EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT
JET

EFDA–JET–CP(02)07/10

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** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives",*
Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).

Preprint of Paper to be submitted for publication in
Proceedings of the 19th IAEA Conference, (Lyon, France 14-19 October 2002)

ABSTRACT.

Recent observations of MHD activity in type-I ELMy H-mode discharges on JET have revealed two phenomena: (i) the so-called palm tree mode, a new, snake-like MHD mode at the q=3 surface which is excited by type-I ELMs, and (ii) coherent MHD mode activity as a precursor to the ELM collapse. Both modes are detected by magnetic pick up coils and can also be seen on the edge ECE and SXR measurements. They are located a few cm inside the separatrix. Palm tree modes have been identified in a wide range of plasma conditions, which comprise standard ELMy H-modes, ITER-like plasma shapes, pellet fuelling, and even pure helium plasmas. The mode frequency increases in time and starts to saturate until the mode finally decays. A possible explanation of the palm tree mode is, that it is the remnant of a (3,1)-island created due to edge ergodisation by the ELM perturbation. The type-I ELM precursor modes have toroidal mode numbers n in the range 1 to 14, a kink-like structure, and appear commonly 0.5-1ms before the ELM, but can appear much earlier in some cases.

1. INTRODUCTION

One important topic in present tokamak research is to find means to control ELMs and operate the plasma in a state where the energy confinement is sufficient to allow the extrapolation to a burning fusion plasma, and the power loss per ELM is tolerable for the divertor. Although the nature of the ELM is still unclear, progress in operating the plasma at high confinement with reduced heat loads on the divertor has been achieved recently [1]. During plasma operation in the JET tokamak type-I ELM precursor modes [2] as well as a new MHD mode triggered by type-I ELMs [3] have been observed. The understanding of both modes can probably give new insight into the ELM process itself [4].

2. THE PALM TREE MODE

The ELM postcursor, named a palm tree mode because of its typical signature in a magnetic spectrogram, has been identified in a wide range of plasma conditions as long as type-I ELMs are present. Observations of palm tree modes comprise standard ELMy H-modes, ITER-like plasma shapes, pellet fuelling, and even pure helium plasmas. The mode does not occur after every ELM, i.e. during the stationary phase of a discharge ELMs with and without a following P1-palm tree mode can be found.

Figure 1 shows a spectrogram calculated from the fast sampled dB/dt signal of a mag-netic pick-up coil situated near the plasma on the outboard side of the torus. The data are measured during the flat-top phase of an argon seeded ELMy H-mode discharge with $q_{95} = 3.05$. The horizontal lines at frequencies of 11kHz and 22kHz are due to MHD activity in the plasma core, the sawtooth pre-cursor mode and it's first harmonic at twice the frequency. The five vertical structures show the short lasting broad band magnetic perturbation of the type-I ELMs. Modes which start immediately after the ELM and increase in frequency are visible after three of the ELMs . These modes show many harmonic frequencies (up to 6 harmonics can be seen) and last for 5−50ms until they decay. An ELM event occurring during a palm tree mode stops it immediately (see palm tree mode after fourth ELM in Fig. 1, which is stopped by the fifth ELM). The mode could not only be observed with magnetic pick-up coils, but with ECE and soft X-ray measurements, too.

The frequency of the mode increases in time. At start, i.e. immediately after the ELM, the frequency can be close to zero or have some finite value. The observed fluctuation amplitude decays following its initiation at the ELM.

The mode numbers of the palm tree mode have been determined using the CATS system on JET [6]. The toroidal mode number of the lowest frequency component of the palm tree mode has been identified to be n = 1. The corresponding poloidal mode number is m = 3. There-fore, the palm tree mode is located at the rational q = 3 surface. The harmonic frequencies visible in Fig. 1 have toroidal mode numbers n = 2, 3, 4;... and the poloidal mode number of the 2nd harmonic is m = 6, poloidal mode numbers of higher harmonics could not be determined due to the limited angular resolution of the used coil array. The large number of harmonic frequencies show that the signal modulation due to this mode is strongly non-sinusoidal.

The radial localization of the mode can be deduced from closely spaced ECE measurements in the plasma edge. In a set of channels separated to each other by 1cm only one channels at R = 3.84m is modulated by the palm tree mode, the adjacent channels at R = 3.83m and R = 3.85m show no or only a negligible modulation. Therefore, the radial width of the palm tree mode is $w_r \approx 1-2$cm. The EFIT equilibrium reconstruction yields a q = 3 location of 3.00m, taking into account the errorbars this agrees well with the ECE measurements.

The angular localization can be seen in figure 2 which shows the ECE time trace measured at R = 3.84m. The width of the non-sinusoidal spikes amounts to about 10-20% of the mode period. The electron temperature within these spikes is higher than outside the spike structures, but lower than the temperature has been before the preceding ELM collapse which triggered the palm tree mode. From the width of the structure one can estimate a poloidal extent of $\omega_\Theta \approx$ 23-46cm for each structure.

Palm tree modes have been first observed in impurity seeded discharges [5], but an inspection of a large number of ELMy H-modes with type-I ELMs revealed, that the new mode appears in various plasma regimes like standard H-modes, impurity seeded plasmas, pellet fueled plasmas, and ITER-shaped plasmas with high triangularity. The global plasma parameters where palm tree modes occurred are summarized in Fig. 3. The mode appears for different combinations of plasma current and toroidal magnetic field, as long as the q = 3 surface is located near the plasma edge in the region perturbed by the ELM. The observations of palm tree modes seem to be somewhat concentrated at high values of the total heating power, and at better confinement quality. Palm tree modes appear preferentially when the difference between total heating power and radiated power, i.e. the power which goes into the divertor is rather high. The effective charge is around standard values. Observations of palm tree modes are in a wide range of electron densities and Greenwald numbers.

The palm tree mode shows some similarity to the so-called snakes, observed at the q = 1 [7] and q = 2 [8] surfaces. A snake-like mode at the q = 3 surface has been reported in Ref. [9], but this mode was observed in optimized shear scenarios and found to disappear after the L-H transition, whereas the mode reported here does only occur in H-mode plasmas.

The frequency evolution of the mode suggests that the ELM not only leads to loss of particles and energy, but momentum is lost as well. The rotation of the mode is stopped after the ELM, or at least considerably slowed down.

The observed phenomenon might be explained as follows. The magnetic perturbation associated with the ELM collapse ergodizes the magnetic field lines at the plasma edge. It is known from Hamiltonian theory, that situations, where islands (i.e. regions with regular flux surfaces) are embedded in ergodic regions, exist [10]. Modeling of the anticipated field structure of the Dynamic Ergodic Divertor (a device to generate edge ergodization which is presently under construction at the TEXTOR tokamak [11]) showed, that depending on the amplitude of the perturbation field no full ergodization, but situations with embedded islands, can be produced (see e.g. figure 3 in [12]). The palm tree mode may be the remnant of a (3,1)-island generated by incomplete edge ergodization due to the magnetic perturbation of the ELM. The improved confinement within magnetic islands [13] explains the observed higher temperature in the spikes (i.e. O-points), which results during the ELM collapse because the heat from the ergodized region outside the island structures is lost much faster. The self stabilization of the palm tree modes can be explained by this higher temperature in the O-point, which attracts more current, thus compensating for the loss of current in the island.

3. TYPE-I ELM PRECURSOR MODES

Low frequency (5~25kHz) coherent type-I ELM precursor modes have been identified in JET ELMy H-mode discharges. They are ob-served by various diagnostics, especially in the ECE and the Mirnov signals, but also on the SXR arrays as well as on the O-mode edge reflectometer.

Figure 4 shows the toroidal mode number spectrum for an ELMy H-mode where precursors with n = 8 (red structures at 20kHz) occur. The mode numbers are inferred from phase analysis of Fourier spectra taken for closely spaced arrays of magnetic pick-up coils. These precursors are observed prior to almost all type-I ELMs and can have toroidal mode numbers ranging from 1 to 14. The instabilities are localized a few cm inside the separatrix and have a kink-like structure. The mode rotates in the direction of the ion diamagnetic drift. They appear usually 0:5 1ms before the ELM collapse, but there are many cases where they last much longer. The amplitude of these long lasting precursors can grow and shrink repeatedly before the ELM, and changes of their frequency and dominant toroidal mode number may occur several times.

In addition to the coherent modes, broader bands with typical frequencies from 10kHz to 80kHz rotating in the electron drift direction, and with toroidal mode numbers ranging from 1 to 10 are often observed between ELMs (see blue structures in figure 4). These so-called washboard modes were already reported in [14]. In some cases palm tree modes and washboard modes have been observed to occur simultaneously. The lower n mode are known as outer modes and are identified to be external kinks in hot ion H-modes [9, 15]. Modelling using HELENA and MISHKA-1 suggests the higher n modes to be ideal ballooning-kink modes.

The analysis of a large number of ELMs in different discharge scenarios yields, that the coherent precursor modes as well as the washboard modes are a more or less regular phenomenon and could be detected prior to most of them. No precursor activity has been detected prior to type-III ELMs. A ballooning character of the precursor modes could not be established up to now.

The toroidal mode numbers of the precursor oscillations depend on the parameters of the edge pedestal. Figure 5 shows a plot of the toroidal mode numbers the n_e - T_e plane. The mode numbers show a systematic increase from lower to higher density. A higher edge collisionality favors the appearance of precursors with higher toroidal mode numbers. At high pedestal temperatures and low densities the low-n external-kink modes are preferentially destabilized.

CONCLUSIONS

The palm tree mode can be regarded as an ELM postcursor mode, i.e. any model of the ELM collapse should be able to describe the generation of palm tree modes. This favors in particularly ELM models based on field line ergodization [16].

The precursor modes have been observed with toroidal mode numbers from 1 to 14. The further analysis of type-I ELM precursors will help to investigate details of the the plasma edge stability just prior to the ELM collapse.

ACKNOWLEDGEMENTS

This work has been conducted under the European Fusion Development Agreement.

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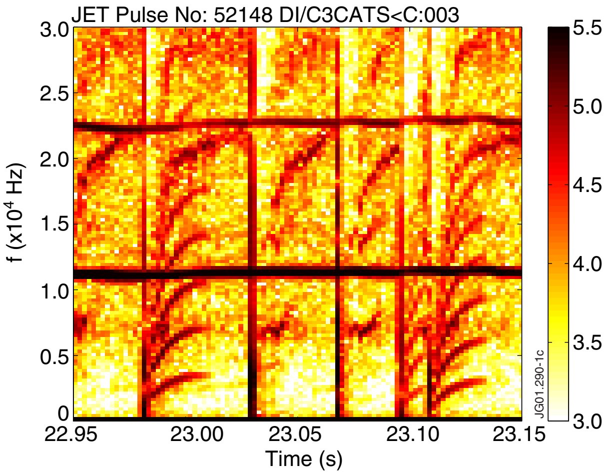

Figure 1: Magnetic spectrogram showing palm tree modes.

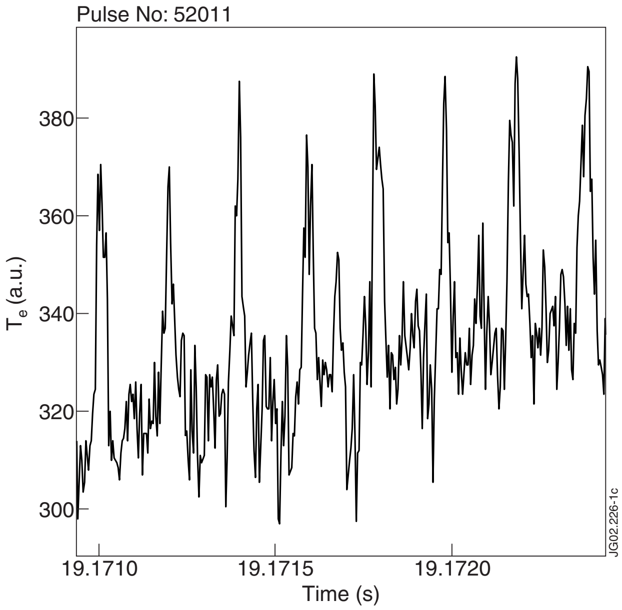

Figure 2: ECE channel at $R = 3.84m$

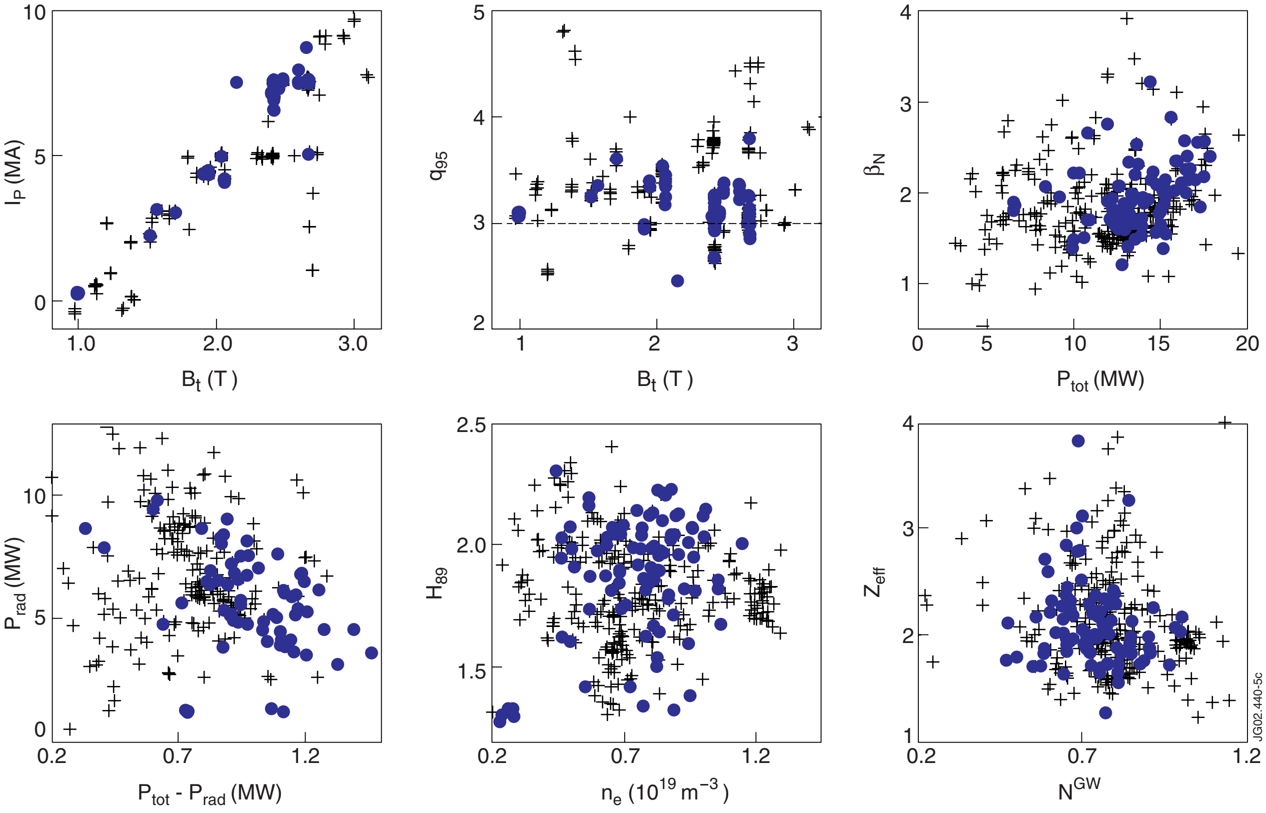

Figure 3: Overview on various global discharge parameters during type-I ELM phases. Data with (blue circles) and without (black pluses) palm tree modes are shown.

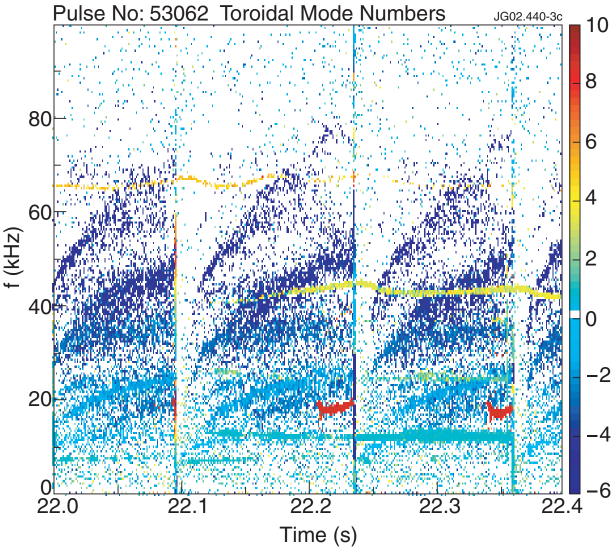

Figure 4: *Toroidal mode numbers of type-I ELM precursor oscillations. The colors denote the toroidal mode number n, modes with negative numbers propagate in the electron drift direction.*

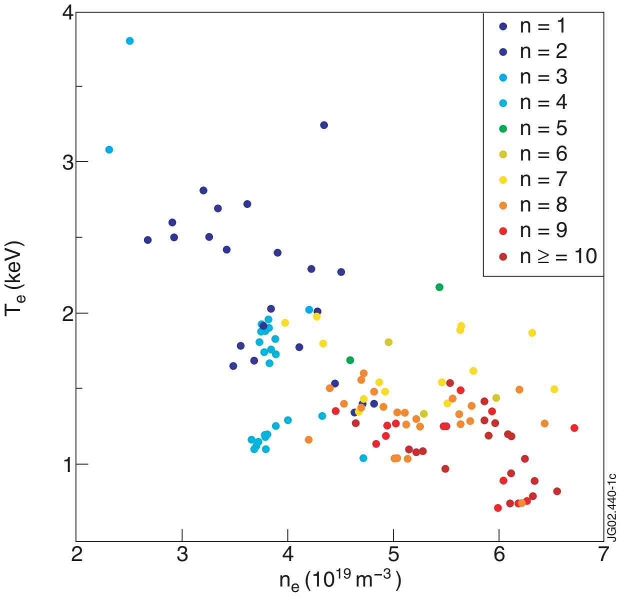

Figure 5: *Toroidal mode numbers of type-I ELM precursor oscillations as function of the edge density and temperature.*