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**Comparisons of small ELM H-Mode regimes
on the Alcator C-Mod and JFT-2M tokamaks**

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Comparisons of small ELM H-Mode regimes on the Alcator C-Mod and JFT-2M tokamaks

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Abstract

Comparisons of H-mode regimes were carried out on the Alcator C-Mod and JFT-2M tokamaks. Shapes were matched apart from aspect ratio, which is lower on C-Mod. The High Recycling Steady (HRS) H-mode on JFT-2M and Enhanced D_α (EDA) regime on C-Mod, which both feature very small or no ELMs, are found to have similar access conditions in q_{95} - v^* space, occurring for pedestal collisionality $v^* \gtrsim 1$. Differences in edge fluctuations were found, with lower frequencies but higher mode numbers on C-Mod. In both tokamaks an attractive regime with small ELMs on top of an enhanced D_α baseline was obtained at moderate v^* and higher pressure. The JFT-2M shape favoured the appearance of ELMs on C-Mod, and also resulted in the appearance of a lower frequency component of the quasiscoherent mode during EDA.

1.0 Introduction

The high confinement or “H-mode” regime, characterized by an edge transport barrier, requires some form of edge relaxation mechanism increasing particle transport, so as to control impurities and maintain steady density while maintaining good energy confinement. This is often provided by Edge Localized Modes (ELMs); the Type I ELM regime is obtained on many tokamaks and is the reference scenario for ITER. However, there are concerns about the heat pulses resulting from such large ELMs and their possible impact on divertor erosion¹. This motivates the exploration of high confinement regimes with smaller or no ELMs. A number of such regimes have been discovered on various tokamaks, as recently reviewed by Oyama². However, understanding of the physics of, the relations between and the access conditions for these regimes is incomplete.

This paper reports on a series of recent experiments aimed at comparing two such regimes, the Enhanced D-alpha (EDA) H-mode regime first observed on the Alcator C-Mod tokamak in 1996³ and the High Recycling Steady H-mode seen on the JFT-2M tokamak in 2002⁴. The EDA regime is characterized by good steady-state energy confinement, with normalized confinement $H_{ITER89-P}$ ⁵ up to 1.9, steady density and low, steady radiation levels⁶. No periodic ELMs are typically seen. Instead, the particles are found to be regulated by a continuous ‘quasiscoherent (QC) mode’ located in the density barrier^{7,8,9}. This mode, observed by several diagnostics, has $f \sim 100$ kHz and poloidal wavenumber $k_\theta \sim 2$ cm⁻¹ near the outer midplane. At high pressure, $\beta_N > 1.7$, the QC mode broadens and is largely replaced by a series of small ELMs appearing on top of the generally high D_α level¹⁰. The HRS H-mode shares many of the global characteristics of the EDA regime, with $H_{ITER89-P} \leq 1.6$. Studies of edge fluctuations have found both high frequency (HF) components, with $f \sim 200$ -350 kHz, $n \sim 8$, and low frequency (LF), broadband fluctuations with $f \sim 50$ kHz, which have $n=1$ and $m \sim 4$ ^{11,12}. Under some conditions, a ‘mixed’ regime with some small ELMs occurs. Both the EDA and HRS regimes are generally favoured by higher target density or neutral pressure and by increased triangularity δ and safety factor q_{95} . It is thus

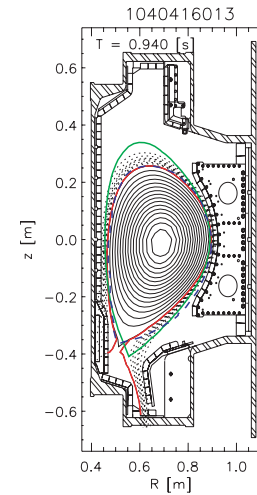
natural to ask whether they in fact represent the same physical phenomenon, and if so, how this would extrapolate to other devices.

2.0 Description of Experiments

H-mode regimes, stability and fluctuations are known to depend sensitively on shape. To reduce these effects in the intermachine comparison, shapes on JFT-2M and C-Mod were matched in poloidal cross-section, as shown in Figure 1. This also shows that the JFT-2M shape is quite different from the more typical C-Mod shapes in which prior H-mode studies have been done, notably lower κ (1.49) and smaller X-point radius. However, it was not practical to match the aspect ratio, which is higher on JFT-2M ($R/a = 1.29/0.26\text{m}=4.9$) than on C-Mod ($R/a = 0.68/0.21\text{m}=3.2$); this means that the plasma dimensionless parameters and safety factor profile $q(r)$ cannot all be matched exactly. B_T was 5.4 T for C-Mod and 1.6-2.2 on JFT-2M.

Experiments were first carried out on JFT-2M, using variation in target gas pressure in a boronized vessel to scan density for several I_p/B_T combinations, giving q_{95} of 2.9, 3.5 and 4.8. Heating was provided by 1.4 MW of balanced NBI. Details of the resulting H-mode regimes, pedestal parameters and fluctuations were reported by Kamiya¹³. C-Mod then conducted experiments in the matched shape on several run days in the 2004 and 2005 campaigns, varying both target density and ICRH power (0-5.2 MW) to vary pedestal parameters at each of the above q_{95} values. The vessel was boronized in most experiments, with some variation in coating thickness. In both tokamaks, boronization was found to be necessary to achieve steady H-modes and to access the EDA or HRS regimes.

Figure 1: C-Mod shape used in comparison experiments (red) is a good match to scaled JFT-2M shape (blue, dashed) and differs from more typical C-Mod shapes (eg, green).



3.0 Results of Comparisons

3.1 H-Mode regimes and access conditions

The H-mode regimes obtained span the range of those observed in prior JFT-2M and C-Mod experiments. The pedestal parameter ranges accessed are summarized in Figure 2. Figure 2a shows typical trajectories of JFT-2M discharges at $q_{95}=3.5$. At the lowest target density, shown by the L-H transition curve, large ELMs were seen with a baseline D_α level below that of L-mode. These appear similar to Type I ELMs, though this has not been definitively established. There is a clear pressure limit, corresponding to toroidal beta at the pedestal $\beta_{e,ped} \sim 0.2\%$. At the highest L-mode n_e , a steady HRS regime is found with very small ELMs and a D_α level more than twice L-mode. A reduced pressure limit, $\beta_{e,ped} \sim 0.14\%$, is found in this regime. The intermediate regime labelled ‘mixed’ has more distinct ELMs but still a high D_α level and $\beta_{e,ped} \sim 0.17\%$. All three regimes lead to H-modes with fairly steady density and temperature.

On C-Mod, the greatest range of pedestal parameters, and regimes, was achieved in the scans at $q_{95}=3.5$ (figure 2c). Because of the variable heating power, a wider range of pressures was accessed in the C-Mod experiments. Pedestal T_i , where measured spectroscopically, was close to that of T_e so total β is about twice the $\beta_{e,ped}$ shown. Steady EDA discharges without any discrete ELMs occurred at high densities and modest pressures. At similar densities but higher pressures, the small ELM regime with enhanced D_α , labeled ‘EDA+ELMs,’ was obtained as described in

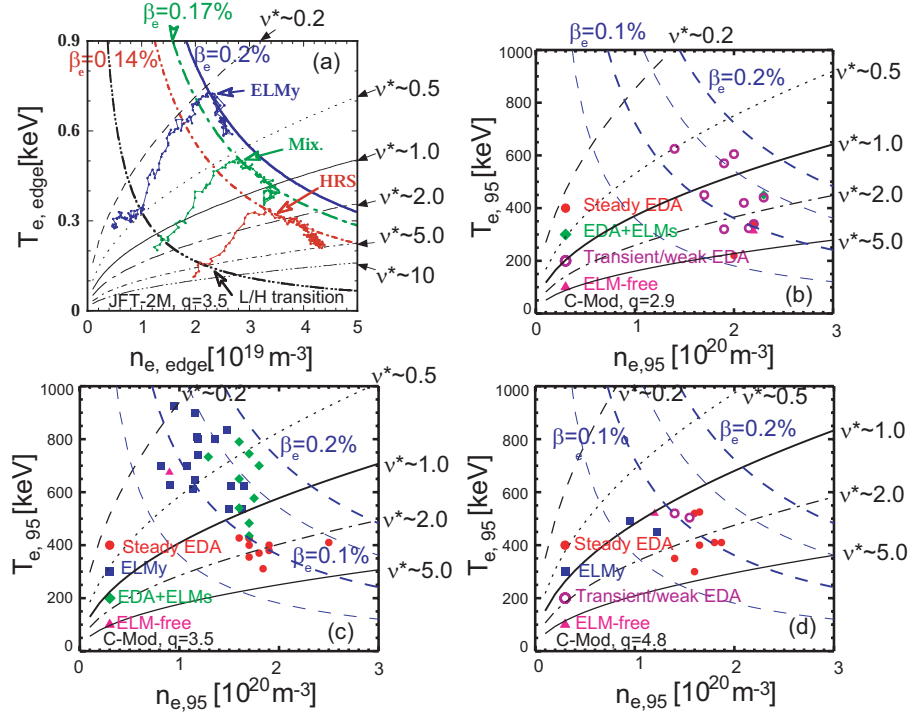


Figure 2: Pedestal T_e and n_e spaces and regimes for (a) JFT-2M, $q_{95}=3.5$ (b) C-Mod, $q_{95}=2.9$ (c) C-Mod, $q_{95}=3.5$, (d) C-Mod, $q_{95}=4.8$. Lines of constant collisionality v^*_{ped} and normalized pressure $\beta_{e,ped}$ are drawn for comparison.

Ref¹⁰. $\beta_{e,ped}$ was up to $\sim 0.17\%$, comparable to the JFT-2M ‘mixed’ regime. Atypically for C-Mod, at lower densities, regular ELMs were seen in many discharges. Their occurrence was sensitive to shape, as discussed further in Section 3.3. Smaller ranges of edge parameters were accessed in the scans at higher and lower q_{95} . At $q_{95}=2.9$, as has been found previously, steady EDA H-modes could only be achieved at high v^* . The discharges labelled ‘Transient/weak EDA’ had a weak QC mode which was insufficient to maintain steady density conditions. Steady EDA was readily obtained at $q_{95}=4.8$. However, the pressure was limited in these experiments, likely because of the scaling¹⁴ of p_{ped} with I_p^2 , and the high β , small ELM regime was not obtained.

Access conditions for regimes on JFT-2M and C-Mod are compared in Figure 3, which plots q_{95} vs v^*_{ped} ; $Z_{eff}=1$ is assumed in the v^* calculation for consistency since measurements were not available in all discharges, so that v^* values are underestimates. A clear separation by v^* is found on JFT-2M (a); HRS occurs at highest values, typically > 1.5 and large ELMs at $v^* \leq 0.5$, with the ‘mixed’ regime at intermediate v^* . There is a weak dependence on q_{95} , with the v^* boundaries shifting to lower values at higher q_{95} . The access conditions on C-Mod are strikingly similar, particularly at $q_{95}=3.5$. As for HRS, EDA H-modes occur for $v^* > 1.5$. Below $v^* = 0.4$, only ELMy discharges are seen. There is overlap of ELMy (low D_α) and EDA+ELM (small ELMs, high D_α) H-modes at intermediate v^* . This may be a result of the wider range of β_{ped} in the C-Mod dataset; the latter regime prevails at higher pressure. L-mode density also seems to play a role. As has been found in prior experiments, steady EDA H-modes were obtained more easily at $q_{95} \geq 3.4$; for $q_{95}=2.9$ the v^* boundary increased to $v^* > 2$. Weak QC modes were, however, observed at lower v^* . ELMs at $q_{95}=4.8$ occurred only at low pressure, $\beta_{e,ped} \sim 0.07\%$.

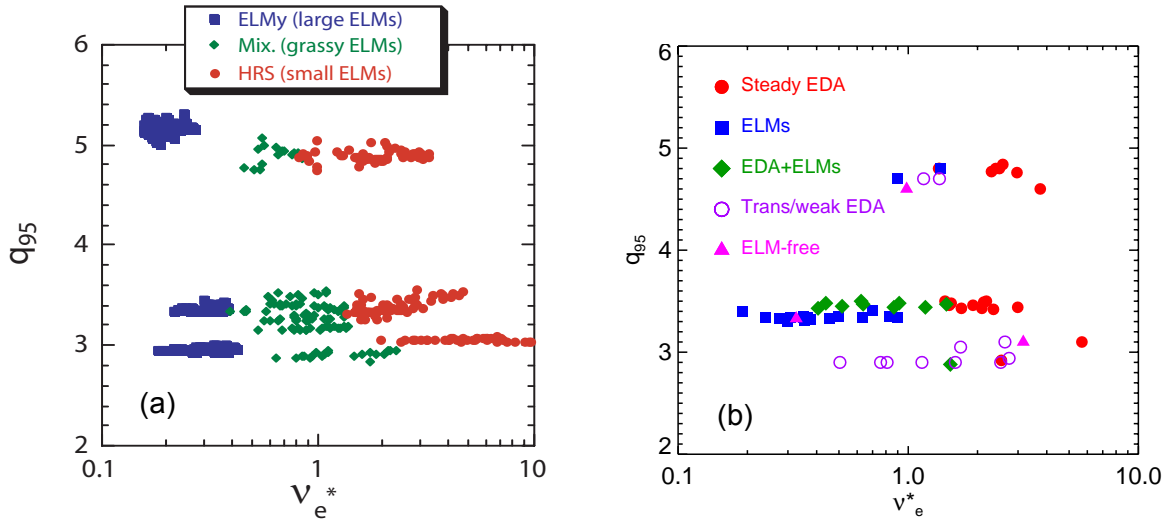


Figure 3: Operational spaces q_{95} vs pedestal v_e^* of H-mode regimes on (a) JFT-2M and (b) C-Mod. Note that the HRS and EDA regimes have similar access conditions, as do the “Mix” and “EDA+ELMs” regimes.

3.2 Edge fluctuations in HRS and EDA H-Modes

Since the HRS and EDA regimes are characterized by edge fluctuations thought to cause the enhanced transport, it is of interest to compare these fluctuations under closely matched conditions. Figure 4 shows magnetic fluctuation spectra for two such discharges, both with $q_{95}=3.4$ and $v_{ped}^*=1.4$. The JFT-2M spectra (a) feature a HF mode at 340 kHz, with a FWHM of ~ 25 kHz. Increased fluctuations are also seen at $f < 100$ kHz. Small ELMs, not shown in the figure, also occur with a period of ~ 3 ms, though the HF and LF modes precede the ELMs and are thought to cause most of the transport¹³. Fluctuations on C-Mod (b), which were measured with a magnetic probe head mounted on a scanning probe close to the LCFS, show peaks at 134 kHz and 67 kHz. The 134 kHz feature, which appears first in time, is typical of the QC mode reported in standard C-Mod shapes and has $k_{0, mid} \sim 2 \text{ cm}^{-1}$. The lower f peak is atypical and appears to be associated with the JFT-2M shape. It has exactly half the wavenumber as well as frequency, indicating that it occurs on the same rational surface; the lower k likely explains the higher apparent amplitude on magnetics. The two-frequency spectrum is also seen on density fluctuations measured by Phase Contrast Imaging⁷, which give slightly higher amplitude for the 134 kHz component. The higher frequency seen on JFT-2M is not expected from dimensional considerations; for identical dimensionless parameters, a higher frequency, $f \sim a^{-5/4}$, would be expected on the smaller, higher field C-Mod device.

Differences are also found in the mode numbers of fluctuations on JFT-2M and C-Mod. On JFT-2M, magnetics arrays show the LF fluctuations have $n=1$ and $m=4 \pm 1$. The HF mode has $n=7$, which, assuming fluctuations at the same location, corresponds to $m \sim 28$. The quasicohherent mode on C-Mod has a wide spectrum of toroidal mode numbers centred at $n \sim 11$ for the 67 kHz component, which corresponds to $n \sim 22$ at 134 kHz. Poloidal wavenumber k_θ is measured both from magnetics, just above the outer midplane, and PCI, viewing the top and bottom of the plasma where typically $k_\theta \sim 5 \text{ cm}^{-1}$, since k_θ varies poloidally as expected. The average poloidal mode numbers corresponding to $k_{\theta, mid}$ of 1 cm^{-1} and 2 cm^{-1} are computed to be $m \sim 65$ and 130 respectively for the low and high frequency components, significantly higher than for JFT-2M.

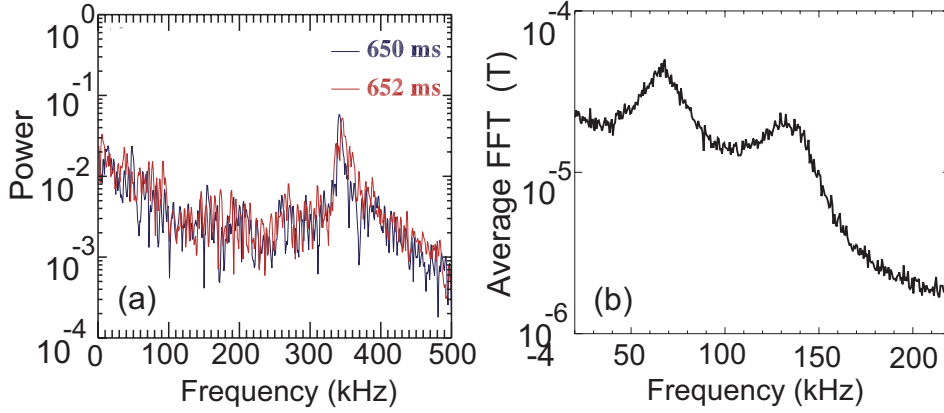


Figure 4: Comparison of magnetic fluctuation spectra measured by probes on (a) JFT-2M, during HRS H-mode (b) C-Mod, during EDA H-mode with matched shape. Both discharges have $q_{95}=3.4$ and $v_{ped}^*=1.4$.

Interestingly, at $q_{95}=4.8$, the QC mode on C-Mod became quite weak at high density ($v^* \geq 2$), although steady H-modes with enhanced D_α were maintained. In these conditions, broadband density fluctuations at $f < 100$ kHz increased markedly on PCI spectra and likely contributed to particle transport. This behaviour is similar to that of the LF fluctuations in JFT-2M.

3.3 ELM behaviour on C-Mod

As mentioned above, the appearance of a regime of distinct large ELMs, without enhanced D_α , is highly unusual on C-Mod. Figure 5 shows an example of an H-mode with large ELMs, corresponding to one of the lowest collisionality points on figures 2c and 3b. No QC mode was seen, indicating that the ELMs are maintaining the fairly steady density. ELM size was quite variable within and between discharges, with the amplitude of D_α spikes ranging from 0.4 to 2.4 times the L-mode level. The largest ELMs occurred only at lowest v^* , < 0.4 . The duration of spikes was also variable, typically 0.5-1.5 ms. MHD precursors with decreasing f , ~ 200 to 50 kHz, occurred ~ 1 ms before ELMs. Fast D_α diode and 2-D camera measurements also show precursors, as well as extended ‘filaments’ in the SOL during an ELM¹⁵.

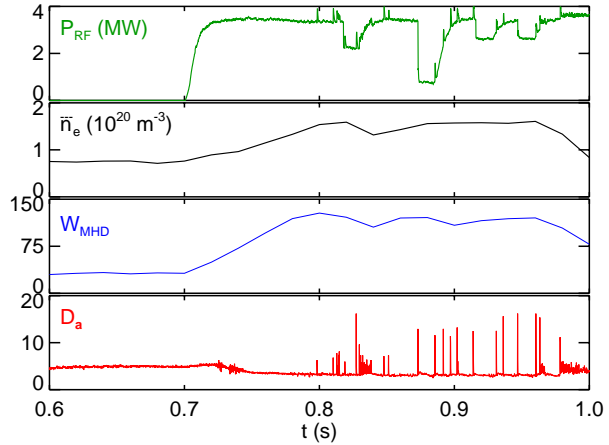


Figure 5: Example of a C-Mod H-mode with low v^* and large ELMs.

The type, or types, of these ELMs is not yet clear. The largest ELMs occur at pressures close to the highest seen in this set of experiments, and may be Type I ELMs. On the other hand, as seen in figure 2 (blue points), many ELMs (typically of lower amplitude) occurred in lower pressure and temperature pedestals, clearly below the pressure limit. Prior stability analysis of the C-Mod EDA+ELM regime (green), in contrast, found pedestals above the peeling-ballooning stability limit¹⁰. In some discharges ELMs stopped when a sawtooth heat pulse transiently raised the

edge T_e . These observations suggest they are more likely Type III than Type I ELMs, though a definitive MHD identification has not been made.

ELM occurrence was reproducible and highly dependent on shape, with the JFT-2M matching shape shown in Fig 1 serendipitously favourable. Low target density, close to that of the H-mode density limit, was required. Further experiments in which the shape was varied show that, when the X-point location was shifted outward by 2-4 cm, ELMs disappeared and were replaced by ‘dithering’ H-mode, with regular L-mode periods of 5-10 ms. H-modes with large ELMs have been seen in a few other C-Mod experiments, also at low collisionality, in which the plasma was limited, or nearly limited, on the inner ‘nose’ of the divertor¹⁶. Comparison of those shapes with that used in these JFT-2M comparison experiments also suggests that the location of the x-point at small R, closer than usual to the inner wall, may be important for stability. Detailed stability analysis and more systematic scans of shape are required to confirm and understand this sensitivity, as well as to clarify the ELM type and responsible MHD instability.

4.0 Discussion and Conclusions

Comparison experiments between JFT-2M and Alcator C-Mod have provided considerable information on the similarities and differences between H-mode regimes. The similarities in dimensionless parameters required to access various regimes are striking. Both the EDA and HRS regimes, steady regimes with continuous high frequency fluctuations, occur for $v_{ped}^* \gtrsim 1$, with the exact collisionality boundary weakly depending on q_{95} . The upper bound of $\beta_{e,ped} \sim 0.14\%$ was also comparable, though this was not scanned systematically. The ‘mix’ regime seen on JFT-2M, with small ELMs on an enhanced D_α baseline, appears quite similar to the C-Mod regime of small ELMs arising from EDA at higher β . For $q_{95}=3.5$, both occur in these experiments at $0.4 < v_{ped}^* < 1.5$ and at $\beta_{e,ped}$ up to 0.17%. These results strongly suggest a correspondence of these regimes. The situation regarding ELMy H-modes is less clear. As on JFT-2M, at $v_{ped}^* < 0.3$ H-modes with discrete ELMs and low D_α were seen on C-Mod. However, ELMs also occurred on C-Mod at higher v^* and lower β , a parameter range which was not accessed in the JFT-2M comparison discharges at constant P_{NBI} .

Differences were found in the details of edge fluctuations in the HRS and EDA regimes. In particular, the frequency of the HF mode on JFT-2M was higher (340 kHz) than that of the QC mode in corresponding C-Mod discharges (134 kHz); this is opposite to what might be expected from dimensionless considerations. The C-Mod QC mode has significantly shorter wavelength ($k_{\theta, mid} \sim 2 \text{ cm}^{-1}$) and higher mode numbers ($n \sim 22$, $m \sim 130$) than the HF mode on JFT-2M ($n \sim 7$, $m \sim 28$). The reasons for these differences in fluctuation characteristics are not currently understood. They presumably reflect conditions which were not matched in this comparison, such as the aspect ratio, the heating technique or the plasma rotation, which is significant in C-Mod H-modes despite the lack of external momentum input¹⁷. It is also possible that higher k fluctuation components exist on JFT-2M which were not resolved by the available diagnostics; wall mounted magnetic coils, as shown on C-Mod, are less sensitive to higher k modes^{8,9}.

It should be noted the C-Mod H-mode observations reported here differ in several respects from those found in more typical shapes with higher elongation. Quasicoherent fluctuations in EDA exhibited two components, with the second component having half the frequency (67 kHz) and wavenumber (1 cm^{-1}) of the usually observed QC mode. The lower frequency component is closer in m to, though still higher than, that on JFT-2M. ELMs occurred much more readily in the JFT-2M shape indicating differences in edge stability. This will be exploited to further study ELM dynamics and scalings on C-Mod. Prior C-Mod studies have also found somewhat different access conditions for the H-Mode regimes, with more overlap in v^* between EDA and

EDA+ELM regimes; the conditions are clearly complex and cannot be simply expressed in 2-D parameter spaces^{14,10,2}. These differences, many unexpected, illustrate the importance of conducting dedicated inter-machine comparison experiments to reduce to the extent possible the complicating effects of differences in shape as well as in the dimensionless plasma parameters typically accessed on various tokamaks. Such experiments are helping to reveal the underlying physics and unify to some extent the observations of many interesting small ELM H-Mode regimes.

Based on the results of this comparison, the regime of small ELMs and high recycling found on both C-Mod and JFT-2M appears potentially interesting for burning plasma experiments. It has been extended to moderate collisionality and has β comparable to Type I ELM regimes. It is not clear from these experiments, which were limited in power, what represents its ultimate pressure limit. This regime may well be connected to “Type II” ELMs reported on several tokamaks, and possibly to Type V ELMs on NSTX¹⁸, motivating further comparisons.

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