# Non-linear mode coupling during spontaneous and induced magnetic reconnection events in RFX-mod

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***Discrete reconnection events.*** The magnetic equilibria of Reversed Field Pinch (RFP) plasmas are sustained by the dynamo mechanism, a self-organized process that comes naturally with the resistive relaxation of the magnetics, as occurs for the non-linear tearing mode [1]. The dynamo action regenerates the toroidal magnetic flux from the poloidal one through the reconnection of magnetic field lines, and as a result the plasma relaxes to a new MHD equilibrium [2]. In the RFP RFX-mod [3], this mechanism is often characterized by a discrete nature whose signature is a sudden drop in the reversal parameter, the ratio between the toroidal magnetic field at the plasma radius and its poloidal section average, $F=B_t(a)/<B_t>$, as it can be seen in Fig.1(a). The exchange of magnetic flux occurs by means of discrete reconnection events (DREs) whose non-linear dynamics has been investigated in this work. RFX-mod is equipped with a large set of biaxial pick up coils, 48 in the toroidal direction and 4 in the poloidal one, which are regularly distributed all over the inner surface of the torus. Through a 2D Fourier's analysis of these signals the time evolution of modes with helicity n=[-24; 23] and m=[0; 2] can be evaluated, where n and m are the toroidal and the poloidal mode numbers, respectively.

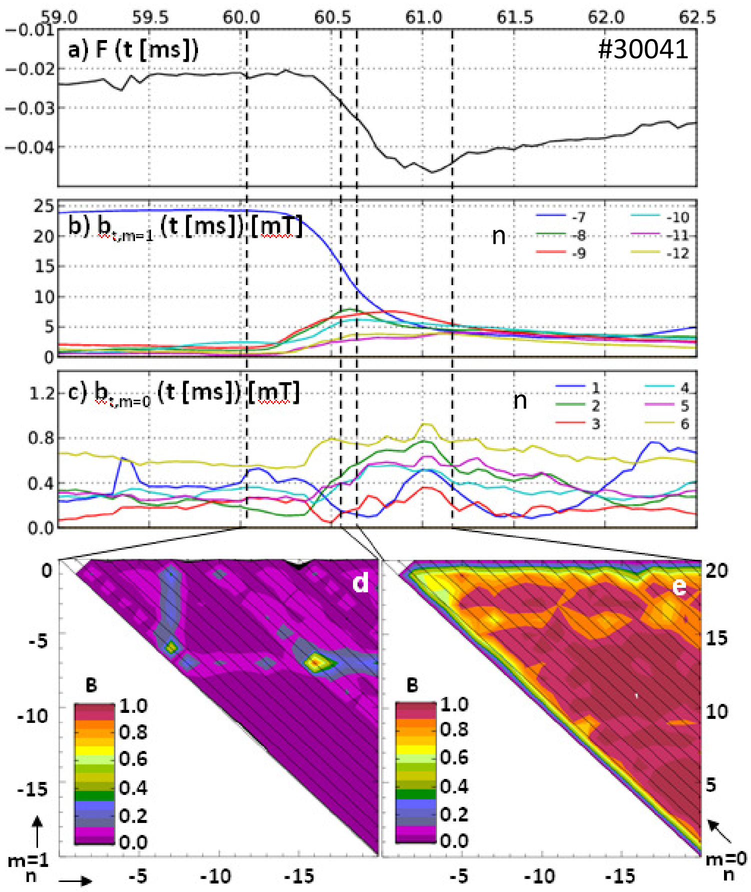


**Fig. 1** *Time evolution of (a) F, (b) the m=1 and (c) m=0 toroidal field amplitudes, bicoherence analysis at (d) t=[60.1,60.6]ms and (e) t=[60.7, 61.2]ms*

***Mode dynamics.*** During a

DRE the m = 1 modes are destabilized so that a cascading process propagates from the innermost resonant harmonics to outer ones, namely from the (1, -7) towards (1, -n) with |n|>7, as it can be seen in Fig.1(b). Fig.1(c) shows that the cascading process triggers an almost simultaneous destabilization of the m=0 modes. This energy exchange between different modes regenerates the toroidal flux, as marked by the sudden crash of F reported in Fig.1(a).

***Non-linear coupling.*** The mode energy exchange is not a linear process, indeed modes interact non-linearly by means of 3-wave coupling during such events. Bicoherence allows to discriminate between non-linearly coupled waves and spontaneously excited ones. It is defined as: $B(k,l) = \left|\left\langle X_k X_l X^*_{k+l} \right\rangle\right| \left[\left\langle \left|X_k X_l\right|^2 \right\rangle \left\langle \left|X_{k+l}\right|^2 \right\rangle\right]^{-1/2}$ where the triangular parentheses indicate a time average, while $X$ denotes the interacting wave. Bicoherence takes a value close to unity when the wave $X_{k+l}$ is excited by coupling of the waves $X_k$ and $X_l$, while it vanishes whenever $X_{k+l}$ is a spontaneously excited independent mode [4]. A bicoherence analysis has been performed on the DRE reported in Fig.1(a). The average has been evaluated on 0.5ms time windows that overlap for the 75%. The analysis reveals that the non-linear coupling between the m and the n modes increases as the time window slides down the F crash. As reported in Fig.1(d,e), the minimum and the maximum bicoherence values are reached respectively at the beginning (t=[60.1,60.6] ms), when only the (1, -7) mode is actively involved in the interaction, and at the end (t=[60.7,61.2] ms) of the DRE. The same analysis has been carried out in the same shot for a case with positive F values, i.e.

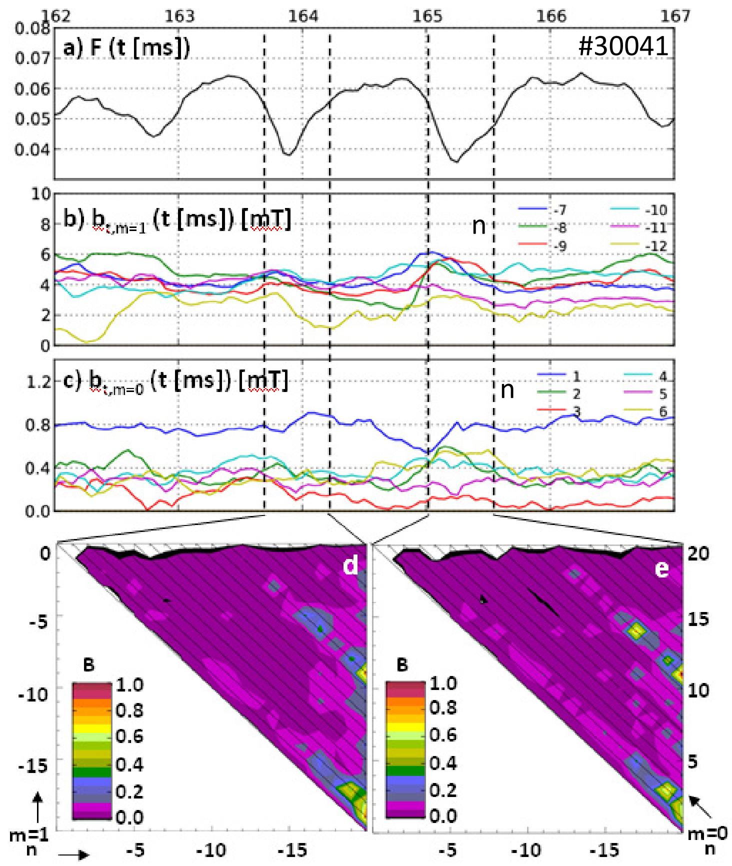


**Fig. 2** *Time evolution of (a) F, (b) the m=1 and (c) m=0 toroidal field amplitudes, bicoherence at (d) t=[163.8,164.3]ms and (e) t=[165.2,165.7]ms.*

when the toroidal field reversal is lost. Fig.2 shows that neither the m nor the n modes follow any regular dynamics and that bicoherence assumes low values at any time. This evidence, compared to the results reported in Fig.1, demonstrates that the absence of resonant m=0 modes suppresses the non-linear coupling.

***Induced magnetic reconnection events.*** DREs can be artificially induced by altering the current density profile. Two different techniques can be applied for this purpose: pellet injection and inductive plasma current drive. In both cases the perturbations trigger instabilities in the plasma that enhance its departure from the equilibrium state. The equilibrium prior the perturbation is then recovered as the plasma relaxes by means of discrete reconnection events. The injection of Hydrogen pellets modifies the current profile by locally perturbing the plasma density distribution, i.e. the resistivity profile. As shown in Fig.3, the mode and the bicoherence analyses confirm that the dynamics of a DRE, which is inducted by a pellet injection, is similar to what described for the spontaneous ones. The time traces of the mode amplitudes reveal that the m=1 mode energy cascade occurs as well as the increase of the m=0 mode amplitudes thanks to the non-linear coupling between the m=1 modes. The analogy with the spontaneous events seems to indicate that the main effect of the pellet injection is to hasten the current peaking process that is the origin of the instability that drives the mode growth [5]. Otherwise the plasma current profile can be perturbed by inducing external poloidal currents, i.e. Pulsed Poloidal Current Drive (PPCD). PPCD successfully rules out the dynamo-induced poloidal electric field slowing down the growth of the m = 1 fluctuations and thus suppressing the DREs

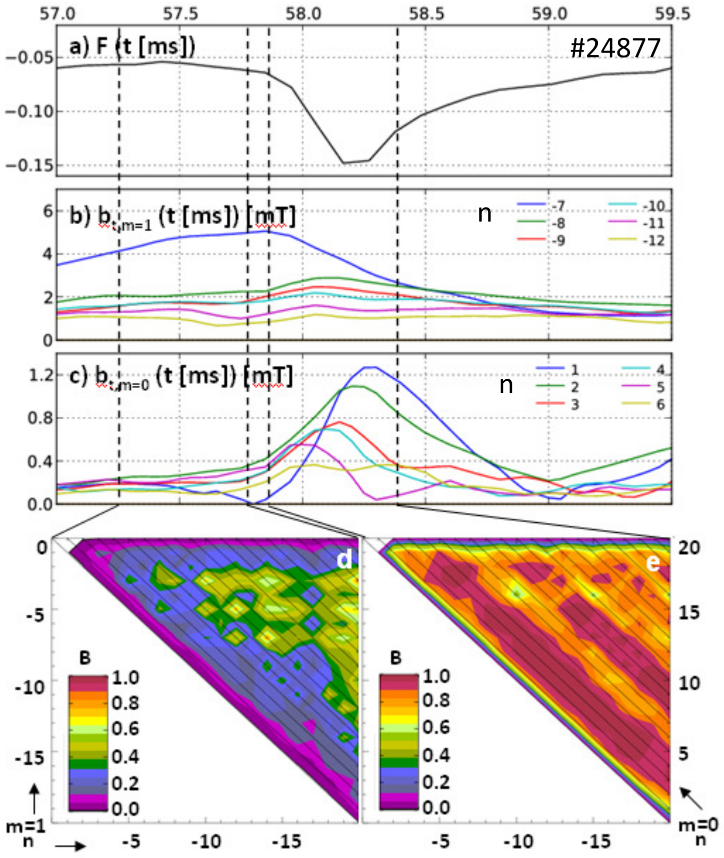


**Fig. 3** *Time evolution of (a) F, (b) the m=1 and (c) m=0 toroidal field amplitudes, bicoherence at (d) t=[57.3, 57.8]ms and (e) t=[57.9, 58.4]ms.*

associated with them. Fig.4 (b,c) show that the amplitudes of both the m=1, n<-7 and the m=0, n>1 modes deplete during the PPCD application. Note that the mode non-linear coupling is reduced too, as shown in Fig.4(d). The bicoherence analysis reveals that the mode non-linear coupling further diminishes as the PPCD drives the plasma towards deeper toroidal field reversal. Note that as soon as the plasma becomes unstable, because of the current profile flattening, the co-dynamo PPCD action is no longer sufficient to provide the toroidal magnetic flux that the plasma needs to sustain the magnetic profiles. Several DREs occur until the reversal parameter reaches the value that it has before the PPCD switch on. Besides being much larger than typical spontaneous DREs, PPCD inducted DREs are characterized by an analogous dynamics. The m=0 modes mediate the interaction between the m=1 ones by non-linear coupling, as shown in Fig.4(e), and as a result the amplitude of the former increases, Fig.4(c). The results of the bicoherence analyses applied both to spontaneous and inducted DREs have proved that the non-linear dynamics, which characterizes the former type of DREs, can be widely applied to describe the plasma relaxation mechanism notwithstanding the cause that triggers it.

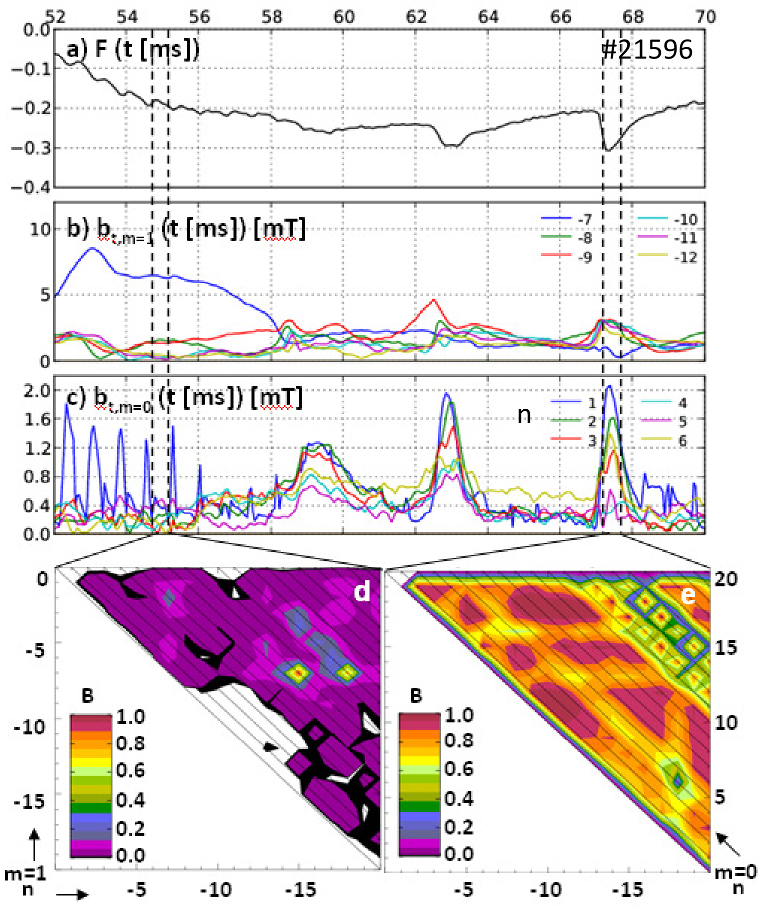


**Fig. 4** *Time evolution of (a) F, (b) the m=1 and (c) m=0 toroidal field amplitudes, bicoherence at (d) t=[54.6 55.1]ms and (e) t=[67.2, 67.5]ms.*

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## References

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