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INTRODUCTION

The “enhanced D_α” (EDA) H-mode developed on Alcator C-Mod is a high density, quasi-stationary state with good confinement but no large ELMs [1] , therefore potentially suiting ITER standard operation. Initial studies of it on JET did not recover the regime [2] , but plasma conditions particularly in the edge pedestal remained far from those typical for C-Mod. The definitive test of reproducibility of tokamak plasma behaviour is provided by repeating identical values of the dimensionless variables ν_{*e}, ρ_*, β, Z_{eff} (normalized collisionality, Larmor radius, pressure[†] and effective charge), since its essential physics can be written as functions of only these quantities, plus magnetic equilibrium parameters $\varepsilon \equiv a/R_0$, κ, δ, q (inverse aspect ratio, elongation, triangularity and safety factor) defining the specific geometry[3]. Such identity constraints then imply scaling of main control variables with minor radius a according to [4]:

$$\sim B_t \sim a^{-5/4},\ I_p \sim a^{-1/4},\ P_{in} \sim a^{-3/4}\ ,\ n_e \sim a\ \text{-}2\ ,\ T_e \sim a^{-1/2}$$

Note that matching pedestal properties is expected to matter most for near ELM-free EDA-like effects [2, 4]. Using ($a^{JET} / a^{C\text{-}Mod}$) = 4.2 leads to the unusual low field, current and power conditions for JET presented in Table 1.

	C-Mod	**JET**
B_t (T)	5.4	0.89
I_P (MA)	0.8 – 1.2	0.56 – 0.83
P_{in} (MW)	1.0 – 4.0	0.34 – 1.36
n_e^{ped} (10^{19} m^{-3})	20 – 40	1.1 – 2.3
T_e^{ped} (eV)	300 – 600	150 – 290

$\varepsilon = 0.28$, $\kappa = 1.65$, $\delta^{upper} = 0.32$, $\delta^{lower} = 0.5$, $q_{95} \geq 3.5$

Table 1: Pedestal identity scaling from C-Mod to JET

1. JET H-MODE CHARACTERISTICS

Very similar high δ single-null divertor configurations were duplicated in C-Mod and JET, as illustrated by the respective separatrix surfaces plotted against co-ordinates normalized by a JET,C-Mod in Fig.1. Pedestal conditions were set by choosing field and current as in Table 1, then adjusting density and input power, initially using second harmonic H-minority ICRF heating at 28MHz. In contrast to steady EDA phases, however, repetitive ELM-free periods separated by bursts of small, high frequency ELMs emerged on JET, as shown in Fig.2 (left panel). Note that spikes visible on divertor $D\alpha$ in each ELM-free interval were merely due to sawtooth effluxes. Furthermore, recycling tended to rise to a peak in each interval, while stored energy and especially edge density remained

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[†] definitions applied : $\nu_{*e} \propto Z_{eff}\, q_{95}\, (R_0/\varepsilon^{3/2})\, (n_e/T_e^{\,2})$; $\nu_* \propto (\sqrt{T_e}) / (B_0\, a)$; $\beta \propto n_e\, T_e/B_0^{\,2}$.

almost constant. This is unlike usual ELM-free behaviour in JET, where these quantities rise cyclically as well, again as depicted in Fig.2 (right panel) for a plasma at higher field, current, density and ICRH power, but particularly at lower magnetic shaping. In both situations, radiation grew throughout each interval, until it provoked ELMs (or a return to L-mode) plus a drop in properties, before the cycle restarted. An explanation of constant edge density for the identity case remains under study, but calculations with the JETTO transport code reveal an increased level of neo-classical transport. Hence this itself may contribute to stabilization of the pedestal density. Further investigation of particle source effects is presented in a companion paper [5] .

Electron properties in the pedestal are measured for such low fields in JET by a dedicated edge Thomson scattering diagnostic. Outer channels of the core LIDAR system may also be used to infer upper bounds for density and temperature heights, but uncertainties tend to be substantial. Resulting estimates for edge ν_{*e}, ρ^*, β during ELM-free periods with ICRH are compared with C-Mod values in Fig.3. Pairs of JET data points from the maximum of edge, and outer core, LIDAR systems are connected by lines. Moderately collisional conditions are indeed found, as in C-Mod, but above the normal level for JET [2] . A number of points at 1.3T, 0.8MA, $q_{95} \approx 5$ using second harmonic ICRH at 42MHz are also included, and interestingly match C-Mod more closely in ρ^* and β despite initial predictions above. Corresponding JET pedestal values during ELMy phases in fact show no significant differences from the ELM-free results either. Alternative heating by NBI can be applied by reducing beam voltages to 75kV and modulating injectors where necessary, but it produced only ELMy H-modes, like the plasma illustrated in Fig.5 later. Analysing RF and NB power deposition profiles with the PION and PENCIL codes respectively indicates the former led to more central electron heating, but the electron pedestal actually seemed marginally more dense and cooler with NBH. These findings therefore imply that edge stability must be affected by other factors, such as current density and possibly rotation. It should be noted that C-Mod plasmas in the identity series also tended to exhibit bursts of small ELMs resembling those in Fig.2 , but the intervening periods retained definite EDA signatures, notably coherent edge fluctuations believed to mediate its continuous exhaust [1,4] .

2. FLUCTUATION SPECTRA

Power spectra of fast edge magnetic signals on JET are exemplified in Fig.4 for an ELMy and a consecutive ELM-free period, similar to the cyclic features shown in Fig.2 , but here at 1.3T, 0.8MA, with ICRH. A strong low frequency core mode (≈ 3kHz) is evident in both phases, probably associated with sawteeth. Whereas only broadband disturbance is otherwise visible during ELMs, though, in the ELM-free period two coherent frequencies ≈ 14kHz, ≈24 kHz are clearly observed. These frequencies are also seen in density fluctuations detected by the 18.5GHz channel of an O-mode reflectometer (Fig.4), returning from a layer $\approx 4 \times 10^{18}\ \mathrm{m}^{-3}$, and significantly are absent from its 29GHz channel reflecting from $\approx 10^{19}\ \mathrm{m}^{-3}$. Note there is no detectable Doppler shift in the former, but one becomes clearer in the latter. Hence localization in a narrow edge region may be suggested, reminiscent of the quasi-coherent mode (QCM) underlying EDA regime in C-Mod [1,4] . The frequencies in JET Fig.5

JET plasma at 1.8T, 1.2MA using NBH, with small shape change after 26.4s. also roughly comply with expected scaling [4,6] from the latter $\nu \sim a^{-5/4}$, if plasma rotation is consistent. Correlation analyses between different pick-up coils on JET indicate negative toroidal periodicities (Fig.4) for the pair of modes, denoting rotation in the electron drift direction, which again is coincident with the QCM and actually counter to features in earlier JET experiments not meeting identity conditions [2] At the same time, however, some very similar electron-drift-directed coherent fluctuations are seen during the conventional ELM-free periods in Pulse No: 56877 depicted in Fig.2 , the main differences being occurrence of more frequency bands moving in either electron or ion directions and localization around slightly higher density further into the plasma. Presently, it therefore remains unclear whether coherent modes described are specific to identity cases, or are involved in fixing edge density throughout their ELM-free intervals.

DISCUSSION

Plasmas in JET reproducing the configuration and pedestal dimensionless numbers of EDA states in C-Mod exhibit recurrent ELM-free periods, during which pedestal density and stored energy remain nearly constant, and which are separated by bursts of small, high frequency ELMs. Coherent edge fluctuations detected during the ELM-free intervals are suggestive of QCMs thought to mediate EDA regime [1,4] , but at present they appear insufficient to produce quasi-stationarity and to avert ELMs altogether. In this respect JET results are similar to previous EDA-related identity experiments on DIII-D [4] and ASDEX-U [6] . A surprising feature is the strong sensitivity to only small changes in parameters, as demonstrated for a higher power NBH plasma at 1.8T, 1.2MA in Fig.5 . Mid-way through this pulse a relatively modest increase in upper triangularity is imposed, while all other conditions remain constant. Nevertheless there is a marked impact on ELM character and pedestal density. The operating window for EDA H-mode may consequently have a tendency to become quite narrow on larger devices like JET.

ACKNOWLEDGEMENTS

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REFERENCES

[1]. M. Greenwald et al Phys Plasmas **6** (1999) 1943
[2]. G. P. Maddison et al Plasma Phys Control Fusion **44** (2002) 1937
[3]. J. W. Connor & J B Taylor Nucl Fusion **17** (1977) 1047
[4]. D. Mossessian et al Phys Plasmas **10** (2003) 689
[5]. D. Mossessian et al this conference
[6]. W. Suttrop et al paper EX/P5-07, 19th IAEA FEC, Lyon 2002

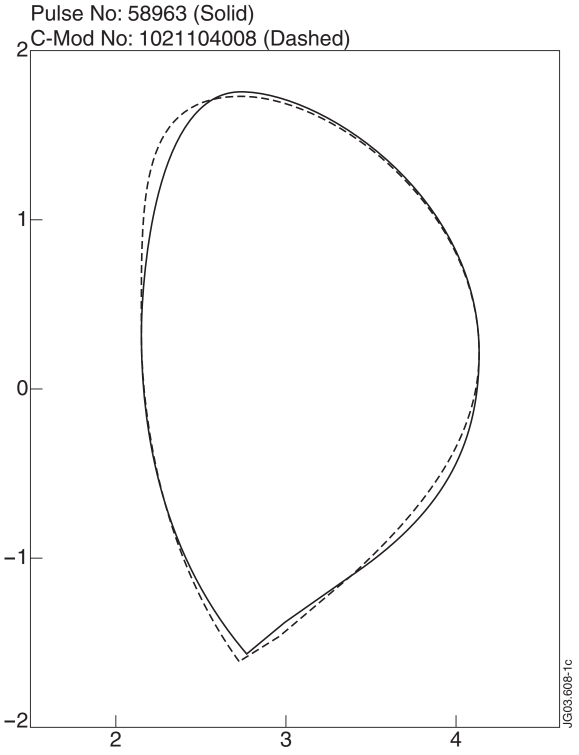

Figure 1: Overlay of scaled separatrix surfaces for C-Mod and JET. steady EDA phases, however, repetitive ELM-free periods

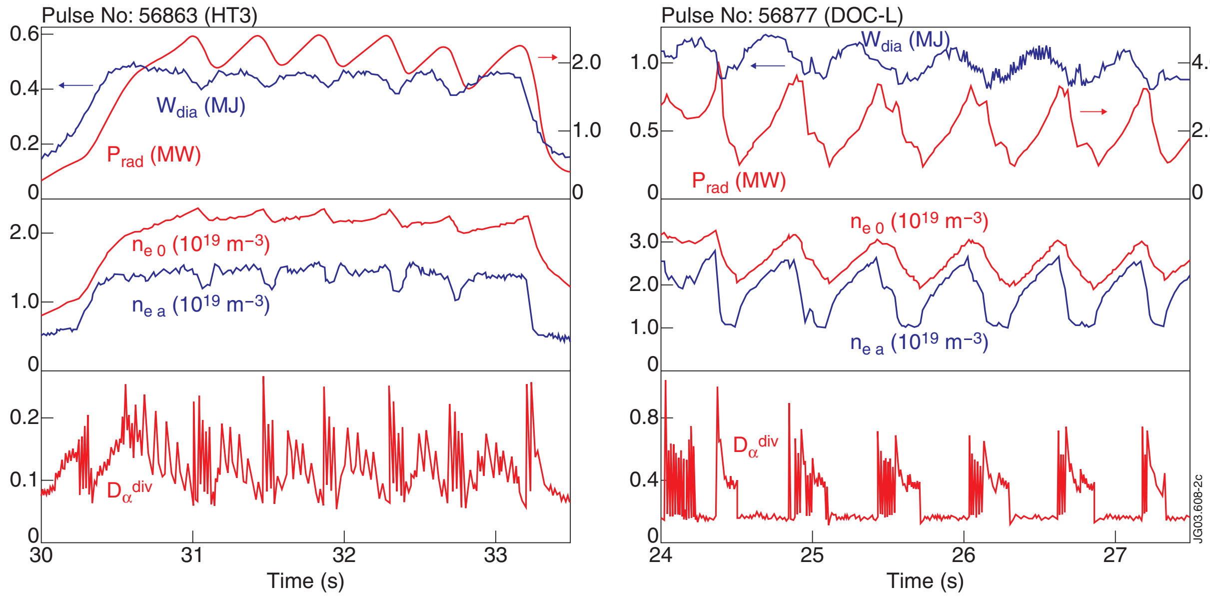

Figure 2: JET identity pulse (left, Pulse No: 56863) at high HT3) and conventional ELM-free periods (right, Pulse No: 56877) at 1.2 T, 1.2 MA in low shaping (designated DOC-L).

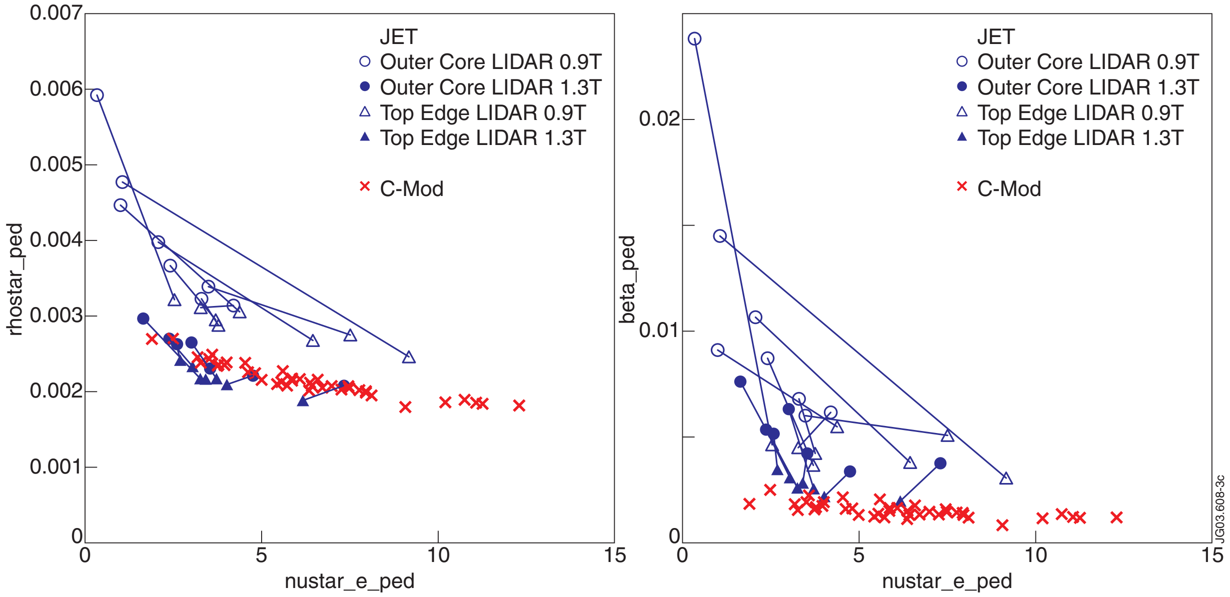

Figure 3: Pedestal dimensionless properties in JET and C-Mod ELM-free periods with ICRH. JET data pairs from edge and core LIDAR systems are connected by lines.

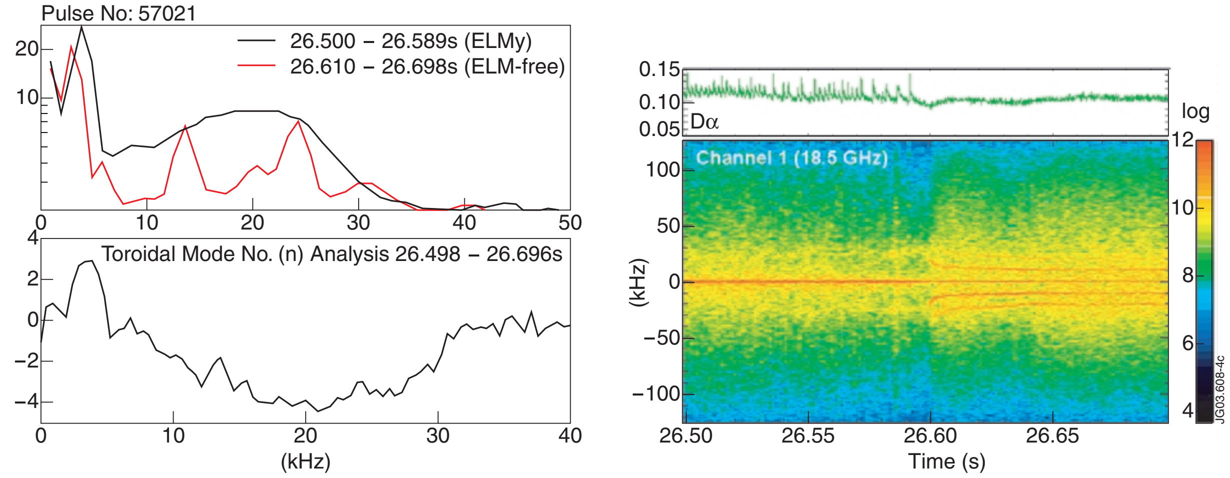

Figure 4: Fluctuations during JET identity pulse at 1.3 T, 0.8 MA with ICRH. Left: magnetic power spectra in an ELMy and an ELM-free period (top), plus correlation analysis of toroidal mode numbers over both (bottom). Right: corresponding density fluctuations from O-mode reflectometer channel probing the plasma edge.

Figure 5: JET plasma at 1.8T, 1.2MA using NBH, with small shape change after 26.4s. quasi-stationarity and to avert ELMs