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Magnetic turbulence associated with confinement changes in JET

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Introduction: Depending on auxiliary power, magnetic configuration, and impurities, plasmas in Joint European Torus (JET) exhibit L-H or H-L transitions at the plasma edge [1] and formation of Internal Transport Barriers (ITB) in the plasma core [2]. Amplitude, frequency, and the characteristic wave-vector of electrostatic turbulence were investigated on JET in relation to transport theories by measuring density fluctuations with reflectometry [3]. Some transport theories, such as the "accretion" theory of spontaneous toroidal plasma rotation [4], or the theory of radiative impurity modes [5], predict also changes in *sign* of the phase velocity of prevalent turbulent modes, from the ion drift direction to electron drift direction. In order to identify the *sign*, phase shifts between signals measured at spatially separated points have to be determined. Toroidally separated Mirnov coils [6] measuring the *magnetic* component of the perturbations, dB_{POL}/dt, were used for the sign measurements on JET. This paper shows that the *phase* magnetic spectrograms exhibit a strong correlation between the types of the magnetic turbulence and confinement regimes in JET with NBI heating. This correlation shows a possibility for MHD spectroscopy similar to [6, 7], which could identify the confinement regimes from the measured magnetic turbulence spectrum

Experimental setup and typical magnetic spectrograms during H-L and L-H transitions: A high resolution array of toroidally separated Mirnov coils ($\varphi_1=2.94^0$, $\varphi_2=13.11^0$, $\varphi_3=18.74^0$) is used for measuring the phase shifts / direction of the wave propagation. Amplitudes down to $|\delta B/B_0| \approx 10^{-8}$ and toroidal mode numbers in the range $-20 < n < 20$ can be measured at a sampling rate 1 MHz [6]. Figure 1 shows schematically directions of magnetic field, current, NBI, ion and electron drift waves. Figure 2 shows a typical amplitude magnetic spectrogram measured with a single Mirnov coil. Figure 3 shows the colour-coded phase spectrogram derived from toroidally separated Mirnov coils. It is seen that the magnetic "noise" in Fig.2 is not white noise, but it consists of modes with well-determined toroidal mode numbers, which occupy a broad frequency range. The toroidal mode numbers are *negative*, $-12 < n < -2$, before 21 s, and become *positive*, $n \approx 1$, after 21 s.

As Figure 1 shows, negative *n*'s correspond to the phase velocity of the wave in counter-current (i.e. in electron drift) direction, while positive *n*'s correspond to the phase velocity of the wave in co-current (i.e. in ion drift) direction. This abrupt change in the *sign* of magnetic turbulence occurs at *the time of H-L transition*. The correctness of the phase spectrogram shown in Fig.3 obtained with Fourier transform is further confirmed by performing a wavelet analysis [8].

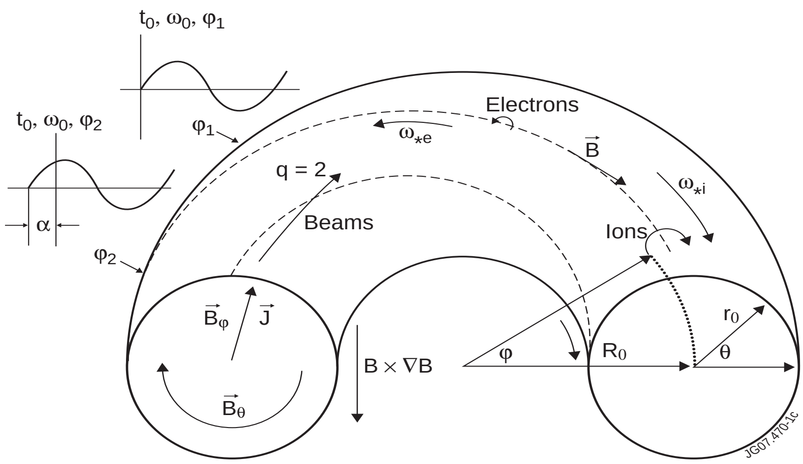
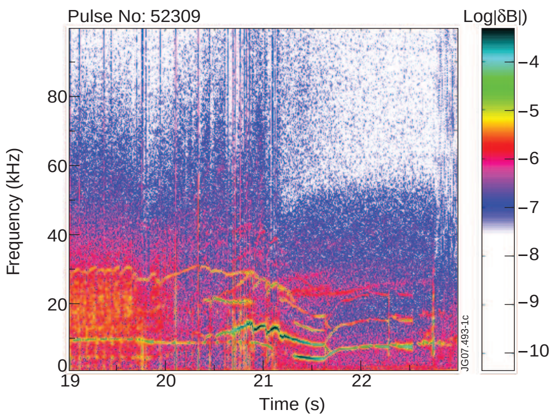


***Figure 1**. Sinusoidal signals measured at different toroidal angles, φ_1 and φ_2, at the same time and at same frequency are shifted in phase by α.*



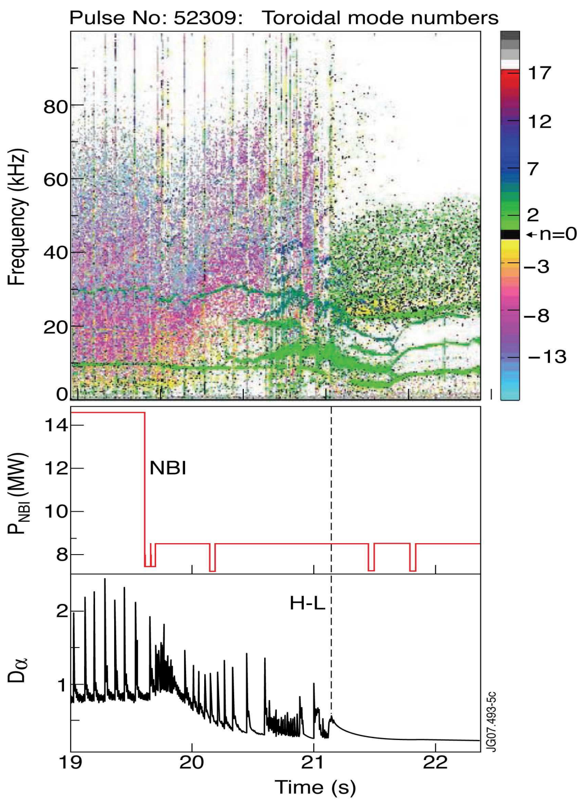
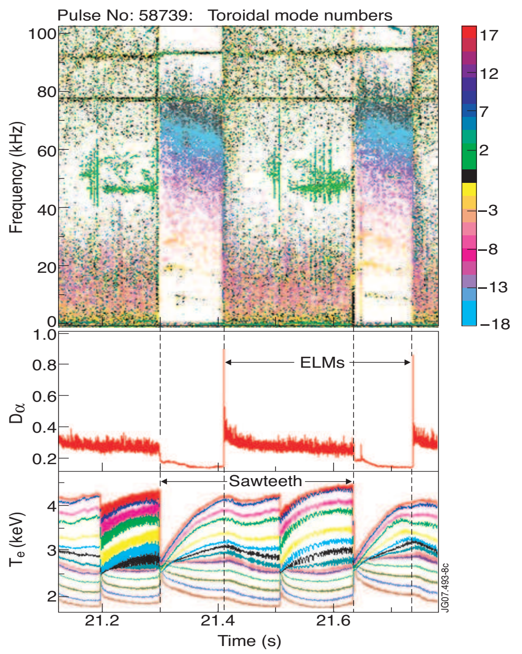


***Figure 2.** Magnetic spectrogram showing amplitude of magnetic perturbations. Magnetic noise of amplitude δB ~ 10^{-7}-10^{-6} T is seen up to 80 kHz. JET discharge #52309. B=2.7 T, I_P=2.5 MA.*

***Figure 3. (Right)** Top: Magnetic spectrogram showing phase of magnetic perturbations in the same case as Fig.2. Abrupt change of magnetic broad-band turbulence from n<0 to n>0 occurs at the H-L transition at ~21 s. Bottom: NBI power step-down waveform and D_α signal.*

Abrupt changes in the magnetic turbulence are also observed during transitions from type-III ELMy H-modes to type-I ELMy H-modes. Figure 4 shows that the signs of the propagation



of the prevalent turbulent modes remain negative (counter-current propagation corresponding to electron drift waves), but both toroidal mode numbers and frequency bands of the magnetic turbulence change from $n \approx -10$, $0 < f[kHz] < 30$, to $n \approx -15$, $50 < f[kHz] < 80$.

Figure 4. ***(Left)*** *Top: abrupt changes in toroidal mode numbers of the magnetic turbulence seen in JET with transitions from type-I ELMy H-modes to to type-III ELMy H-modes. Bottom: The changes correlate with sawteeth triggering transitions to type-I ELMy H modes, while back transitions correlate with type-I ELMs.*

Magnetic turbulence during ITB formation: ITB formation is found to associate with a sudden build-up of magnetic turbulence with positive n (co-current propagating modes corresponding to the ion drift direction).

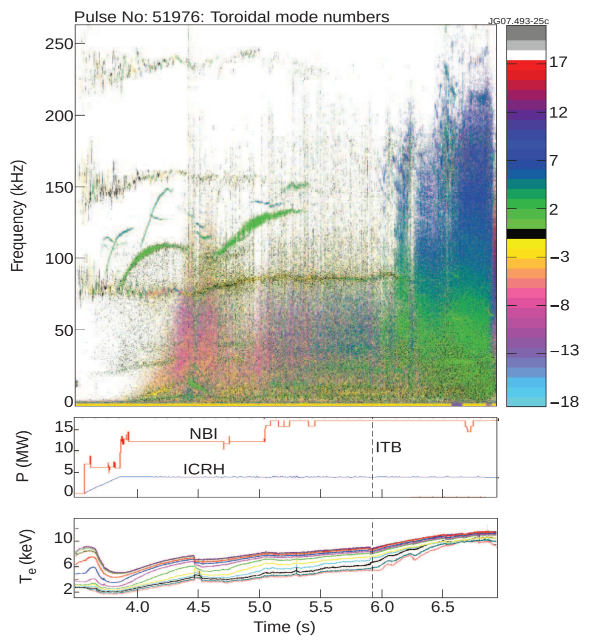


Figure 5*. Top: Phase spectrogram showing a build-up of n>0, n=1-10, magnetic turbulence in a broad-band frequency range, up to 250 kHz, at 6 s when ITB is triggered. Bottom: NBI and ICRH power waveforms and T_e from multi-channel ECE in JET #51976. B=3.45 T, I_P=2.5 MA.*

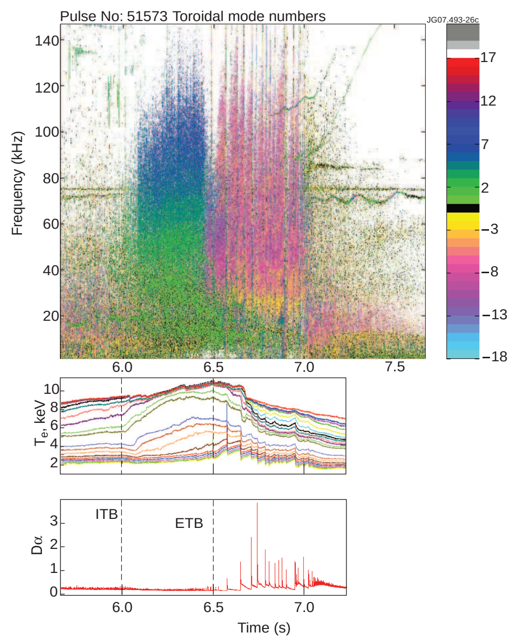


Figure 6. *Top: Phase spectrogram showing a build-up of n>0, n=1-10, turbulence at 6 s when ITB is triggered. The sign of turbulence changes to n < 0 at 6.5 s when ETB forms and transition to H-mode occurs. Bottom: T_e and D_α signal in JET #51573. B=2.6 T, I_P=2.2 MA.*

Figure 5 shows how the turbulence with n = 1 - 10 builds up at the time of ITB formation at 5.8 s, and how it occupies the frequency range up to 200 kHz - 250 kHz in about 100 msec. In discharges with ITB formation, followed by an external transport barrier (ETB) causing transition to type-I ELMy H-mode, co-current magnetic turbulence with $n > 0$ builds up first, and it changes sign of the wave propagation to $n < 0$ at the *time of ETB formation.* Figure 6 shows an example of such case, in which an ITB formed at 6 s is associated with a build-up of $n > 0$ turbulence in the frequency range up to 140 kHz, while the formation of ETB at 6.5 s is associated with $n < 0$ magnetic turbulence in the same frequency range.

Conclusions: *Phase* spectrograms of magnetic perturbations measured with Mirnov coils show a very good correlation between the measured n of the waves and transport transitions in JET plasmas with NBI heating. L-H transitions are found to associate with change in the sign of the phase velocity of prevalent turbulent modes: in L-mode the modes have co-current, n>0, propagation in ion drift direction, while in H-mode the modes have counter-current, n<0, propagation in electron drift direction. This directivity was predicted in [4]. Within H-mode, transitions from type-I ELMs to type-III ELMs shown in Figure 4 are associated with abrupt changes in the prevalent mode numbers: type-I ELMy H-mode has higher-n counter-current, n<0, prevalent modes, while type-III ELMy H-mode has lower mode numbers. ITB formation is found to be associated with a sudden build-up of n>0 magnetic turbulence. Taking into account that this build-up of the magnetic turbulence coincides in time with a suppression of electrostatic turbulence [3], this may indicate that ITB formation is associated with energy transformation from $\varphi \rightarrow A_{||}$ (from electrostatic to electromagnetic) rather than with an overall wave energy decrease. In summary, we underline that the observed correlation between magnetic turbulence and transport properties of the plasma can reliably be used for MHD spectroscopy of the confinement regimes.

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