasmas display pronounced MHD behaviour. In addition to the fishbone or sawtooth activity in the core there is a continuous edge mode with a pronounced harmonic spectrum, dubbed the "Edge Harmonic Oscillation" (EHO, [3]) during all time intervals when ELMs are suppressed. This mode is seen in magnetics signals on the highand low field side, Soft X-Ray (SXR, channels with sightlines near the plasma top and near the X-point), reflectometry measurements from the low and high field sides, and electron cyclotron emission (ECE) measurements. The sightlines of these diagnostics are shown in Fig. 1 (a). A radial localisation in the steep gradient region, near the separatrix, is found from 1-D deconvolution of the modulated SXR emissivity and ECE profiles [4].

The sensitivity of the mode localisation to the edge safety factor is studied with toroidal field ramped from $B_t = 2.1$ to 1.9 T at fixed $I_p = 1$ MA. QH mode is obtained between $B_t = 2.025$ and 2.08 T, corresponding to $q_{95} = 3.5$ and 3.7. The wavelet spectrogram of a Mirnov coil signal (Fig. 3, upper left panel) reveals the existence of the EHO throughout the QH mode phase with more than 8 harmonics. The EHO modulation is seen in several ECE channels which cross the plasma edge at different times, strongest at the times when the ECE emission originates from near the q = 4 or q = 5 surfaces (indicated by hexagons and squares in Fig. 3, respectively). This is always near R =2.12 m, or at about 1 cm from the separatrix, i.e. in the steep gradient region. This position



Figure 3: Wavelet spectrograms of a Mirnov coil signal and 6 ECE channels showing the EHO during a ramp of toroidal field and safety factor. The positions of the ECE resonance and q surfaces are given in the upper right panel.

does not seem to change during the ramp. Channels with ECE resonance in the scrape-off layer, which is optically thin for ECE in these shots, pick up a signal from downshifted emis-

sion from the tail of the electron energy distribution. This effect occurs for channels 17 and 18 and is marked "shine through" in the figure. An interesting feature occurs from t = 3.0 to 3.2 s when the frequency of the EHO dithers between two distinct values at a frequency ratio of 5/4 while the q = 4 surface approaches the plasma edge. This indicates a transition of the EHO fundamental from m = 5, n = 1 to m = 4, n = 1, consistent with the phase relation of a set of poloidally distributed Mirnov coils. QH mode is also obtained at higher toroidal field of $B_t = 2.5$ T ($q_{95} = 4.4$), with EHO mode numbers m = 5, n = 1.

The EHO is in phase with the amplitude of another MHD mode at much higher frequencies, between 350 and 490 kHz, termed the "High Frequency Oscillation" (HFO, [4]). The EHO cycles are also correlated with the outer divertor D_{α} intensity with a time delay of 22 μ s, consistent with the transit time of beam ions from the outer midplane to the divertor.

Summary and Discussion

New experiments with counter neutral beam injection have been made in ASDEX Upgrade to study the Quiescent H-mode regime. The different vessel history of the previous and the present QH mode experiments highlight the importance of good wall conditioning: After fresh boronisation in ASDEX Upgrade, QH mode is more readily achieved and plasmas with counter injection have considerable smaller Z_{eff} , demonstrating the importance of impurity influx in QH mode.

We have now obtained QH mode over a broader range of parameters than previously studied [4]: With different neutral beam injection angles, with and without ICRH, with outer midplane gap as small as 5 cm, and at different values of the edge safety factor, $q_{95} = 3.5 \dots 4.4$. In all cases the Edge Harmonic Oscillation (EHO) is found, and it is always localised at the edge, in the steep gradient region. The mode numbers of the EHO fundamental are n = 1 and m assumes the lowest value for which the q = m/n surface is still in the gradient region. The low mode numbers and the fact that the EHO is observed on several outboard and inboard poloidal locations seems to exclude a purely pressure gradient driven ballooning mode as the underlying instability. Equilibrium reconstruction with the CLISTE code, leaving sufficient freedom in the parameterisation of the edge toroidal current, can be used to identify the integrated edge current density from magnetic measurements alone [5]. In the present experiment, the edge current, aligned with the pressure gradient region and therefore presumably bootstrap-driven, does not differ significantly in ELMy and QH phases. This observation seems to exclude that in QH mode the ELMs are suppressed by a reduction of the edge bootstrap current [6], e.g. due to high Z_{eff} . In fact many of the new discharges show no significant difference of Z_{eff} in ELMy and QH phases. On the other hand, it is possible that the edge bootstrap current plays a role in driving the EHO, analogous to external kink modes.

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