Proceedings of ITC18,2008

Quasi-Coherent Modes in the High Density H-mode Regime of W7-AS

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The high density H-mode (HDH) is an ELM-free H-mode regime at the Wendelstein 7-AS (W7-AS) stellarator exhibiting no impurity accumulation. Quasi-Coherent (QC) modes found recently on Mirnov coil signals are thought to be prime candidates responsible for the low impurity concentration in this regime based on their strong correlation to impurity radiation. These modes are high frequency (50-150 kHz), high poloidal mode number (m~40), possibly pressure-driven oscillations, showing strong amplitude modulation. QC modes are occasionally accompanied by low frequency oscillations (principle frequencies <50 kHz plus higher harmonics) not unique for the HDH regimes detected by both the Mirnov coils and Langmuir probes, as well as high frequency oscillations (250-350 kHz) that - when present - decrease the QC amplitude. QC modes on W7-AS show similarities to quasi-coherent modes found on the Alcator C-Mod tokamak, responsible for the low impurity concentration in the similar ELM-free, high density H-mode called Enhanced D-alpha mode, prompting a careful comparison between the two modes.

Keywords: ELM-free H-mode, high density H-mode, quasi-coherent modes, impurity transport, W7-AS

1. Introduction

The High Density H-mode (HDH) [**1**] is a stationary ELM-free improved H-mode regime at the Wendelstein 7-AS (W7-AS: major radius R = 2 m, minor radius $a_{eff} \leq 0.16$m, toroidal magnetic field $B_t \leq 2.5$T) [**2**] stellarator not subject to impurity accumulation even at high line averaged electron densities up to $4 \cdot 10^{20}$ m^{-3}. It has been obtained above a threshold density after the realization of the island divertor concept on W7-AS. It is characterized by flat density profiles, edge-localized radiation and energy confinement times about $2 \cdot \tau_e^{ISS95}$ beside significantly low impurity retention times. This is of particular interest as future fusion-oriented devices are mainly preferred to be run at high densities, a regime often susceptible to impurity accumulation and ensuing radiation collapse as it is the case for the standard ELM-free H-mode regime of W7-AS called the Quiescent H-mode (H*). The mechanism responsible for this low impurity concentration of the HDH regime has not yet been identified.

Recent investigations of Mirnov coil data found an MHD mode appearing in the HDH phase showing remarkable correlation with the impurity radiation making it a promising candidate for the impurity flushing mechanism.. The mode was named quasi-coherent (QC) mode due to its similarity to the QC modes [**3**] found in the Enhanced D-alpha (EDA) regime [**4**] of the Alcator C-Mod tokamak, responsible for the low impurity concentration in that high density ELM-free regime. Characteristics of these modes and their relation to the impurity transport are reported here. Other MHD modes accompanying the QC modes are investigated here as well. A careful comparison of the QC modes to other similar MHD modes present in stable ELM-free regimes of other devices is attempted as well, in order to gain better insight into the nature of these modes.

2. Quasi-Coherent Modes in Wendelstein 7-AS

Quasi-coherent modes are bursty, narrow band (~10-15 kHz) oscillations in the 50-150 kHz frequency range detected in the poloidal magnetic field fluctuations showing good correlation with the impurity radiation. Fig. 1. shows a spectrogram of a Mirnov coil signal and the corresponding impurity radiation from bolometry for two ELM-free H-mode time windows, namely the quiescent H* and the HDH mode. In H* the impurity radiation increases due to impurity accumulation in the core and broadband fluctuations can be observed that appear to be the reminiscent of small ELMs. In the HDH phase a QC

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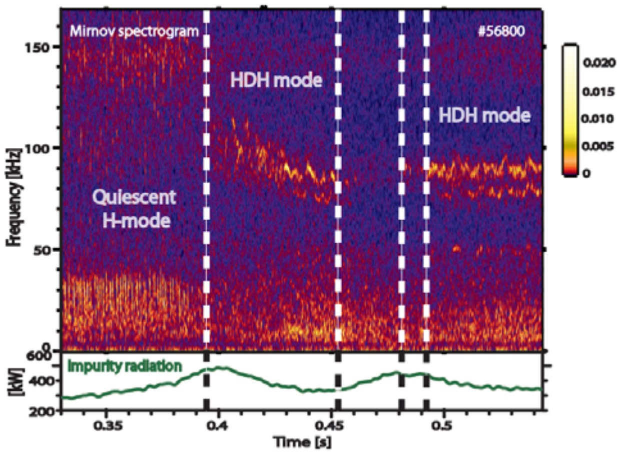

Fig. 1. Spectrogram of the magnetic fluctuations measured by a Mirnov coil for the Quiescent H-mode and HDH phase showing the presence of a quasi-coherent mode. The corresponding impurity radiation is indicated as well.

mode appears with its frequency sweeped down from about 120 kHz to 90 kHz, and the impurity radiation decreases corresponding to an outward flux of impurities. Bolometer tomography confirms that the radiation profile becomes strongly localized to the edge in the HDH phase [2]. At around 0.455-0.48 s the mode's amplitude drops an order of magnitude whereas the impurities start to accumulate anew and the radiation increases. This phase is then followed by a stable HDH phase with the QC mode reappearing at 90 kHz. A subsequent accompanying oscillation is present as well around 78 kHz, its presence is however not correlated with the impurity behaviour. For a quantitative comparison between radiation and the QC mode amplitude first, the frequency of the QC mode is obtained from a 16 channel poloidal Mirnov array by determining the frequencies present in at least a preset (10 and 13) number of Mirnov coil signals. The QC amplitude is then defined as the mean of 16 normalized bandpower signals [**5**] in the narrow frequency band containing the QC frequency obtained from the 16 Mirnov coil signals. The frequency band, QC amplitude and impurity radiation is shown in Fig. 2. The clear correlation between the QC mode amplitude and the radiation is obvious. The strong amplitude modulation of the QC mode can also be seen.

Determination of the mode number has been attempted from three poloidal Mirnov coil arrays (16, 8 and 8 channels respectively) by time-windowed Fourier decomposition of the signals and analysing the relative phase shift of the fluctuations. No poloidal mode number (m<6) could be obtained, indicating a higher value than what the limited number of Mirnov channels could resolve. A reciprocating probe housing two poloidal field pick-up coils (MRCP), based on the concept of Snipes et al [**6**], has been inserted into the plasma measuring the radial decay of the magnetic field perturbations along the distance to the separatrix. As shown in Fig. 3., the amplitude of the mode falls off rapidly, in about 2 cm-s, with the distance from the separatrix with an exponential decay length of k_r~2.82 (±0.78) cm^{-1} and k_r~ 3.18 (±0.79) cm^{-1} respectively for the 90 kHz and 110 kHz QC modes. By assuming a field aligned perturbation and using the Laplace equation outside the fluctuating current layer (method described in [**6**]) $k_r \approx k_{pol}$ (as $k_{tor} \sim k_{pol} \cdot 0.037$ can be neglected). Thus using this rapid radial decay of the amplitude a rough estimate of the poloidal mode number of m ~ 40 is obtained. This corresponds to roughly n~20.

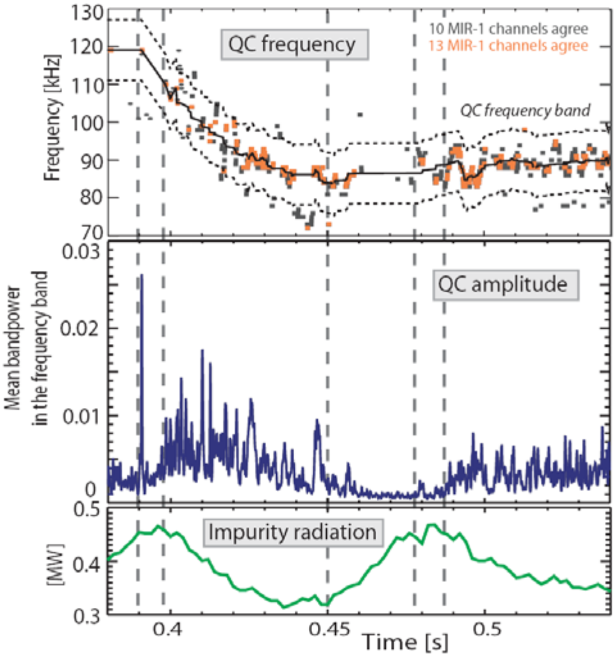

Fig. 2. Frequency band (dotted lines) and QC amplitude (defined as the mean normalized bandpower for the given frequency band for the 16 poloidal Mirnov coil array. The corresponding impurity radiation is indicated as well.

In order to get information on the driving force of the QC modes, the end phase of the discharge is studied in detail. Fig. 4 shows main plasma parameters at and after the shut down of the NBI heating (at 0.9s). Spectrogram of the Mirnov coil signal is shown as well, including the corresponding amplitudes for the QC mode at 90 kHz and the second MHD mode at 78 kHz. Two back-transitions can be observed, first after about 5 ms the impurities start to accumulate indicated by the increase of the radiation power as the plasma transitions back from HDH to H-mode. At about 10 ms the plasma goes through a second transition, i.e. an H-L back-transition indicated by

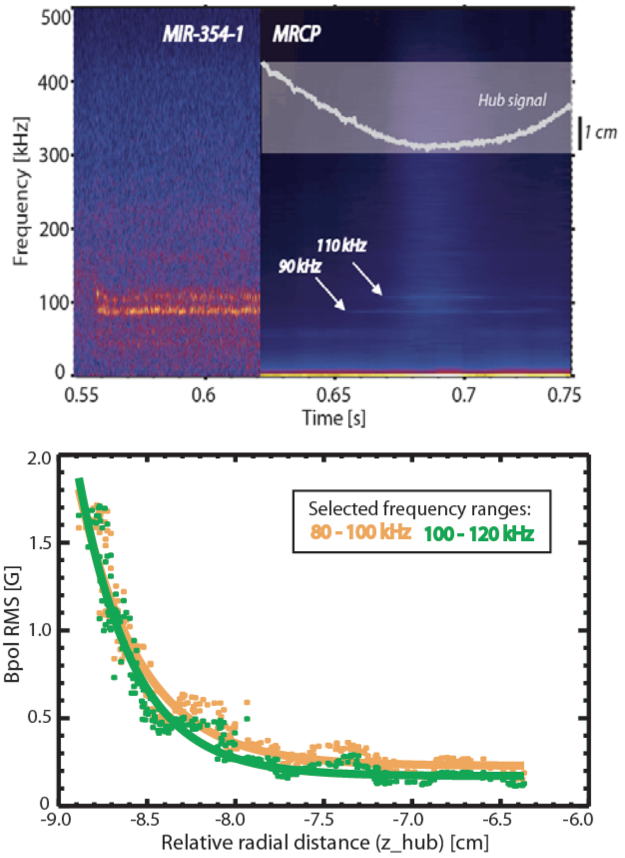

Fig. 3. (a) Spectrogram of the magnetic fluctuation measured by the high resolution Mirnov coil array and the MRCP coil including the Hub signal showing the relative distance of the MRCP coil to the separatrix (#56172). (b) Radial decay of the magnetic fluctuations measured by the MRCP probe in the frequency range of the QC modes respectively.

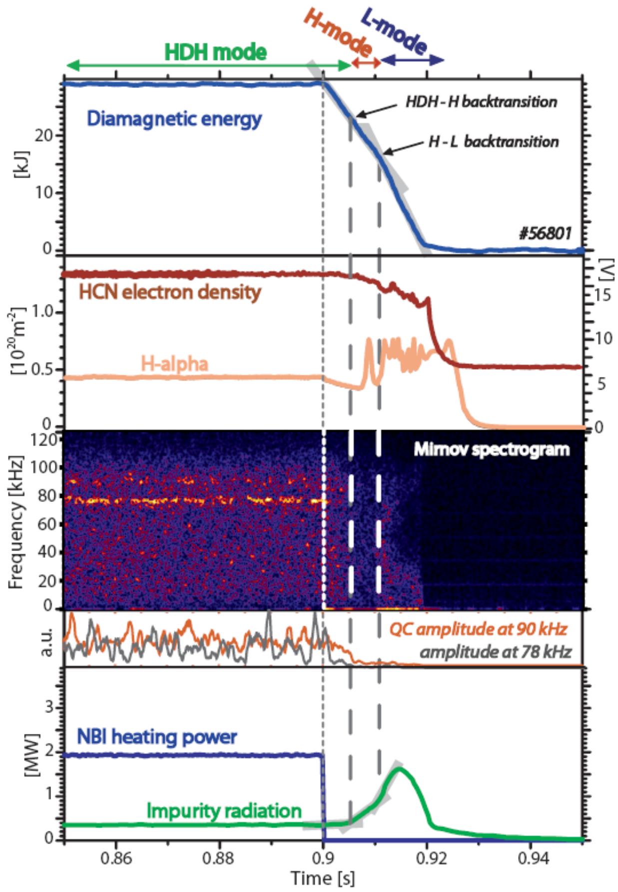

Fig. 4. Overview of the global parameters and Mirnov coil spectrogram including the amplitudes of the two MHD modes present in the discharge (#56801).

the change in the diamagnetic energy, H-alpha signal and the impurity radiation (a single ELM can be seen in the H-alpha signal before). By studying the disappearance of the MHD modes, an indication at their driving forces can be obtained. The QC mode at 90 kHz disappears about 5 ms after the shut down of the NBI in correlation with the HDH-H mode back-transition, indicating that it could be a pressure-gradient driven mode, whereas the second MHD mode at 78 kHz disappears rapidly, in only about 1-2 ms, indicating that it could have a different drive.

QC modes are not the only MHD oscillations present in the HDH regime. They are occasionally accompanied by low (LFO) and high (HFO) frequency oscillations. LFOs are oscillations with principle frequencies below 50 kHz often with higher harmonics detected by Mirnov coils, H-alpha diagnostic and Langmuir probes. These modes are not unique for the HDH phase, are often present in Quiescent H-mode as well, and do not correlate well with the impurity accumulation. HFOs are, on the other hand, observed in HDH regimes with frequencies of 250-350 kHz. They are detected by high resolution 1 MHz) Mirnov coil signals operated only in a relatively short time window, thus its relation to the impurity transport or more information on these modes could not be obtained. Preliminary analysis shows that both these low and high frequency oscillations are accompanied by quasi-coherent modes, whereas the amplitude of the QC modes seem to decrease in the presence of HFOs.

The detection and localisation of the QC modes remains an open question. It is still unresolved whether these modes are present in all HDH phases. The investigations are based on three poloidal arrays of Mirnov coils (16 channels sampled at 350 kHz, two 8 channel arrays at 1 MHz for limited time intervals) for given time interval and a single Mirnov channel at 250 kHz available throughout the discharge. Fig. 5. shows the setup of the MIR-1 16 channel poloidal Mirnov array and the magnetic reconstruction of the discharge series shown in Fig. 1,2 and 4.

At present, the modes are only detected in the magnetic fluctuations measured by Mirnov coils, as other diagnostics fail to measure the needed frequency regime and location due to the very high densities. The Lithium Beam Emission Spectroscopy did not detect these modes in the SOL, thus the location of these modes is thought to be inside the separatrix, presumably in the pedestal area. This is also supported by the fact that the QC mode frequency appears to be extremely sensitive to small changes in the rotational transform, therefore it is probably localized to a narrow radial region in the pedestal.

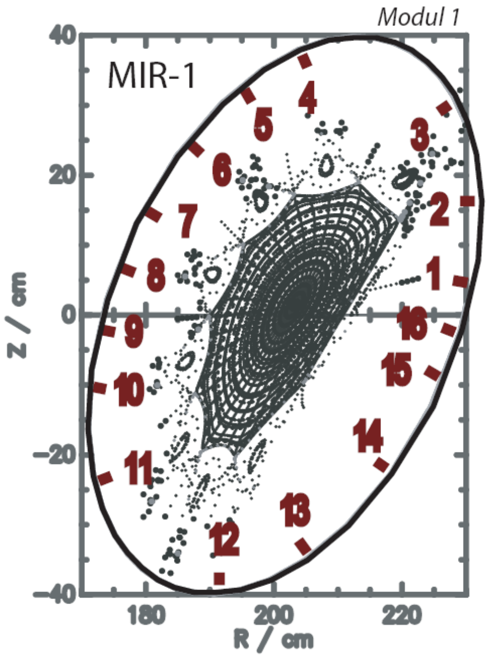

Fig. 5. Setup of the 16 poloidal Mirnov coil array and magnetic reconstruction of flux surfaces (#56801).

The universality of the QC mode is tested by analysing specific parameter scan, such as density scans for given heating powers (1, 2 MW NBI), magnetic configurations (different divertor configurations and iota values) and isotope plasmas (Hydrogen or Deuterium). An example is shown in Fig. 6. for 2 MW NBI, Deuterium plasma discharges at an iota value of 0.55. The mean coherence between Mirnov coil signal pairs is plotted for a normal confinement phase (n_e= $2.25{\cdot}10^{20}$ m^{-3}) and an HDH phase (n_e= $2.38{\cdot}10^{20}$ m^{-3}), just before and just after the density threshold of the 2 MW NBI HDH regime. At the HDH phase, modes are present appearing to be QC modes. The universality of the QC modes is, however, still unresolved. It should be noted that detection can be clearly hampered by the high mode numbers and small plasma sizes. In large plasmas (increase of 2cm in the plasma minor radius compared to standard configurations, shown in Fig. 1,2,4) a clear behaviour of QC modes is observed. They are present in and through all HDH phases showing remarkable correlation to the impurity radiation.

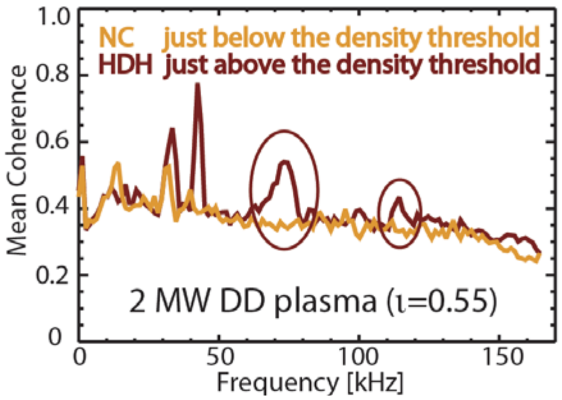

Fig. 6. Mean coherence between pairs of mirnov coil signals of two discharges in normal confinement and the HDH phase, just below and above the density threshold for the HDH regime respectively. The QC mode peaks are circled.

3. Conclusion

Quasi-coherent modes found in the HDH regime are high mode number (m~40), high frequency (f~50-150 kHz), and possibly pressure-driven oscillations that show strong amplitude modulation and correlation to the impurity radiation. At this time, no definite answer can yet be given, whether the QC mode is the mechanism responsible for the enhanced impurity transport in the HDH regime or it is a by-product of the real mechanism. The strong correlation, however, makes it a promising candidate. Further work is under way to deepen the physical understanding of this mode. At the Alcator C-Mod tokamak, similar QC modes are known to be responsible for the impurity transport in the ELM-free, stable, high density H-mode regime, the Enhanced D-alpha (EDA) H-mode. This prompts a careful comparison of the QC modes in the two regimes to gain more insight into the nature of these modes.

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