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MHD in JET hybrid plasmas with the ITER Like Wall

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The achievable performance in terms of beta and duration of hybrid scenarios is often limited by the onset of MHD modes that degrade confinement or even induce disruptions. The most dangerous modes have tearing structure with poloidal and toroidal mode numbers $(m, n) =$ (2, 1), (3, 2), (4, 3). In addition, studies in JET plasmas with the ITER-like wall (JET-ILW), which includes tungsten divertor surfaces, revealed that also the internal (1, 1) mode can assume tearing character [1] and that tearing modes can foster central accumulation of tungsten [2].

This paper is aimed at a statistical survey of MHD instabilities that can affect the performance of JET hybrid discharges, with particular attention to onset conditions and saturated amplitude in terms of the normalised beta (β_N); other issues such as the influence on impurity accumulation and on energy confinement will be reported elsewhere [3].

The database includes about 260 pulses for JET-ILW and 180 selected pulses for the previous carbon wall (JET-C). Modes appearing after radiated power exceeds 70% of input power are discarded; this eliminates instabilities associated with heavy impurity influxes and hollow temperature profiles. Modes with $n = 4$ or higher are not considered. Toroidal numbers and mode amplitudes (zero-to-peak poloidal field oscillation) are evaluated by cross-spectral analysis of a toroidal array of Mirnov coils. Poloidal numbers are identified from the mode location as inferred by matching the mode frequency against the plasma rotation profile [4], e.g. the $n = 2$ mode location is close to the $q = 1.5$ and then its poloidal number is $m = 3$.

Statistical overview

The maximum amplitude reached by the $n = 2$ mode during each pulse is shown in Fig. 1 for JET-C and JET-ILW datasets separately. A similar trend to increase mode amplitude with normalised beta can be observed in both cases, with about 30% larger values for JET-C. Data clustered near zero amplitude correspond to weak (1-2 cm island width) and generally transient modes that are not relevant to the present analysis. These modes are discarded in the following by imposing a threshold of 3×10^{-6} T s on the time-integrated amplitude. Maximum amplitudes of $m = 1$, $n = 1$ and $n = 3$ modes with the ILW are shown in Fig. 2. Threshold values of 10^{-5} T s for $n = 1$ and 10^{-6} T s for $n = 3$ are used in the following. The $m = 2$, $n = 1$ occurs rarely; it is easily recognized for having location at $q = 2$ and large amplitude ($> 1.5\times10^{-3}$ T typical).

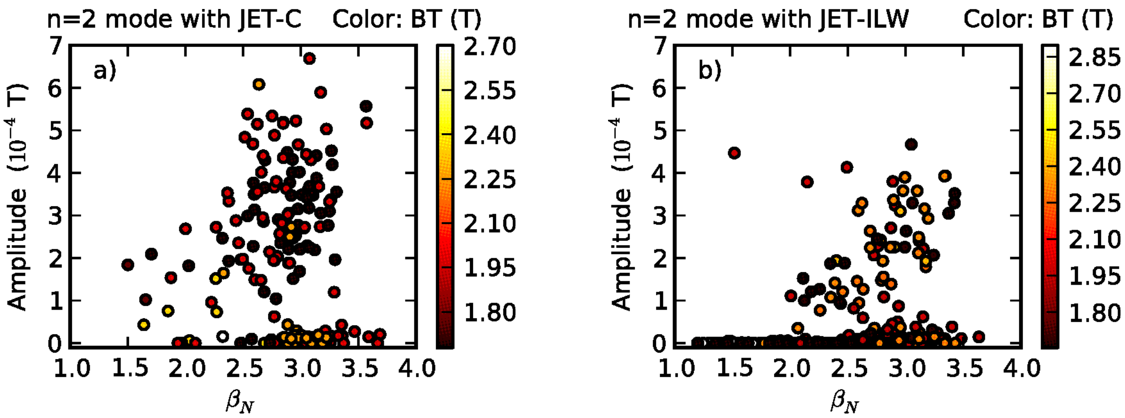

Figure 1. Maximum amplitude of the $m = 3$, $n = 2$ mode during each pulse as a function of normalised beta a) with the C-wall and b) with the ILW. The toroidal field is shown by color code. Outliers above 3×10^{-4} T at $\beta_N < 2.5$ in b) are from pulses with early NBI timing at $q_{95} = 3$.

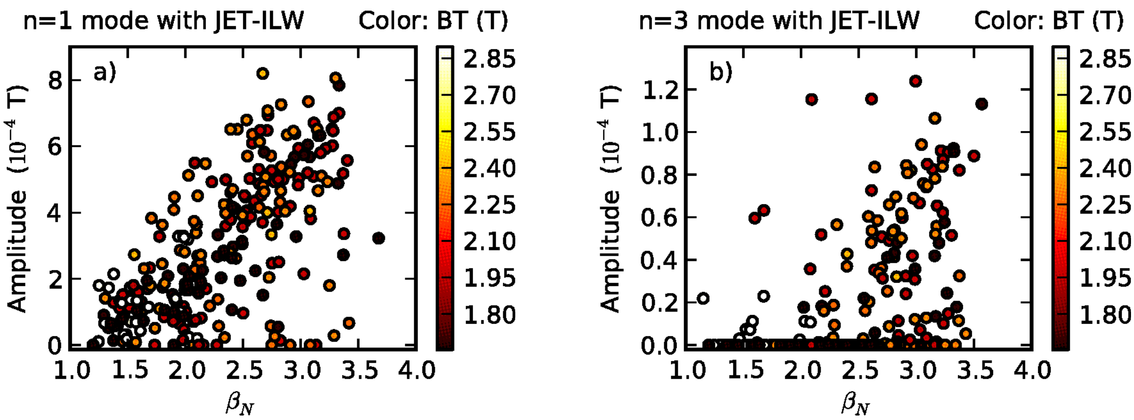

Figure 2. Maximum mode amplitude detected during each pulse with the ILW as a function of normalised beta a) for $m = 1$, $n = 1$ and b) for $m = 4$ (or 5), $n = 3$. Color code refers to toroidal field.

The incidence of modes above threshold with $n = 1$, 2 or 3 is compared in Fig. 3 for the JET-C and JET-ILW. The $n = 1$ activity is in the core ($q \approx 1$) region; cases with $m = 2$, $n = 1$ activity are rare and have been ignored to stay with three-sets Venn diagrams; four-sets ones will be shown elsewhere [3]. Generally the $n = 3$ activity is at the $q = 4/3$ surface, but in some pulses it is at the $q = 5/3$ surface. The incidence of pulses without MHD activity or with core $n = 1$ activity alone is much larger in the ILW database.

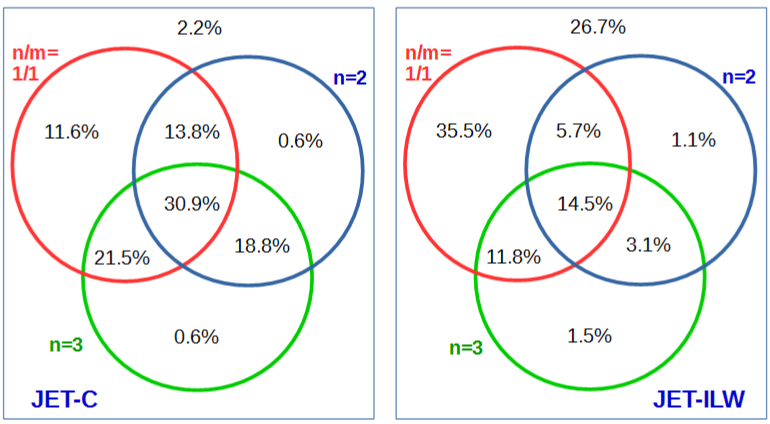

Figure 3. Venn diagrams of mode incidence observed in pulses with JET-C (left) and with JET-ILW (right). Data outside circles indicate pulses without modes above threshold.

From Fig. 4 it can be observed that a possible reason for the differences is that the proportion of pulses with lower β_N is much higher with the ILW. The systematic difference in density (due to operation constraints to avoid impurity influx with the ILW) could also play a role by increasing collisionality, which probably affects the density peaking and then the bootstrap drive with it. Another difference is the earlier NBI timing (< 4 s) in several JET-C pulses at low toroidal field (1.7 T): the 1/1 mode is very rare and other modes are very frequent in these pulses.

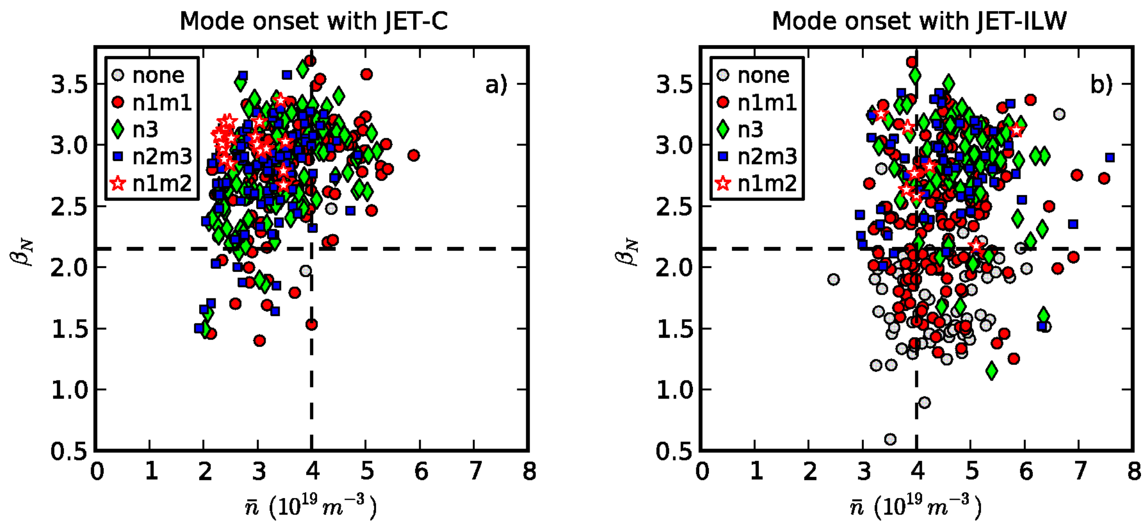

Figure 4. Normalised beta as a function of line-average density at mode onset, i.e. at threshold crossing time, or at time of maximum beta for mode-free cases (with "none" label). Cross-hairs are to help the comparison.

Mode onset

The first question addressed in this section is how long the high performance phase of hybrid pulses lasts before the onset of MHD activities. From Fig. 5 it can be seen that presently achieved durations from NBI start to mode onset time with JET-ILW can only exceed 3 s at $\beta_N < 2.5$, while longer durations were obtained with the JET-C at any β_N. However, the main reasons for the systematic lack of long high power pulses with the ILW were heat load and impurity problems. The second question, how q_{95} affects the maximum β_N that can be reached before the onset of MHD activities with $n/m > 1$, is addressed in Fig. 6, from which it can be seen that the maximum β_N decreases from 3.5 to 3 as q_{95} is lowered from 4 to 3. Also the mode-free region at low β_N tends to disappear at $q_{95} \approx 3$.

The last addressed question concerns the role of sawtooth crashes (or of strong fishbones) as triggers of the observed modes. Different shapes of temperature profile variation inside the sawtooth inversion radius were observed, ranging from the usual flattening to partial flattening to unperturbed central temperature (annular crash). Two onset types, with trigger by ordinary (i.e. with central temperature drop) and by annular sawtooth respectively, were classified in order to recognize the occurrence of the annular shape. The onset of modes in the presence of frequent fishbones, for which no clear-cut time coincidence can be appreciated, was classified as uncertain. Last, there are mode onsets that occur far from sawtooth crashes or even in sawtooth-free pulses, and were then classified as not sawtooth triggered. From Fig. 7 it can be seen that, for the $n = 2$ mode, ordinary sawtooth triggers are dominant at lower β_N and higher q_{95}, while triggers by annular crashes appear at higher β_N. Modes without sawtooth trigger are more frequent at high β_N or at low q_{95}; cases at low β_N and low q_{95} are from pulses in which the minimum q was raised and the sawtooth was suppressed by advancing NBI timing. Qualitatively similar results are found for $n = 3$ modes.

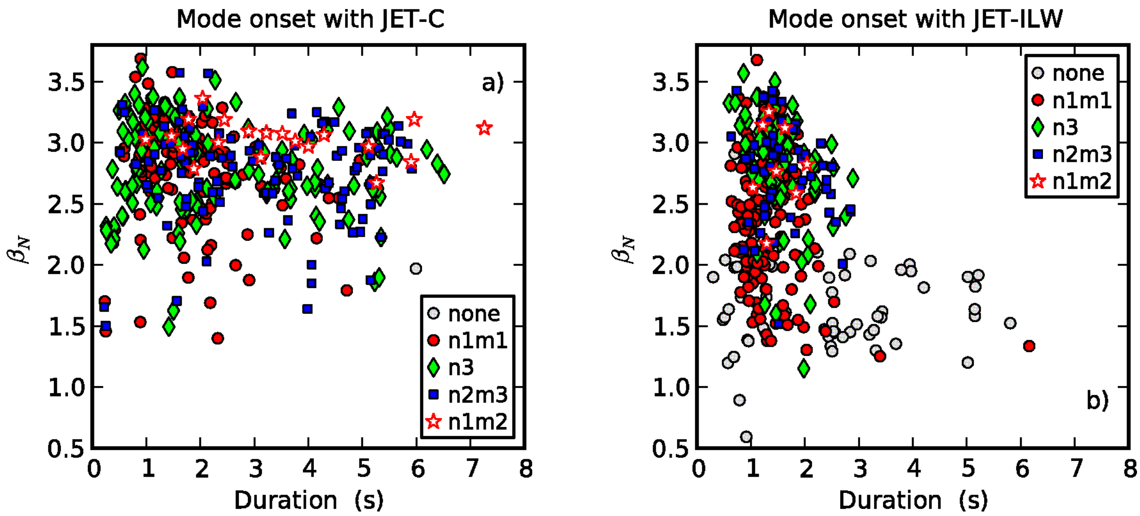

Figure 5. Normalised beta at mode onset as a function of duration from NBI start to mode onset time. Duration before radiation exceeds 70% of input power is used for pulses without MHD (grey dots).

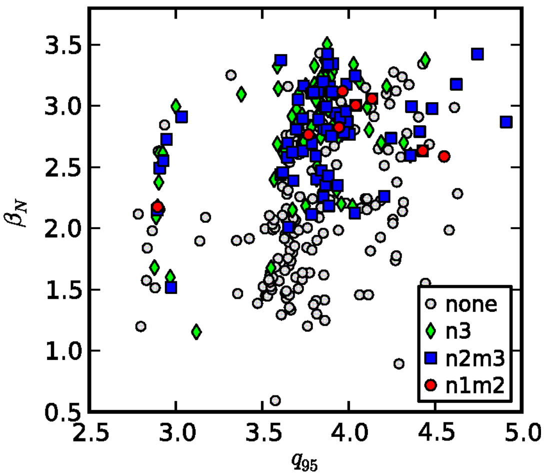

Figure 6. Normalised beta at the onset of instabilities with m/n = 2/1 (red), 3/2 (blue) and 4/3 or 5/3 (green) in ILW hybrid plasmas. Grey dots represent the maximum beta in discharges without the mentioned modes.

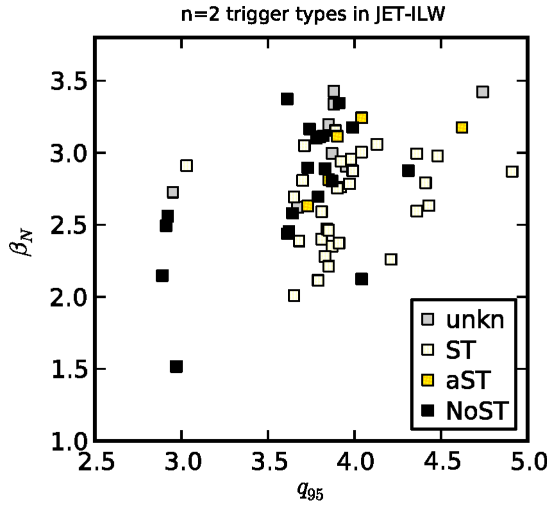

Figure 7. Onset types for the $m = 3$, $n = 2$ mode in ILW, ordinary sawtooth trigger in white, annular sawtooth trigger in yellow, uncertain in grey, not triggered by sawtooth in black.

Summary

High β_N pulses with the ILW develop MHD instabilities after 2-3 s of NBI heating; presently, pulses with MHD-free duration in excess of 5 s only exist at $\beta_N < 2$. Short durations at $\beta_N > 3$, with the ILW, appear to be caused by intrinsically less stable profiles, in fact sawtooth triggers seldom occur in this range. It is important to remark that, rather than to MHD onset, the systematic lack of long high power pulses with the ILW was due to heat load and impurity problems. Improved impurity control should also lead back towards the previous JET-C stability conditions.

[1] M. Baruzzo *et al 40th EPS Conf.* (2013) P5.161
[2] T.C. Hender *et al 41th EPS Conf.* (2014) P1.011
[3] T.C. Hender *et al* in preparation.
[4] P Buratti *et al 41th EPS Conf.* (2014) P1.014

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