Study of Secondary Instability of 2/1 Magnetic Island in COMPASS High Density Limit Plasmas

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Introduction

For generating fusion power, high plasma density is indispensable for ITER and subsequent reactor tokamaks but it may lead to the density limit disruption (DLD). The physical mechanisms behind the underlying processes of DLD are only partially understood. The growing MHD instabilities, usually dominated by rotating magnetic islands of helicity $(m,n) = (2,1)$, are often regarded as precursors to DLD where m and n are poloidal and toroidal mode numbers respectively. At some stage of the development of this mode, the energy confinement is abruptly destroyed which is termed as thermal quench (TQ) phase of the disruption. This is usually attributed to stochastization of the field lines, due to overlapping of magnetic islands, leading to enhanced transport in the radial direction. Contrary to this hypothesis, a secondary instability (SI) to the rotating $(2,1)$ magnetic island was observed prior to the TQ, when the amplitude of the magnetic island is large and its rotation frequency is low, first in JET [1] and then in COMPASS [2].

The SI is characterized by small amplitude perturbations, with no m or n mode numbers, superimposed on the perturbations of the precursor magnetic island. The frequency of the SI is higher than the rotating frequency of the island itself and is also clearly observed in dB_p/dt (rate of change of poloidal magnetic field) signal. As the TQ approaches, the evolution of the magnetic island perturbation $d\widetilde{B}_p/dt$ becomes anharmonic, while the frequency of the SI perturbations increase, displaying a broader spectrum. In Fig. 1, this transition is illustrated and marked at t_{TR}. The present work will focus on the study of the SI behaviour in the period $\Delta t_{SI} = t_{CQ} - t_{TR}$, where t_{CQ} is the time of the minimum in V_{loop}, the outset time for the current quench (CQ) phase of the disruption. During this period, as the amplitude and frequency of the SI increase, a degradation of the energy confinement is observed that culminates abruptly in the

TQ-phase of the disruption. Therefore, SI can be considered as a possible cause of TQ.

Experimental Results

In this work, a set of Ohmic (L-mode) diverted plasmas with fixed $q_{95} \sim 4$ is analysed. The plasma current I_p was scanned in the range of 130 kA $< I_p <$ 230 kA, corresponding to a toroidal magnetic field of 0.92 T $\leq B_\phi \leq$ 1.38 T in order to keep q_{95} constant. The electron density n_e was ramped up in Deuterium (D_2) plasmas by gas puffing until the DLD is triggered. The maximum n_e achieved, in these cases, was typically 50% of the Greenwald limit. The impurity content of the plasma was also changed with Ne-puffing in some discharges. The maximum density attained with Ne-puff was almost half of the density attained with D_2-puff.

The perturbations of the magnetic island and of the SI were followed both with 3 arrays of 24 Mirnov coils in different toroidal positions, sensitive to B_p, and a set of 4 saddle loop coils displaced in four quadrants (NW, SE, SW and NE) located outside of the vacuum vessel [3], in the low field side (LFS). The saddle loops are particularly sensitive to the radial magnetic field B_r. The $n = 1$ component of the perturbed radial magnetic field, $\widetilde{B}_{r\_n=1}$ was estimated as:

$$\widetilde{B}_{r\_n=1} = \sqrt{\left(\frac{B_r^{NW} - B_r^{SE}}{2}\right)^2 + \left(\frac{B_r^{SW} - B_r^{NE}}{2}\right)^2}.$$

In all the discharges, the $(2,1)$ island starts rotating at $\sim$ 15 kHz and slows down as its amplitude increases. In the majority ($\sim 85\%$) of COMPASS DLDs attained with D_2-puff, when the TQ occurs, the island is still rotating at $\approx$ 5 kHz (see Fig.1). For simplicity, these cases will be called rotating modes henceforward. However, around t_{TR}, the island rotation reaches a minimum and increases afterwards (see Fig.1(c)). Although $\widetilde{B}_p$ keeps increasing, $\widetilde{B}_{r\_n=1}$ saturates at $\approx$ 0.5 mT (see Fig.1 (g) and (h)) until it displays an explosive growth at the TQ. In the remaining D_2-puff DLDs, the island is quasi-locked to the wall rotating at $<$ 2 kHz when the TQ occurs (see Fig.1). For these cases, Δt_{SI} is very short $\approx$ 0.2 ms and it is not so clear to assess if the mode rotation reaches also a minimum at t_{TR} (see Fig. 1 and Fig. 2) followed by $\widetilde{B}_{r\_n=1}$ saturation.

Regarding the rotating modes, Δt_{SI} displayed a larger variability, 0.4 ms $\lesssim \Delta t_{SI} \lesssim$ 0.9 ms when I_p was scanned keeping $q_{95} \approx 4$ (see Fig. 2). So, the duration of the high frequency phase of the SI for quasi-locked modes can be up to 4 times shorter than for rotating modes. This means that in COMPASS DLDs, energy confinement is destroyed faster with quasi-locked modes. Comparing the value of $\widetilde{B}_r$ with the rotation frequency of the magnetic island at t_{TR}, the transition time when the spectrum of the SI perturbations broadens, it is observed that $\widetilde{B}_r$ decreases as the rotation frequency increases (see circular data points in Fig. 2(c)). Concerning the island, this

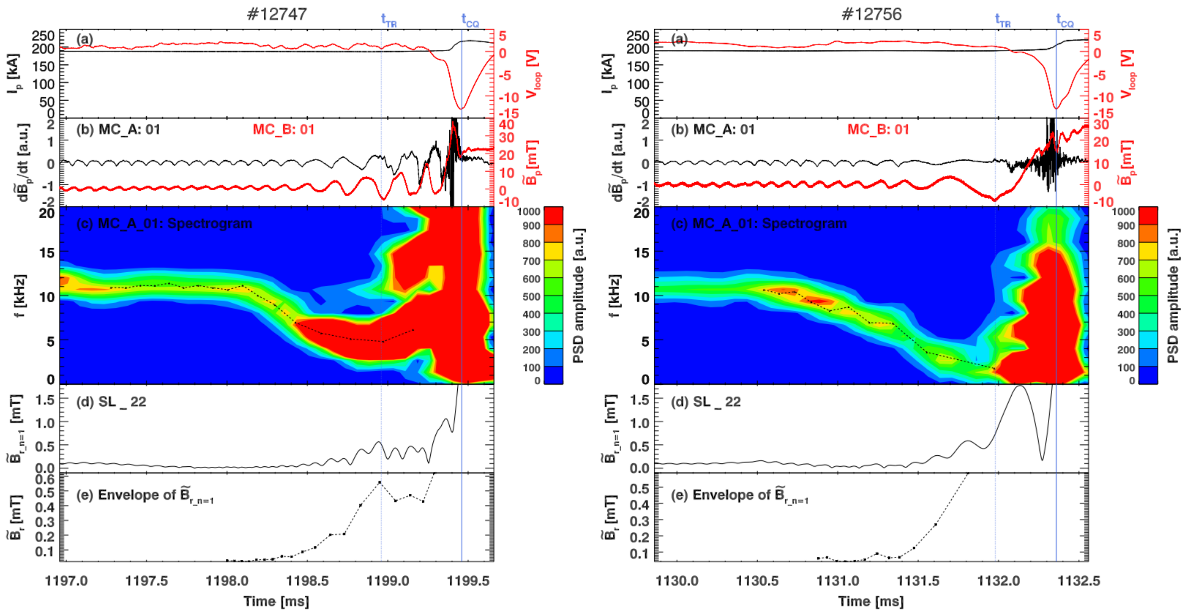

Figure 1: Left, DLD preceded by a rotating (2,1) mode (a) I_p and V_{loop}, (b) $d\widetilde{B}_p/dt$ and $\widetilde{B}_p$, (c) spectrogram of $d\widetilde{B}_p/dt$ (d) $\widetilde{B}_{r\_n=1}$ (e) envelop of $\widetilde{B}_{r\_n=1}$. Right, same signals for a DLD preceded by a quasi-locked mode.

behaviour is expected since a large value of $\widetilde{B}_r$ (larger island) leads to a stronger interaction with the wall and consequent lower rotation frequency. However, regarding the SI, it is not clear why for some plasmas the transition time t_{TR} occurs at lower values of $\widetilde{B}_r$ (higher island rotation frequency) and for other plasmas, the opposite is observed. Putting it in other words, in plasmas with a quasi-locked mode, why did the secondary instability not develop when the magnetic island was rotating at ≈ 5 kHz?

On the other hand, this indicates that the TQ can be triggered at different distinct values of $\widetilde{B}_r$. As Fig. 2(d) shows, changes in the distance Δr between the $q = 2$ rational surface and the position of the coils are small. This indicates that, from the analysis of DLDs preceded by rotating modes and by quasi-locked modes, the TQ does not occur at a particular island width. Rather, it is initiated when the frequency of the SI increases and broadens its spectrum at t_{TR}. If this study was focused only on quasi-locked modes, it would seem that TQ was triggered at a certain value of $\widetilde{B}_r$, i.e., at a certain value of the island width [4].

For the DLDs attained with Ne-puff (see triangular data points in Fig. 2(b)), it was observed that Δt_{SI} was in the short range of values of the quasi-locked modes attained with D_2-puff. It is expected that the presence of Ne contributes to the increase of Z_{eff} and radiation losses, leading to a faster growth of the (2,1) mode [5]. However, again, DLDs preceded by rotating or quasi-locked modes occur at distinct values of $\widetilde{B}_r$ as shown by the triangular data points in Fig. 2(c).

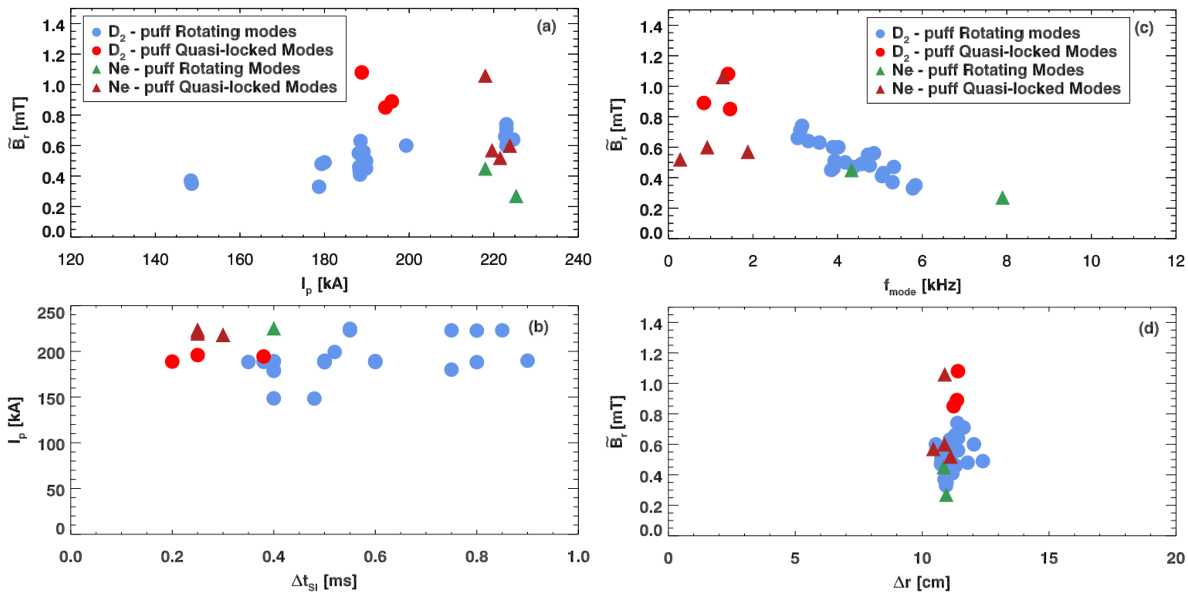

Figure 2: (a) (2,1) mode perturbation $\widetilde{B}_r$ vs I_p, (b) I_p vs Δt_{SI}, (c) $\widetilde{B}_r$ vs f_{mode}, frequency of the (2,1) mode, (d) $\widetilde{B}_r$ vs Δr. Except Δt_{SI}, all other indicated parameters are measured at t_{TR}.

Conclusions

It was observed in COMPASS DLDs that the period Δt_{SI}, when the frequency of the SI perturbations increase displaying a broader spectrum, is independent of the plasma current I_p at constant q_{95}. In DLDs preceded by quasi-locked modes, Δt_{SI} was up to 4 times shorter than for DLDs preceded by rotating modes. At the outset of Δt_{SI}, distinct values of $\widetilde{B}_r$ are measured. For the conditions of these experiments, this seems to correspond to different values of the (2,1) island width implying that the island size is not the only factor to influence the development of the secondary instability and the thermal quench phase of the disruption.

Acknowledgements

This work was funded by Portuguese FCT - Fundação para a Ciência e Tecnologia, through project UID/FIS/50010/ 2013 and grant SFRH/BD/52415/2013 (PD-F APPLAuSE) and co-funded by Czech MEYS project LM2015045. The views expressed herein are the sole responsibility of the authors.

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