# Mode Coupling in Hybrid discharges at JET

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## Introduction

Multiple magneto-hydrodynamic (MHD) instabilities may contemporarily appear in a Tokamak discharge, and interact with one another if certain spatial and temporal conditions are satisfied. Each MHD mode produces a perturbed magnetic field over the whole plasma with a given spatial periodicity (**K**) that satisfies:

$$\mathbf{K}^*\mathbf{B}=0 \qquad (1)$$

With the magnetic field lines **B** of a given rational surface. Assuming that magnetic islands are dragged by the ion population [1], a (m, n) mode will appear at external magnetic coils as fluctuating at:

$$2\pi f_{m,n}=\Omega_D \qquad (2)$$

where $\Omega_D$ is the ion rotation at the q=m/n rational surface.

If different perturbations are present, a coupling can happen if a component of the perturbation induced by the other modes on a m/n rational surface "resonant" with a further m/n mode satisfy (1) and (2). Such requirements pose constraints on the fluctuation frequencies seen from magnetic coils as well as on the wave vector **K** of the modes involved.

Matching of (1) by modes with different spatial periodicity can be achieved by geometrical effects [2] or by non linear superposition [3] of two modes on a third.

Geometrical effects as the toroidicity allows matching the spatial periodicity between modes resonant with m/n and (m+1)/n surfaces [2,4]. In this case, called as linear coupling, the two modes must rotate with the same appearing frequency:

$$f_1=f_2 \text{ and } n_1=n_2 \text{ ; } m_2=m_1+1 \qquad (3)$$

A two modes coupling can occur through the linear coupling between an harmonic of a mode and a second one. For instance, two modes couplings have been observed between the second harmonic (2/2) of a 1/1 mode and 3/2 NTMs. Under the assumption (2), two modes coupling can be regarded as an indication of a flat rotation profile in the plasma core.

* See the Appendix of F. Romanelli et al. Proceedings of the 24th IAEA Fusione Energy Conference 2012, San Diego, USA

Condition (1) can be satisfied by matching the non-linear superposition of two modes with a third mode, then leading to a three modes (or non-linear) coupling [3]. The constraints posed on the frequency and on mode order numbers of the three modes are:

$$f_1+f_2 = f_3 \text{ and } n_1+n_2 = n_3;\ m_1+m_2=m_3 \quad (4).$$

In this case, it is possible to validate the coupling evaluating the degree of phase coherence between the fluctuations associated to the three modes.

Both coupling phenomena described by (3) or (4) can be the cause of seeding of a NTM [5], or of an evolution of the plasma rotation profile. In case of a not perfect matching of the frequency constraints, (relative) slowly varying electromagnetic disturbances will act on the rational surfaces being involved in the coupling. This electromagnetic disturbance will produce an electromagnetic torque [6] on the surface (or on the mode if present) to be compensated by the viscous torque. However, such compensation will change the plasma rotation profile in order to match exactly the condition given in (3) or (4).

During 2013 campaign, around 100 pulses in Hybrid scenario performed at JET with ITER Like Wall (ILW) were analysed. In several cases (41 out of 100), multiple magneto-hydrodynamic (MHD) instabilities were contemporarily affecting the discharge and often (30/41) showing evidence of mutual coupling behaviour. After the appearance of three modes coupling, it is observed (13/30) that the natural frequencies of the modes being involved change to satisfy the condition for two modes coupling, then flattening the rotation profile. From the above consideration, it has been decided to study the changes occurring on the rotation profiles in case of mode coupling. In the next section, the analysis for a case found during 2013 JET experimental campaign is presented.

**Coupling phenomena in a Hybrid discharge**

JET pulse #84788 ($I_p$=1.4MA, $P_{NBI}$=16MW, $B_T$=1.7T) has been performed in Hybrid scenario. While NBI power was turned on and kept at constant input power, four phases can be distinguished on the spectrogram of a Mirnov coil (Figure 1, each phase highlighted by different colours). During each phase, plasma experienced different evolution of the rotation profiles (RP), see Figure 2. In the first Phase (yellow shading in fig.1), (1,1), (4,3) and (5,4) modes are already present but without matching conditions for coupling, and the RP changes to a peaked shape. In the second phase (green shading in fig.1), conditions (4) are matched by $f_{1,1}+f_{4,3}=f_{5,4}$, while rotation at the mid plasma radius is speeding up (the two top pictures in fig.2 show RP at the start (left) and at the end (right) of the second phase). RP evolves in such a way to allow matching conditions (4) for $f_{1,1}+f_{3,2}=f_{4,3}$, then the (3,2) mode is triggered. In the third phase (blue shading in fig.1), three modes coupling $f_{1,1}+f_{3,2}=f_{4,3}$ takes place and core

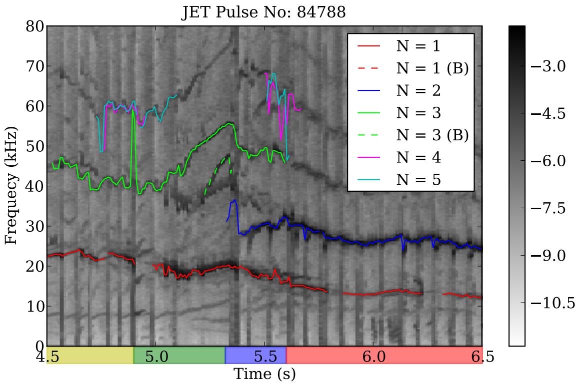


**Figure 1**. Spectrogram from a Mirnov coil [dB]. Four phases are evidenced by different shadings. Solid lines: mode detected by mode analysis, colors refer to toroidal order number N as in legend. Phase I (yellow shading): multiple modes without coupling -(1,1), (4,3) and weak (5,4)-. Phase II (green shading), three modes coupling between (1,1), (4,3) and (5,4): a (5,3) MHD activity is also present. Phase III (blue shading): three modes coupling between (1,1), (3,2) and (4,3). Phase IV (red shading): two modes coupling between second Harmonic of (1,1) and (3,2).

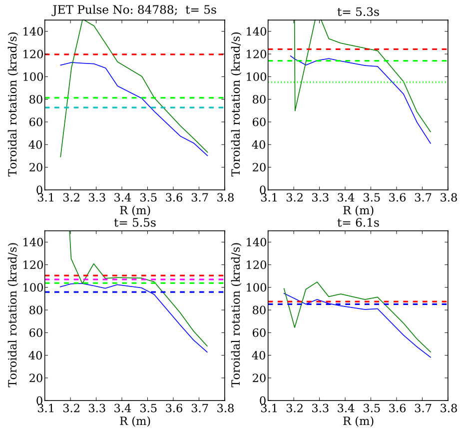


**Figure 2**. Toroidal rotation profiles from CXS diagnostics with (blue lines) and without (green) diamagnetic correction. Dashed lines show the rotation expected by the surface affected by a detected mode with toroidal order number N (see also [4]). Colors as in the legend on Figure 1.

plasma rotation is slowing down (see Figure 2, bottom pictures from left, third phase RP, to right, fourth phase RP). The RP turns to be completely flat in the plasma core then matching the conditions for two modes coupling. In the fourth phase, the second harmonic of the (1,1) and the (3,2) mode are linearly coupled and RP keeps a flat shape till NBI power turning off.

**Validation of three modes coupling**

In order to ensure the effectiveness of three modes coupling, the phase coherency between the frequencies involved has to be checked by estimating the bicoherence degree [7]. The bicoherence is a quantity related with the bispectrum [8] of the signal, after normalization with the power densities of the frequencies being involved in calculation. Using a direct approach to calculate such quantities, one can express the bispectrum in terms of the Fourier transform X(f) of the magnetic fluctuations x(t) sensed by a Mirnov coil, as

$$B(f_1, f_2)= E\{X(f_1)\, X(f_2)\, X^*(f_1+f_2)\} \qquad (4)$$

and the bicoherence $b^2(f_1,f_2)$ as:

$$b^2(f_1,f_2)= |B(f_1,f_2)|^2/E\{|X(f_1)\, X(f_2)|^2\}P(f_1+f_2) \qquad (5)$$

where $P(f)=E\{|X(f)|^2\}$ is the power spectral density. Bicoherence ranges from 0 to 1, and higher values (greater than 0.5) indicate good phase coherence and then a coupling at the frequency triplet $(f_1, f_2, f_1+f_2)$.

The quantities involved in (4) and (5) are calculated for 65 intervals (1ms, 50% overlapping) of a time window 33ms long, and then averaged in order to reduce the variance of the bicoherence to less than 0.001 [9, 7]. Length of the frame has been chosen to keep a

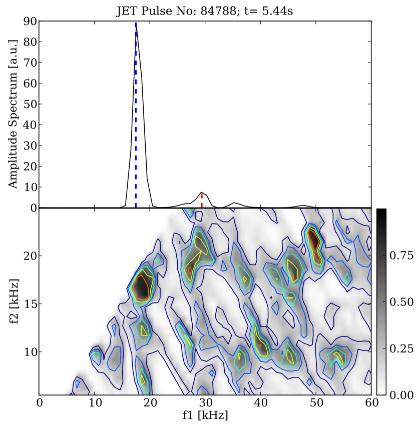


**Figure 3.** Bicoherence Validation of (4,3)-(1,1)=(3,2) coupling Top figure: Magnetic fluctuation amplitude Spectrum. $f_{1,1}$~18kHz and $f_{3,2}$~29kHz frequencies are marked with blue and red (respectively) dashed lines. Bottom figure: Bicoherence values in the range f2~[5,25] kHz, and f1~[0,60] kHz.

frequency resolution of 1kHz [9]. However, magnetic disturbances produced by ELMs occurring in the time window of computation can result in a large bias while evaluating the bicoherence. Moreover, errors can rise if the underlying hypothesis of stationary process is not achieved (i.e. natural frequencies are rapidly varying). In case of two modes coupling, phases of the magnetic fluctuations over all the spectrum are strictly related to one another and results given by the bicoherence are not well understandable [9]. Under these limitations, it has been possible to check the bicoherence only in the third phase (at t=5.44s, see Figure 3), i.e. where the non linear coupling between (1,1), (3,2) and (4,3) modes was taking place, and it has been found a value of ~0.75 for f2~18kHz(=$f_{1,1}$) and f1~29kHz(=$f_{3,2}$) that confirms the coupling with f1+f2~47kHz=$f_{4,3}$ (small lobe in top fig.3).

## SUMMARY

Modes coupling can happen in JET Hybrid discharges as seen (30 out of 100) in the 2013 experimental campaign. In particular, in 16 discharges non linear coupling involving (1,1), (3,2) and (4,3) modes occurs and in 12 of these complete flattening of the toroidal rotation profiles follows, then leading to two modes coupling. In the particular case (JET pulse No 84788) here presented, two different kinds of three modes coupling happen leading to different evolutions of the rotation profile.

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