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Secondary Instability to Tearing Modes in JET Density Limit Disruptions

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INTRODUCTION

Major disruptions are the most dangerous instabilities in tokamak plasmas. Understanding the cause and dynamics of major disruptions will improve the strategies to avoid or ameliorate their effects, which is a relevant issue for ITER. In a well established sequence of events the precursor of density limit disruptions starts with the radiative contraction of the current profile, caused by a rise in the impurity radiation due to the increase of electron density in the plasma edge region [1].

Mainly an $m/n = 2/1$ tearing mode is destabilized by the contraction of the current profile, where m and n are the poloidal and toroidal mode numbers, respectively. During the growth of this magnetic island, minor disruptions may be observed before the major disruption occurs. Minor disruptions are characterized by a sudden large heat flux across the $q=2$ surface towards the plasma edge. However only a fraction of the plasma energy is lost and the plasma current is not affected (as discussed ahead, events B, C and D indicated at Fig.1(a) are minor disruptions). A commonly claimed cause of minor disruption is the ergodization of magnetic field lines due to overlapping of the $m/n = 2/1$ magnetic island with other island at a rational surface with $q < 2$ [1]. Usually however, as in the cases here studied, island overlap is not observed and also, it is observed an asymmetric heat flux, relatively to the $2/1$ magnetic island X point. Another important observation is the intermittent character of the large heat flux across the $q = 2$ surface. After the first minor disruption follows a short period where energy confinement is restored, despite the $2/1$ island is monotonically increasing in size, (e.g. between events B and C, or C and D in Fig 1(a)). In this period, large electron temperature gradients are observed in the region with $q \gtrsim 1$ indicating local high energy confinement.

This paper will address the questions raised by these observations, namely why a large magnetic island only destroys energy confinement asymmetrically and intermittently. The experimental observation of a secondary instability (SI) to the magnetic island is proposed as the cause of minor disruptions [2]. Magnetic islands with high m, n values have been observed close to the $2/1$ island elsewhere [3, 4, 5]. Here it will be shown, that no mode numbers could be assigned to the SI. In contrast with the tearing mode, that has a continuous time evolution the SI has an intermittent evolution in time. This behaviour is clear when the tearing mode is quasi-locked to the wall, when the destabilization of the SI coincides with the occurrence of minor disruptions.

1. PLASMA PARAMETERS AND EXPERIMENTAL CONDITIONS

The events described here were observed in several JET plasmas with the following typical range of parameters. Plasma current varied in the range $1 \leq I_p \leq 95 \text{MA}$, and the toroidal magnetic field $2.47 \text{T} \leq B_\phi \leq 3 \text{T}$. The safety factor profile was monotonic and electron density limit varied within $1.1 \times 10^{19} \text{ m}^{-3} \leq n_e \leq 2.15 \times 10^{19} \text{ m}^{-3}$. Events were observed both in single null and limiter plasmas. The majority species was deuterium in these discharges. The radiative collapse was achieved by adding Ne gas, to increase impurity radiation. The density remained below the cut-off value of Electron Cyclotron Emission (ECE) radiometer [6] one of the main diagnostics used in this study. Important information was also measured by toroidal and poloidal arrays of magnetic coils [7].

2. SECONDARY INSTABILITY

A typical discharge where the SI was observed will be used to illustrate some of its properties as well as its relation with minor disruptions and the 2/1 tearing mode. Figure 1(a) shows the evolution of the electron temperature profile $T_e(R, t)$ at the high field side of the plasma, around the $q = 2$ surface, in the last 70ms before a major disruption destroys the plasma thermal energy confinement at 23.639s. ECE time resolution is 4ms, and isothermals starting at 30eV increase in steps of 100eV. To each ECE channel was applied a low pass finite impulse response filter with a cut off frequency of 10 kHz to eliminate a high frequency component that hides the observations here addressed. The figure focus on the Low Field Side (LFS) part of the profile, spanning the region from the edge to $q \approx 1$.

The characteristic signature of an $m/n = 2/1$ tearing mode is the oscillation, starting with small amplitude at 3.62m and 23.572s. The magnetic island rotation frequency slows down from ≈ 2 kHz to ≈ 50 Hz, never locking completely to the wall. The frequency decreases as the island size increases due to island interaction with the conducting tokamak wall. From coherence analysis between $T_e(R, t)$ and $\dot{B}_\theta(t)$ the radial position of the $q = 2$ rational surface is found at ≈ 3.62 m [2].

Four distinct events, labeled A, B, C and D respectively exhibit large heat flows across the $q = 2$. During these events the heat flux is directed to the plasma edge, as indicated by the increase in plasma edge temperature that follows. Heat lost during event A is smaller compared with the other three events. One particular feature common to all these four events is that the sudden heat flux is triggered at the same time a local oscillation, secondary to the 2/1 oscillation, experiences an increase in amplitude. This secondary instability is already present in the plasma before event A occurs, but with a lower amplitude. Due to low spatial coverage of the region around $q = 2$ surface by the fast ECE radiometer channels, combined with higher noise level of the edge channels, it was difficult to follow the SI with this diagnostic, during the 2/1 mode fast rotating phase.

Both the 2/1 magnetic island and the secondary instability are detected also by magnetic coils. Figure 2(a) shows \dot{B}_θ signals from a toroidal array of coils during the fast rotating phase of the magnetic island. Two different oscillations are observed. One with large increasing amplitude and decreasing frequency (from about 2kHz to 100Hz) and another smaller amplitude oscillation at frequencies generally above 2kHz. The gray lines connecting the minima, of the large amplitude oscillations, of the signals from different coils show that the magnetic island has a toroidal mode number $n = 1$. A similar exercise to find the toroidal mode number of the SI fails as neighbour coils do not always detect the same number of minima. Moreover the small amplitude oscillations from the SI are not seen over a complete period of the 2/1 mode oscillation, a feature more clear in the slow rotating phase of the 2/1 island. During the minor disruption the SI is present only in part of the low q side of the 2/1 island O point, causing the asymmetric heat flux across the $q = 2$ surface. These observations are consistent if the SI has no toroidal mode number. Information from a poloidal array of coils and the localization of the SI was discussed at [2]. From Figure 1(c) (red curve) and Figure 2(b) it is possible to infer the intermittent growth rate of the SI. These figures show \dot{B}_θ high pass filtered with a cut-off frequency of 2kHz with the purpose to decrease the 2/1 component in the signal.

CONCLUSIONS

An alternative explanation is proposed for the cause of minor disruptions that precede density limit disruption in JET, based on the observation in JET of the sudden growth of an instability that is secondary to the typically observed 2/1 magnetic island. The secondary instability shows intermittent growth rate, has no poloidal or toroidal mode number and appears to be localized in the region of the low q side of the 2/1 magnetic island separatrix [2]. Its asymmetric toroidal localization relatively to the 2/1 mode O and X points explains the same toroidal asymmetry observed in the heat flux during minor disruptions.

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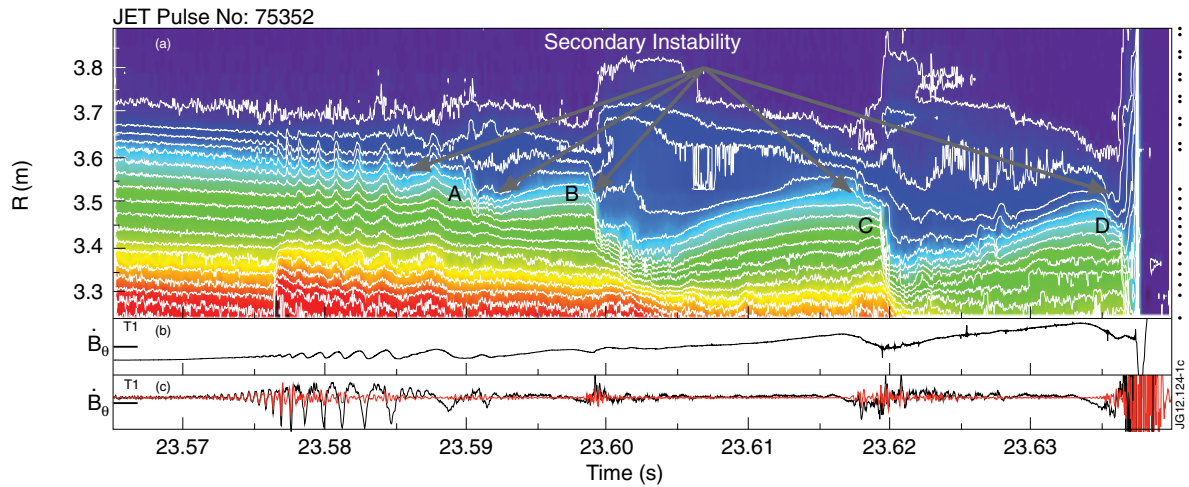


Figure 1: (a) Electron temperature $T_e(r, t)$ isotherms. The ECE channels position is indicated by the dots at the right side. (b) $B_\theta(t)$, numerically integrated. (c) $\dot{B}_\theta(t)$ and the same signal high pass filtered (in red) with a cut-off frequency of 2kHz. In this pulse, $I_p = 1.7\text{MA}$, $q_{95} = 3.5$, $B_0 = 2.7\text{T}$ and $n_e = 2.15 \times 10^{19} \text{m}^{-2}$.

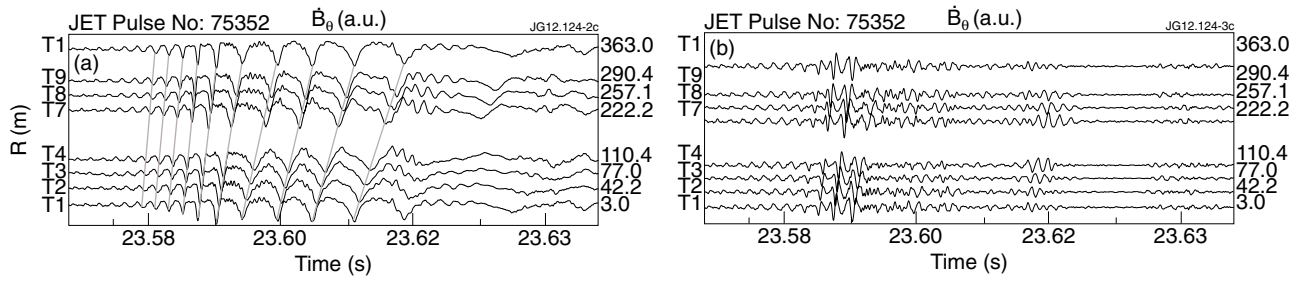


Figure 2: (a) Toroidal array of $\dot{B}_\theta(t)$ coils. (b) Same signals high pass filtered with a cut-off frequency of 2kHz, in order to decrease the $m/n = 2/1$ component.