MHD in JET Advanced Scenarios

S.D. Pinches[1], B. Alper[2], R. J. Buttery[2], C. D. Challis[2], M. Gryaznevich[2], S. Günter[1], T.C. Hender[2], D. F. Howell[2], E. Joffrin[3], Y. Q. Liu[4], J. Mailloux[2], M. Maraschek[1], S. E. Sharapov[2], A.C.C Sips[1] and JET EFDA contributors*

[1]*Max-Planck-Institut für Plasmaphysik, EURATOM-Assoziation, 85748 Garching, Germany*

[2]*EURATOM/UKAEA Fusion Association, Culham Science Centre, OX14 3DB, U.K.*

[3]*Association EURATOM–CEA, CEA Cadarache, 13108 Saint-Paul-lez-Durance, France*

[4]*Chalmers University of Technology, SE-412 96 Göteborg, Sweden*

Introduction

The understanding of MHD instabilities plays an important role in the further development of advanced scenarios. They can manifest themselves in ways that are both beneficial, by supplying diagnostic information, and detrimental, by limiting the achievable performance.

Alfvén Cascades

The reversed magnetic shear discharges in JET reveal so-called Alfvén Cascade (AC) modes excited by ICRH-accelerated ions [1]. The frequencies of these modes start in the range of the rotation frequency and move up to the TAE frequency range, i.e. O(10-100) kHz. They can be described by the following simple dispersion relation,

$$\omega(t) = \frac{1}{R_0}\left|\frac{m}{q_{\min}(t)} - n\right| v_A + \Delta\omega \,,$$

where $q_{\min}$ is the minimum of the safety factor, v_A is the Alfvén velocity, R_0 is the major radius and $\Delta\omega$ is a small correction due to a consideration of plasma rotation, toroidal coupling effects and fast ions. As can be seen, their frequency evolution is sensitive to the magnetic field helicity at the point of zero magnetic shear ($q_{\min}$) making them an ideal safety factor diagnostic. As $q_{\min}$ passes through a low order rational value, modes

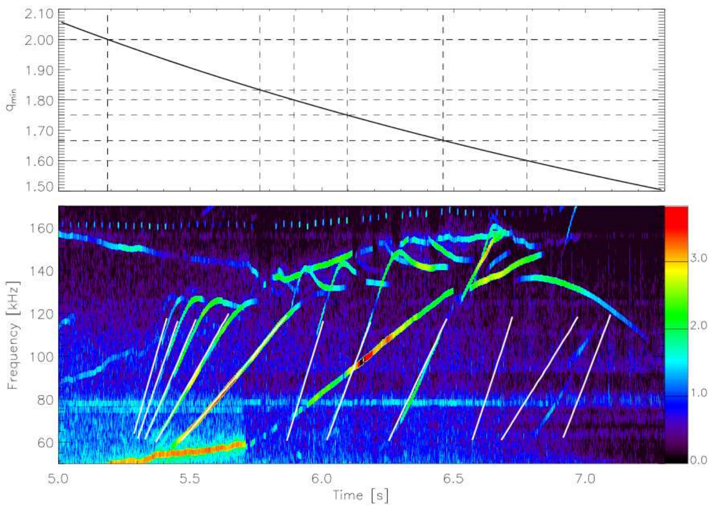

Figure 1: *Determination of q_{min} by fitting experimental Alfvén cascade data, #55495*

* See appendix J. Paméla et al., Fusion Energy 2002 (Proc. 19th Int. Conf. Lyon 2002) IAEA, Vienna

of many n are simultaneously excited leading to a so-called Alfvén Grand Cascade. Grand Cascades associated with integer rational surfaces have been correlated with ITB triggering events over a wide range of plasma conditions, $1.5 < I_p < 2.2$ MA, $2.45 < B_t < 3.4$ T, $3 < P_{total} < 17$ MW, indicating how they are also associated with q_{min} reaching a rational value [2]. Fig. 1 shows a fit of the above dispersion relation to the magnetic data demonstrating how it allows a precise determination of $q_{min}(t)$. The ability to perform this so-called MHD spectroscopy on an inter-shot timescale has made Alfvén cascades a very powerful and routine diagnostic during scenario development. Suitable timing of the main heating phase relative to the appearance of integer q surfaces allows a reduction in the access power required to enter the ITB regime. This information complements the equilibrium constraints provided by other MHD events such as fishbones, sawteeth and tearing modes.

High Performance ITBs

High performance plasmas possess, by definition, a large amount of free energy through which a variety of plasma instabilities can be driven and the performance degraded. One such example is the observation of a snake in #58371 at high current and field (B_t = 3.2T/I_p = 3.6 MA) which resulted in the destruction of the ITB. From Alfvén cascade data the q = 2 surface was observed to enter the plasma at 7.61s and at 8.22s a snake mode with characteristic multiple frequency harmonics is visible in the magnetic spectrogram. The mode is accompanied by a reduction in the stored plasma energy and a series of large ELMs that are visible on the D_α signal.

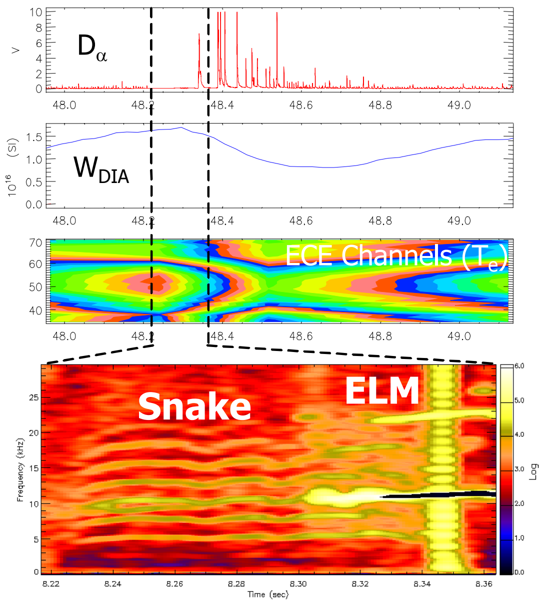

Figure 2: *Snake oscillation leading to ITB erosion and large ELM losses.*

Resistive Wall Modes and Disruptions

Pressure driven n = 1 kinks continue to limit high performance operation leading to disruptions as the plasma rapidly crosses the ideal 'with-wall' stability boundary [3]. As an example, magnetic and ECE data from a high performance ITB (#58094 with T_i = 25 keV, ∇T_i = 130 keV/m, β_N = 1.56 and $p_0/\langle p\rangle$ = 4,) shows that this pulse disrupts due to an n = 1 kink mode within ~50 ms of its onset [4]. However a slower approach to the stability limit can allow the development of Resistive Wall Modes (RWMs). These are expected to be the dominant obstacle to future high performance operation. They are modes that are stabilised by the presence of a conducting wall and grow on the timescale of the magnetic field penetration through the vessel wall. They are rarely observed on JET due to the narrow $\beta_{no\text{-}wall}$-β_{wall} window and a plasma rotational stabilisation effect described below. However, an example is shown in Fig. 3. This mode appears spontaneously with an oscillation frequency around 100 Hz and grows with two distinct growthrates. After an initial growth phase the mode grows exponentially at $\exp(t/\tau_{wall})$ until the mode couples to a zero frequency internal mode and then starts to behave like an ideal mode [5], growing at the faster rate of $\exp(t/\tau_{wall}^{1/2})$.

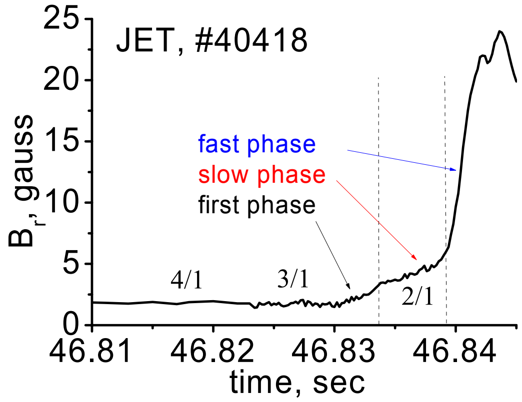

Figure 3: *Naturally unstable RWM*

In many cases on JET it is likely that the wall mode is stabilised by a weak coupling to the bulk plasma rotation such that the mode effectively sees an ideal wall. However, at high beta there is increased amplification of error fields in the plasma, as it naturally responds more readily to a driving perturbation. This leads to a slowing of the bulk plasma, reduced dissipation and wall stabilisation effects, enabling growth of the wall mode [6]. In a set of experiments at JET, DC square wave current pulses through the internal saddle coils were used to investigate the plasma response as a function of β. The results, an example of which is shown in Fig. 4, show a clear increase in the error field amplification factor with increasing β. This also indicates how error field amplification could be used to monitor the approach to the ideal β limit. The increased error field amplification on JET starts well below the no-wall ideal limit, a trend that is well matched by preliminary modelling using the MARS code [7].

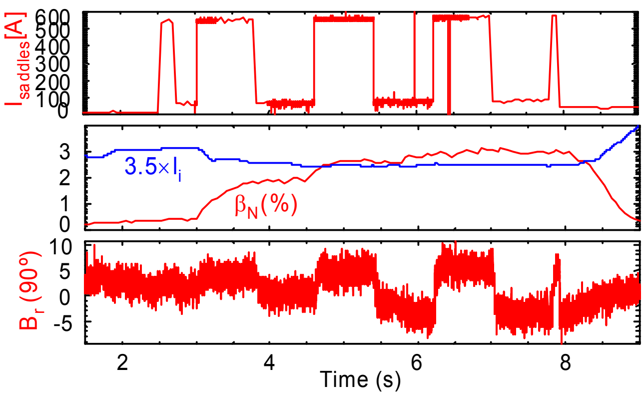

Figure 4: *#59223: Br measurement that sees no vacuum response clearly rises as β_N increases*

Hybrid Scenario

The improved H-mode identity and similarity experiments performed at JET and ASDEX Upgrade [8] exhibit no deleterious consequences from the presence of NTMs and fishbones, indeed the latter may even beneficially contribute to controlling the *q*-profile evolution. These discharges are characterised by a very flat safety factor profile with a central value around unity and a $q_{95} \sim 4$. The plasma β shows a large rise as heating power is increased, corresponding to an improved confinement over standard ELMy H-mode.

This 'hybrid' scenario shows much MHD activity in common with high performance ELMy H-mode operation, i.e. NTMs and fishbones as shown in Fig. 5. The activity is at a low level and does not greatly degrade the plasma confinement. From a consideration of their frequency evolution, the fishbones observed appear to be diamagnetic in nature and typically sweep down by 5-10 kHz (~ ω_{*i}) from their starting frequency of 15-20 kHz (~ $\omega_{rot} + \omega_{*i}$). The repetition period of the fishbones shows a wide variability between 5 and 30 ms with their onset indicating the presence of a $q = 1$ surface.

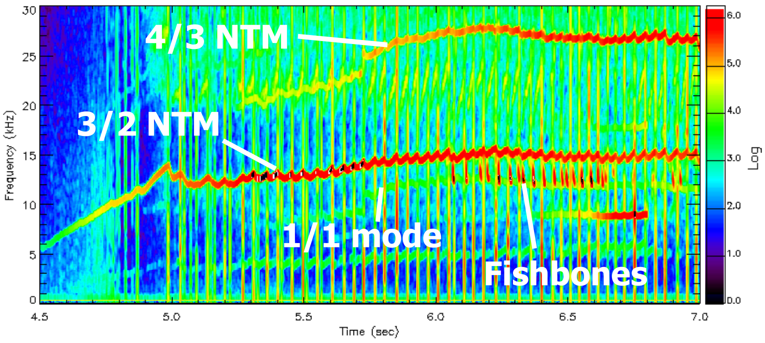

Figure 5: *Magnetic spectrogram showing NTM and fishbone activity in #57822*

At low field (B_t = 1.7 T) NTMs are nearly always present. They lack any obvious triggering mechanism since there are no sawteeth in these discharges and the fishbones typically don't commence until after NTM onset, indicating that seed events are not always required for NTM onset. The most prevalent mode is the 4/3 NTM, which suppresses the 3/2 NTM as it grows as shown in Fig. 6. For comparison, the single example where no 4/3 NTM is present is also shown where the 3/2 island grows to almost twice the size. A comparison of the 4/3 and 3/2 NTM frequencies shows that in this case the frequencies are consistent with a three-wave coupling mechanism, $f_{4/3} = f_{3/2} + f_{1/1}$. However, in some cases, the m/n = 1/1 is not present (due to a higher q_{min}), indicating that a three-wave interaction in not always required. In this case the 4/3 mode frequency locks to that of the 3/2 in the plasma reference frame, $f_{4/3} = 3/2 \times f_{3/2}$.

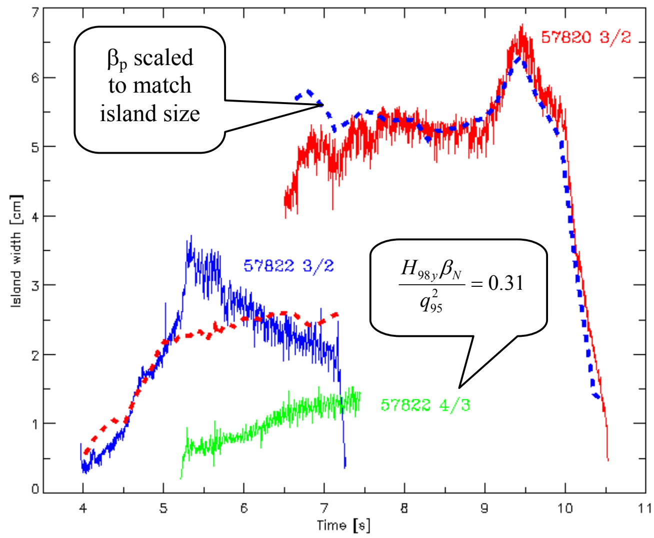

Figure 6: #57822: *3/2 NTM suppressed by 4/3; #57820: 3/2 NTM with no 4/3 present*

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