MHD limit cycles on FTU

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Introduction

The development of large-amplitude tearing modes (TM) during the pre-programmed plasma density ramp-up in proximity of the density limit [1] or after injection of sufficient amounts of Ne gas [2] on FTU ($R_0 = 0.935$ m, $a = 0.30$ m, $B_T = 2$ - 8 T, $I_p = 0.2$ -1.6 MA) shows a complex behavior that can be outlined in three stages. First stage: the magnetic island grows smoothly at constant rotation frequency. Second stage: amplitude and frequency feature large cycles of oscillations, with peak amplitude increasing progressively across cycles. Third stage: the island grows quickly to large amplitude and locks; this stage generally ends in a disruption. The amplitude and frequency oscillations show a well defined phase portrait, determining a so-called "limit cycle" on the Amplitude/Frequency plane. The existence of a stage with large amplitude and frequency modulations could be caused either by interaction between modes of different helicity or by island self-healing phenomena; resonant error field components could also play a role. Dedicated experiments were performed on FTU, in a wide range of plasma current and toroidal magnetic field values, to understand the origin of amplitude and frequency modulations of the (2, 1) TM and to obtain the scaling for transitions between different regimes (saturation, limit cycles, locking) in terms of plasma parameters and mode amplitude.

MHD activity

The magnetic activity on FTU is analyzed by means of poloidal and toroidal arrays of magnetic pick-up coils installed inside the vacuum vessel. All the investigated pulses present a very similar MHD phenomenology [3], as illustrated in Figure 1, where the time traces of some relevant quantities are reported for a pulse with $B_T = 4.0$ T and $I_p = 700$ kA. The onset of a $m/n = 2/1$ TM (m and n are the poloidal and toroidal mode numbers, respectively) is identified at $t = 0.82$ s, when the frequency takes a well-defined value of 6.5 kHz. At first, the mode grows algebraically and its frequency remains

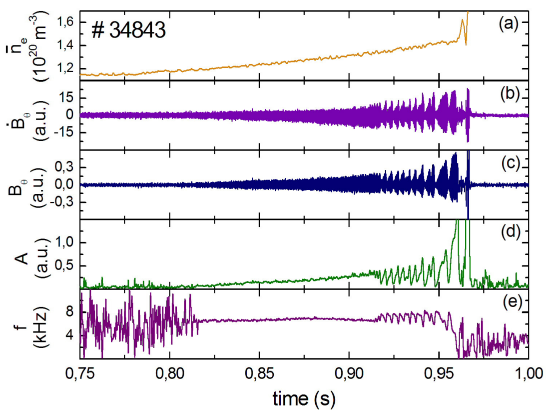

Figure 1. Time traces of some relevant quantities for the MHD activity for a specific pulse on FTU with $B_T = 4.0$ T and $I_p = 700$ kA: (a) central line-averaged density, (b) output from the pick-up coil, (c) poloidal magnetic perturbation, (d) mode amplitude, (e) mode frequency.

*See the appendix of G. Pucella et al., Proc. 25th IAEA Fusion Energy Conference, Saint Petersburg, Russia,2014 constant. Subsequently, the amplitude shows a quasi-periodic modulation, with the maximum value reached during each period still increasing algebraically. In the last phase, the mode growth speeds up and the frequency decreases to zero.

Regarding the signal processing, the output of the pick-up coils is integrated to obtain the poloidal magnetic perturbation associated to the MHD mode. In particular, a high-pass filter (1 kHz) is applied to eliminate slow drifting of the integral and a low-pass filter (20 kHz) is applied to eliminate noise. The Hilbert transform is used to calculate the amplitude and phase of signal starting from the poloidal magnetic perturbation and the derivative of the phase with respect to time is performed to obtain the mode frequency. Finally, a low pass filter is used on both amplitude and frequency to decrease the associated noise. We also considered that an air-core transformer was present on the MHD signal acquisition path. The resulting frequency dependent attenuation (particularly strong on lower frequencies) was analytically calculated and fitted against experimental data (as derived through comparison with a transformer-free acquisition chain), thus obtaining a correction that was applied to the final MHD amplitudes.

Limit cycles

As we can see from Figure 1, the temporal evolution of the TM during the density ramp-up is characterized by a “regular phase” where the mode amplitude increases at approximately constant frequency (from t = 0.82 s to t = 0.91 s in the Figure), and a “bursting phase” where the amplitude and the frequency of the mode oscillate (from t = 0.91 s to t = 0.96 s). Finally the mode amplitude grows up to high values and its frequency reduces rapidly up to the disruption. From a closer inspection of data it is possible to see that both the amplitude and frequency oscillations are higher for higher values of the line-averaged density (linearly proportional to the time for the discharge considered here). In particular, if we report the temporal evolution of the mode on the Amplitude/Frequency plane (see Figure 2), we can observe, after the regular phase (cyan lines), the formation of cycles with increasing area.

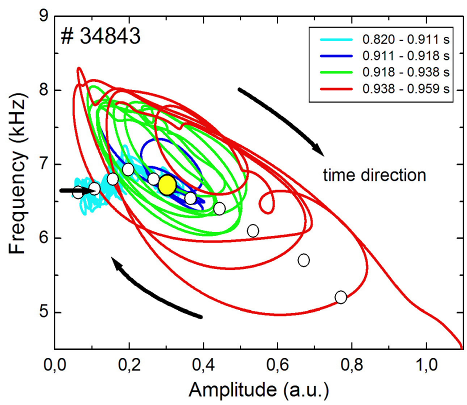

Figure 2. Time evolution of the tearing mode on the Ampltude/Frequency plane (see the legend for the meaning of colours). The evolution of the amplitude and frequency envelopes is also reported as open circles. The yellow circle corresponds to the critical mode amplitude for transition from smooth to cyclic behavior.

The critical mode amplitude for transition from smooth to cyclic behavior (reported as a yellow circle in Figure 2) was analyzed in terms of critical island width in a wide range of operational parameters, with toroidal field ranging from 4 to 8 T and plasma current from 0.5 to 0.9 MA. In particular, considering the well-known expression for the island width and employing the usual analytical estimate based on neglecting plasma current outside the mode resonant surface (good approximation going towards the density limit and for pulses with Ne gas injection), we have:

$$w = 4\sqrt{\left.\frac{rqB_{r1}}{mq'B_\theta}\right|_{r=r_s}} = 4\sqrt{\frac{Rr_s}{nB_z s_s}\cdot\left(\frac{r_c}{r_s}\right)^{m+1}\frac{1-(r_s/r_w)^{2m}}{1+(r_c/r_w)^{2m}}\cdot B_{\theta 1}(r_c)} \qquad (1)$$

where r_s, r_c and r_w are the radii of the mode resonant surface, the pick-up coil and the wall, respectively. Critical values of the full island width for the onset of the limit cycles ranged from 1 cm to 2 cm, which are in the range of the critical island width for local temperature flattening by finite perpendicular heat conduction. The existence of a well defined threshold for the transition from smooth to cyclic behavior has been also confirmed in experiments of real time control of TM performed on FTU by using injection of electron cyclotron waves (ECW) inside the 2/1 magnetic island [4]. In pulses of this kind, a partial suppression of the 2/1 TM has been obtained during the ECW phase and a double transition from cyclic and smooth behavior was correspondingly observed (see Figure 3).

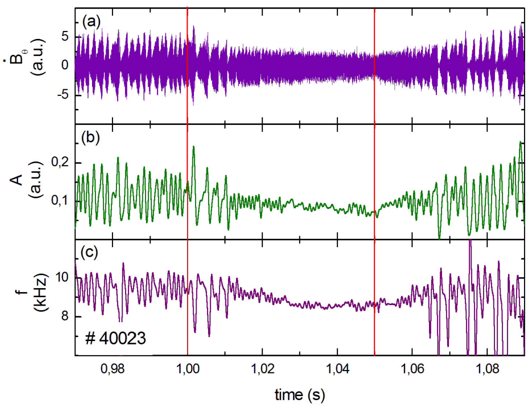

Figure 3. Example of stabilization of the 2/1 mode in FTU pulses at high density, by using injection of ECW. (a) Output from the pick-up coil, (b) mode amplitude, (c) mode frequency. Red bars indicate the ECW phase.

For a more detailed analysis of the MHD limit cycles, we report in Figure 4 the time traces of some relevant quantities for a given cycle of the MHD activity, while in Figure 5 we report the temporal evolution of the MHD mode on the Amplitude/Frequency plane. As we can see, we can distinguish four phases: a blue phase with increasing amplitude and approximately constant frequency, a navy phase with increasing amplitude and decreasing frequency, a green phase with decreasing amplitude and decreasing frequency, and an orange phase with

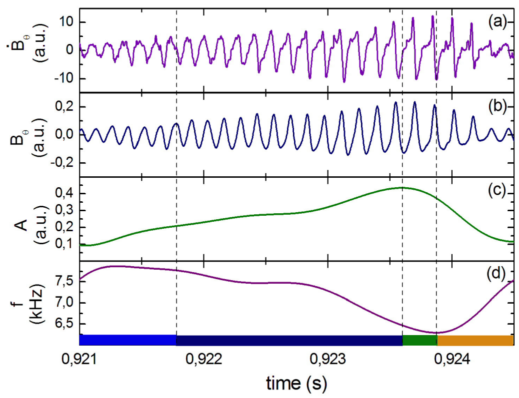

Figure 4. Time traces of some relevant quantities for a given cycle of the MHD activity.

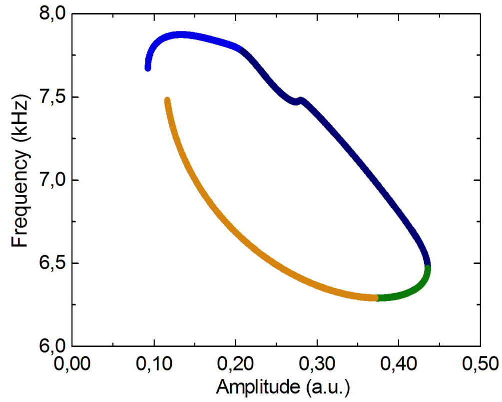

Figure 5. Temporal evolution (clockwise) of the MHD activity on the Amplitude/Frequency plane.

decreasing amplitude and increasing frequency. We noted that the trajectories of the mode on the (A, f) plane form closed curves (with area increasing with the line-averaged density), then the system exhibits, for a given density, an isolated closed trajectory, namely a so-called "limit cycle". For the purpose of this work we can try to understand the closed trajectories on the (A, f) plane by considering the diagrams produced on the phase-space from the oscillation in the four different phases of a limit cycle and comparing these diagrams with those produced by a harmonic oscillator (see Figure 6). As we can see, only on the first phase, characterized by an increasing amplitude and a constant frequency, the behavior of the tearing mode rotation is like a harmonic oscillator, whilst in the third phase, characterized by decreasing amplitude and decreasing frequency, we have a sort of "double system".

Results and discussion

The main results indicate that the presence of the q = 3 resonance in the plasma is necessary for the occurrence of deep and regular limit cycles for the (2, 1) mode. On the other hand, the presence of residual amplitude and frequency oscillations in pulses with $q_a < 3$ implies that other (weaker) modulation mechanisms are acting, such as interaction with the (1, 1) internal mode or with a non resonant (3, 1) surface kink. Stronger overtones are observed that can be justified by intra-wave modulation due to enhanced interaction with the resonant error field.

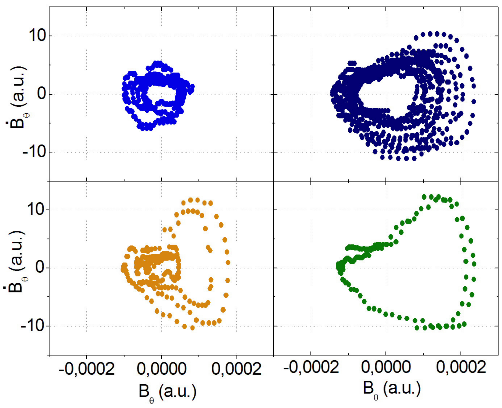

Figure 6. Diagrams in the phase-space for the oscillation in the four different phases of a limit cycle.

Conclusions

The MHD activity near the density limit or after injection of sufficient amounts of Ne gas shows an m/n = 2/1 tearing mode growing up to high amplitude, with a final phase characterized by amplitude and frequency oscillations, giving rise to limit cycles on the Amplitude/Frequency plane. The MHD cycles could be due to recursive island fragmentation (the island distortion increases before amplitude drops), but in the high-amplitude phases of the mode temporal evolution it is difficult to discriminate between a mode coupling mechanism and non-linear effects. A more accurate analysis will be done to better understand the possible physical effects responsible for the occurrence of deep and regular limit cycles for the (2, 1) tearing mode on FTU.

References

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