Abrupt Changes in Magnetic Turbulence during L-H Transitions and ITB Formations on JET

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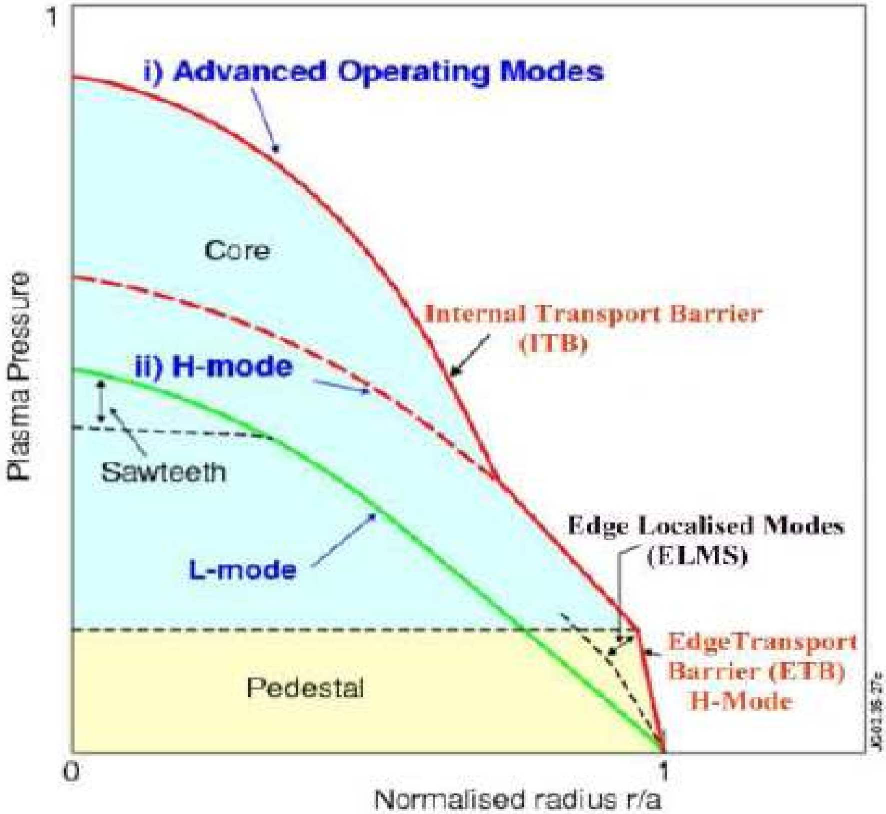
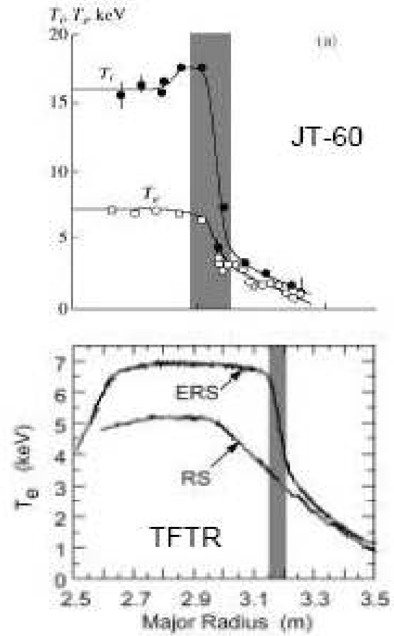
Outline

- Transport barriers and improved plasma confinement. Radiative impurity mode. Why *sign* of phase velocity of the prevalent turbulent modes is important
- Determining the sign from phase shift of waves measured with toroidally separated magnetic probes on JET
- Magnetic turbulence in RI mode
- Abrupt changes of the magnetic turbulence sign during L-H transitions and during transitions from type III ELMs to type I ELMs
- Magnetic turbulence during ITB formation
- Magnetic versus electrostatic turbulence in ITB discharges
- Summary

Introduction: Transport Barriers in Plasma

Enhanced Confinement and Transport Barriers



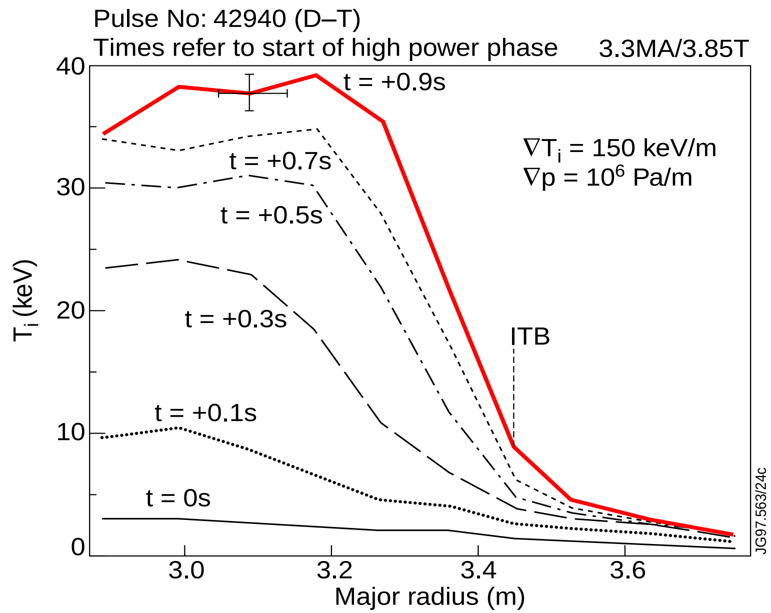


Example of sharp ITBs from 2 large tokamaks

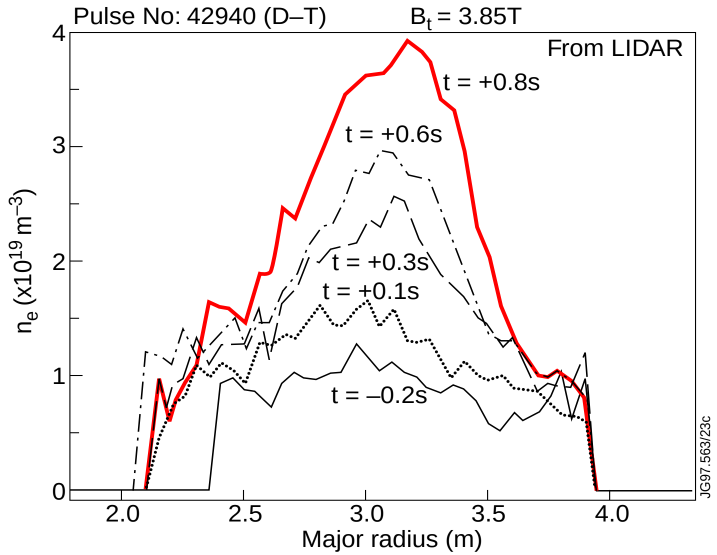
JT-60 *Tobita et al*; TFTR *Bell et al*

Introduction: Transport Barriers in Plasma

- **Example of Deuterium-Tritium ITB plasma**



Ion temperature profile in JET discharge with ITB



Plasma density profile in JET discharge with ITB

C.Gormezano et al., Phys. Rev. Lett. 80, 5544 (1998)

"New" Radiative Impurity (RI) improved confinement mode (2000)

- **RI improved confinement mode was experimentally observed in experiments with Ar and Ne puff on TEXTOR and DIII-D machines**

- **This was explained in [Tokar et al., PRL 84 (2000) 895] as the suppression of Ion Temperature Gradient (ITG) turbulence due to the increase in Z_{eff}**

- **In the absence of ITG, the only remaining drift turbulence was dissipative trapped electron turbulence**

↓

- ***Change in the sign* of the wave propagation from ω_{*i} (ITG) to ω_{*e} (dissipative trapped electron) was expected in the *radiative impurity (RI) mode***

- **We were asked to investigate the sign of the turbulence on JET**

Starting point in our study: measuring *the sign* of the prevalent turbulent mode

- **The RI-mode theory considered *electrostatic* modes.**
- ***Amplitude, frequency range, and characteristic wave-vector* of electrostatic modes were investigated well on many machines by measuring *density fluctuations* with, e.g. X-mode reflectometry on JET [G.D. Conway et al., Phys. Rev. Lett. 84 (2000) 1463]**
- **For measuring the *sign* of phase velocity of electrostatic modes, toroidally separated channels of reflectometry are required – *not available on JET*.**
- **However, *the sign* of waves with *perturbed magnetic field* can be identified reliably from the *phase shifts* of the same waves detected with toroidally-separated Mirnov coils (measuring $d(\delta B_{POL})/dt$)**

MAGNETIC DIAGNOSICS ON JET

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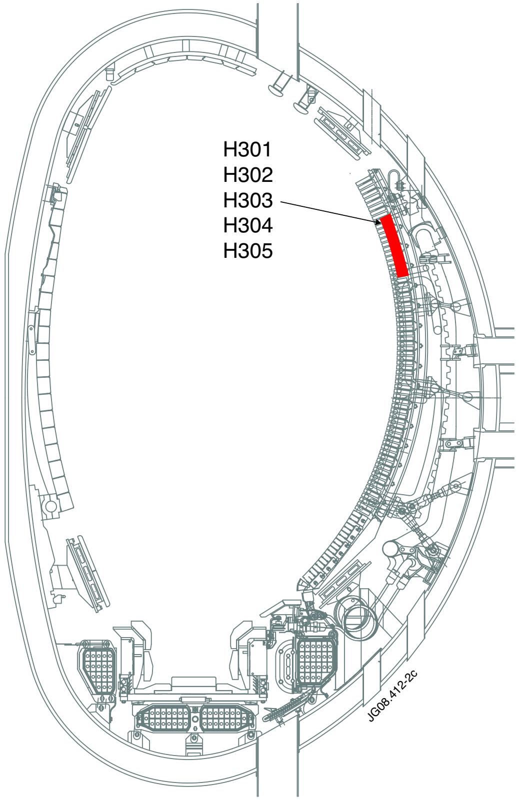
MIRNOV COILS



JET cross-section showing the position and directivity of five Mirnov coils separated in toroidal angle

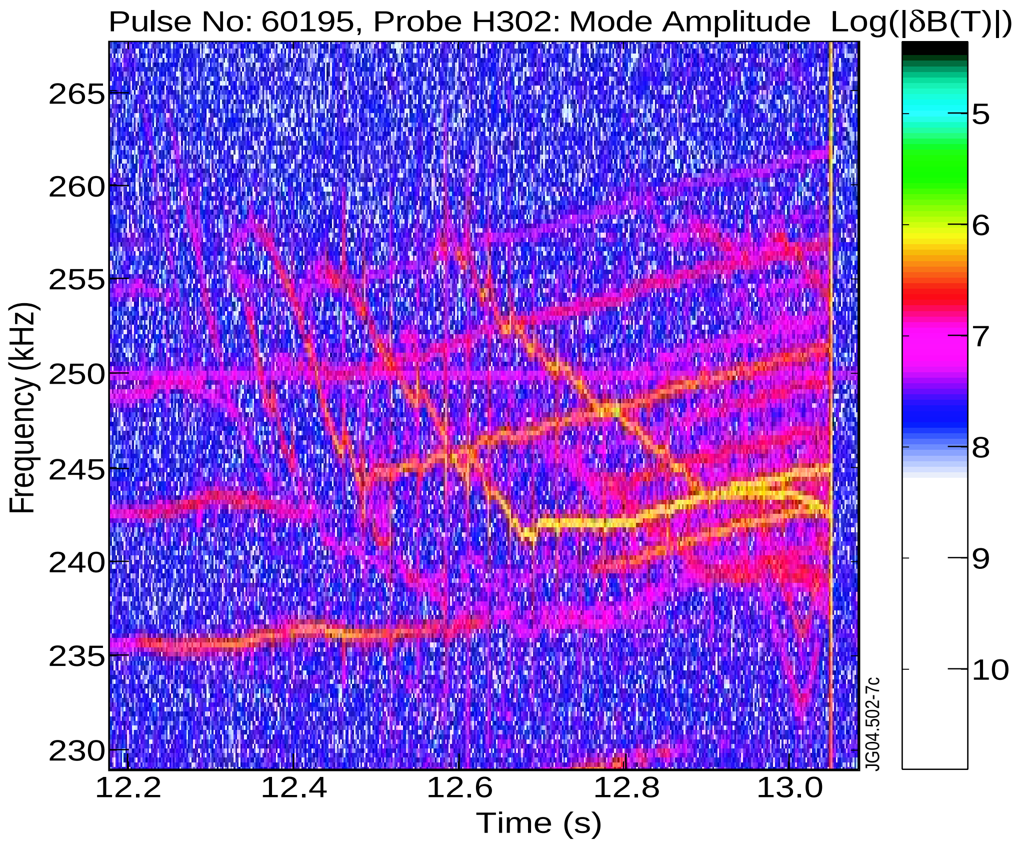
- Mirnov coils for measuring magnetic flux due to δB_{ϑ} are best performing on JET
- The coils measure

$$\frac{\partial}{\partial t}\delta B_{\vartheta}^{edge} \cong \omega \cdot \delta B_{\vartheta}^{edge}$$

and are VERY sensitive! Thanks to high values of $\omega \cong 10^{6}\ \sec^{-1}$ perturbed fields $\left|\delta B_{\vartheta}^{edge} / B_0\right| \cong 10^{-8}$ are measured

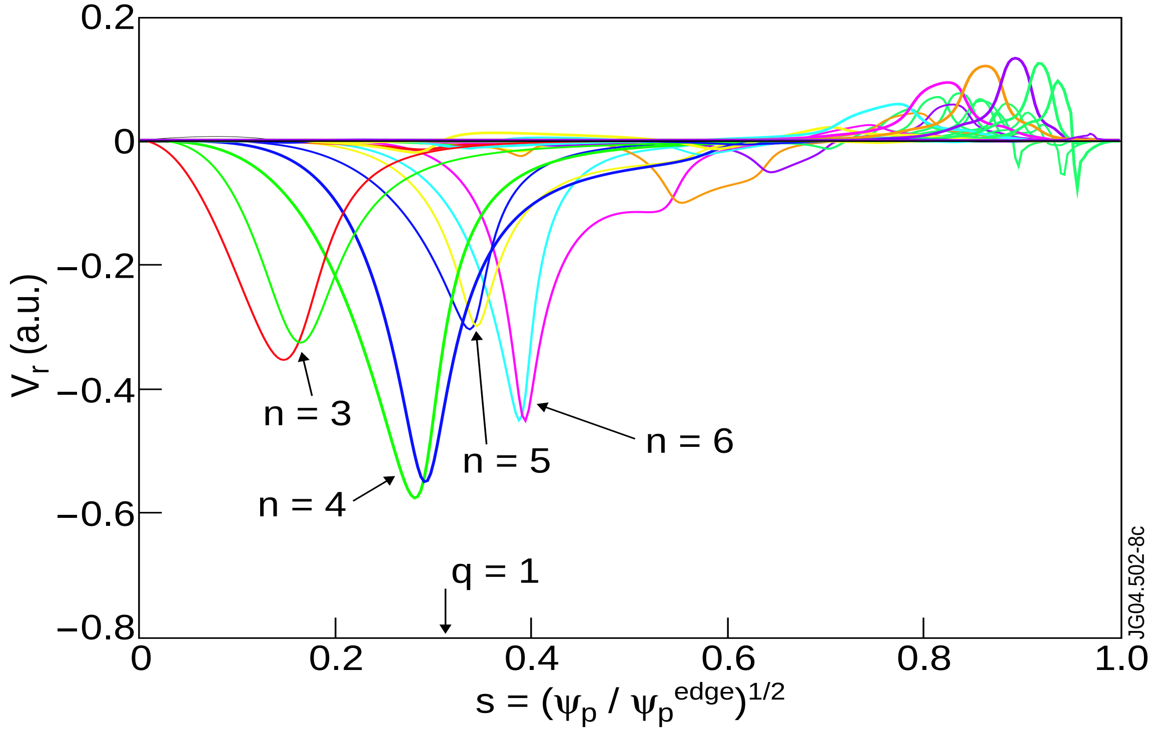
- Sampling rate 1 MHz allows measurements of AE up to 500 kHz to be made
- The coils are well calibrated, i.e. give the same amplitude and phase response to the same test signal

CAN MIRNOV COILS SEE MODES IN THE PASMA CORE?



TAE-modes inside the q=1radius on JET

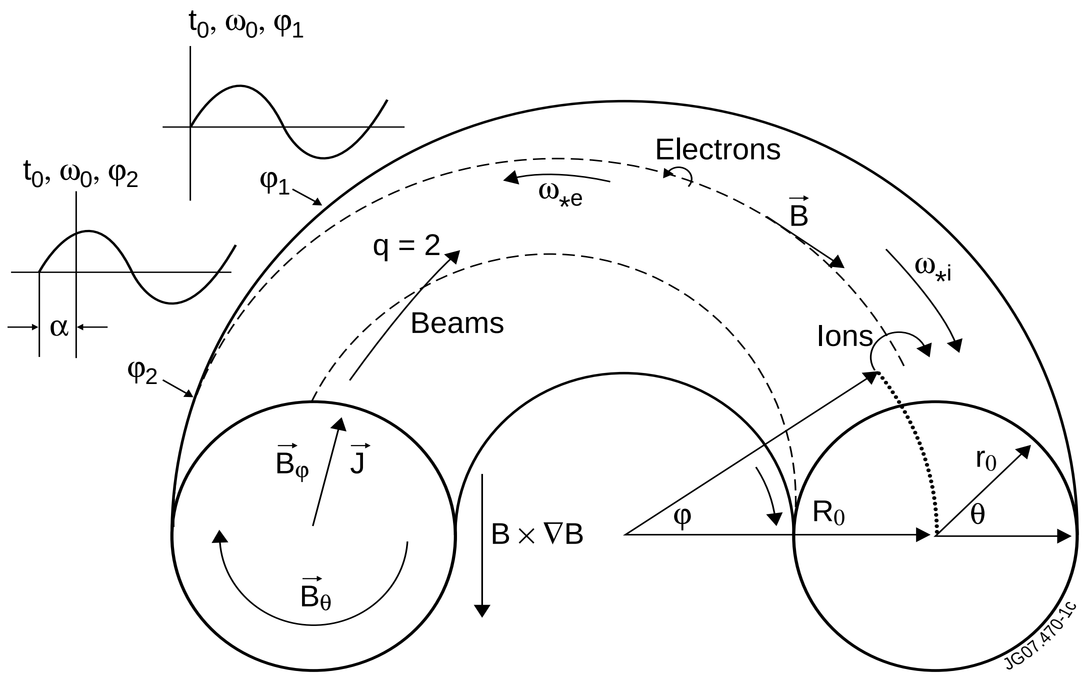
MODELLING CORE-LOCALISED TAE



TAEs with n=3, 4 within the q=1 radius (tornado), and n=5,6 TAEs outside the q=1 radius

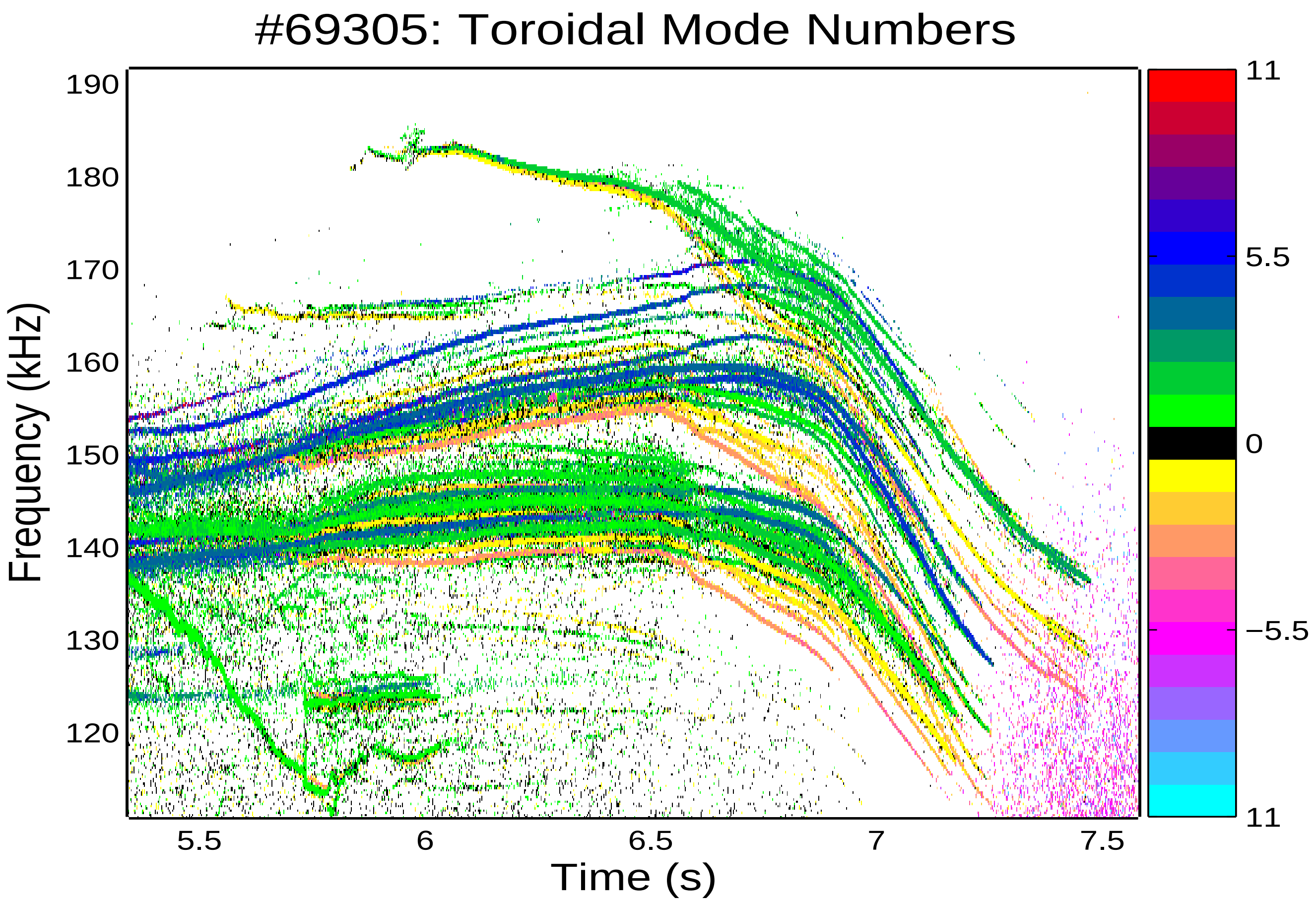
MIRNOV COILS – FOURIER TRANSFORMED *PHASE* DATA

- **For determining toroidal mode number of the mode, phase shift is measured between two (or more) Mirnov coils at different toroidal angles**



Sinusoidal signals measured at different toroidal angles at the same time and at same frequency are shifted in phase by α.

Example of TAEs with both n>0 and n<0



Change in sign of prevalent magnetic modes

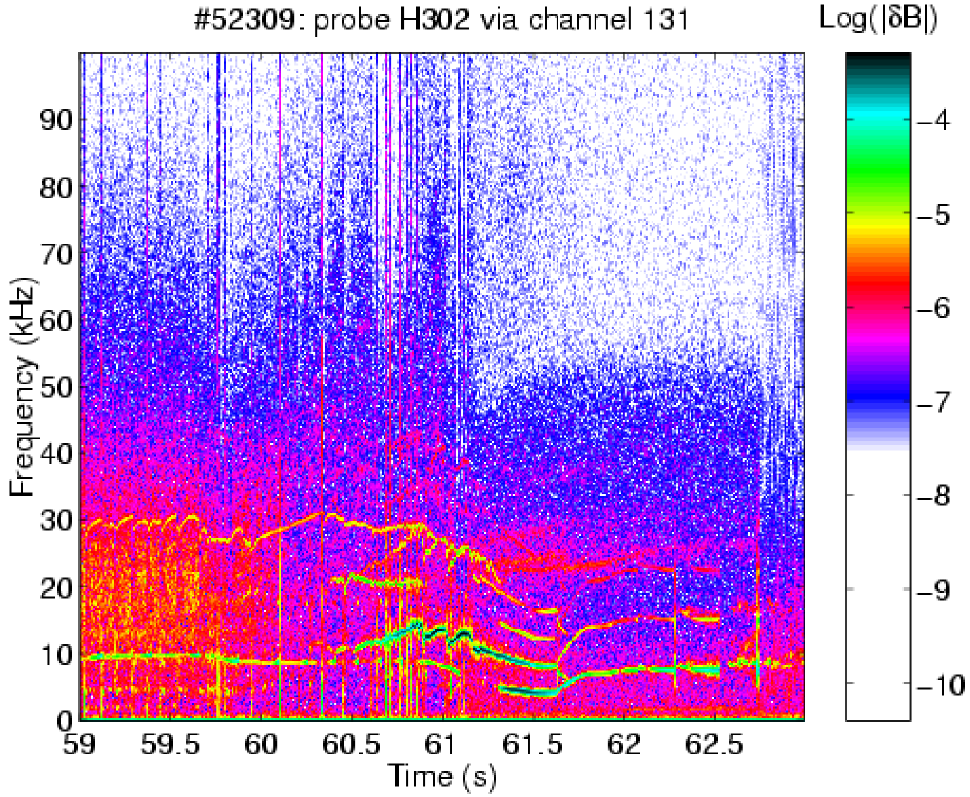
- **Co-current, toroidal mode numbers n>0, propagation corresponds to ω_{*i} direction**

- **Counter-current, n<0, propagation corresponds to ω_{*e} direction**

- **The phase shift technique was used extensively and reliably for identifying toroidal mode numbers of regular MHD modes, such as TAE, Alfvén cascades, NTM, sawtooth and ELM pre- and post-cursors**

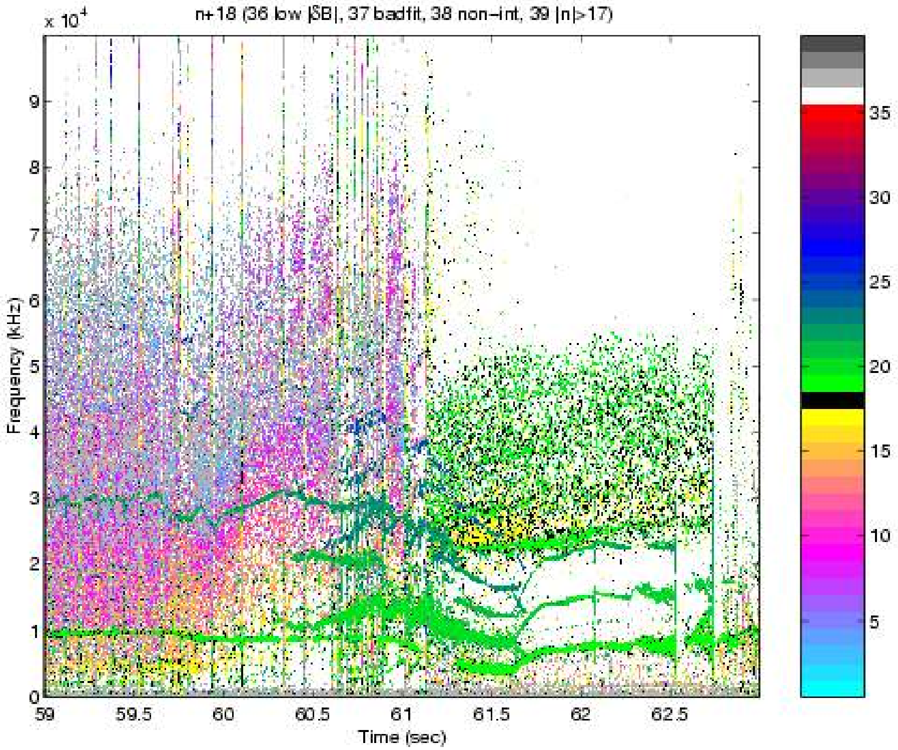
- **Let us look at *broad-band magnetic noise* now**

Magnetic coil data



- ***Single*** **Mirnov coil provides info on** ***amplitude and frequency*** **of MHD modes and broad-band, up to 80 kHz, magnetic turbulence**

Change in sign of prevalent magnetic turbulence



- **Magnetic spectrogram showing phase shifts for modes measured by toroidally separated probes. A change from counter-current, n<0 (pink-blue), n=-2 to -12, to co-current, n>0 (green), n=1 to 2, magnetic turbulence is seen.**

Magnetic turbulence in RI mode discharges

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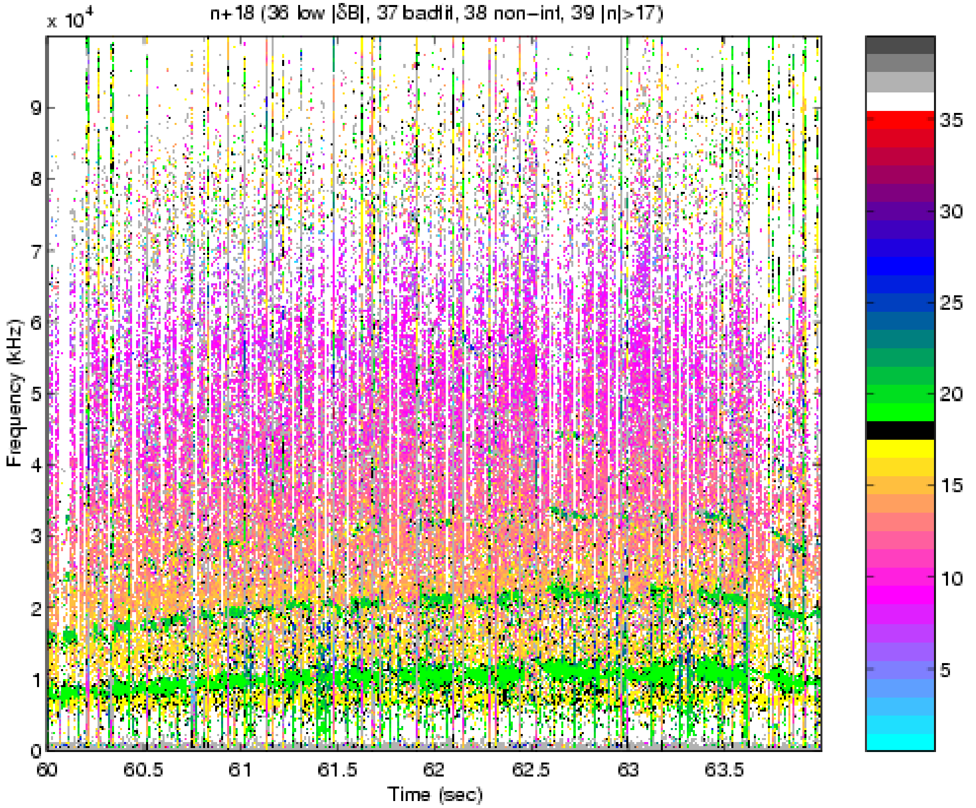
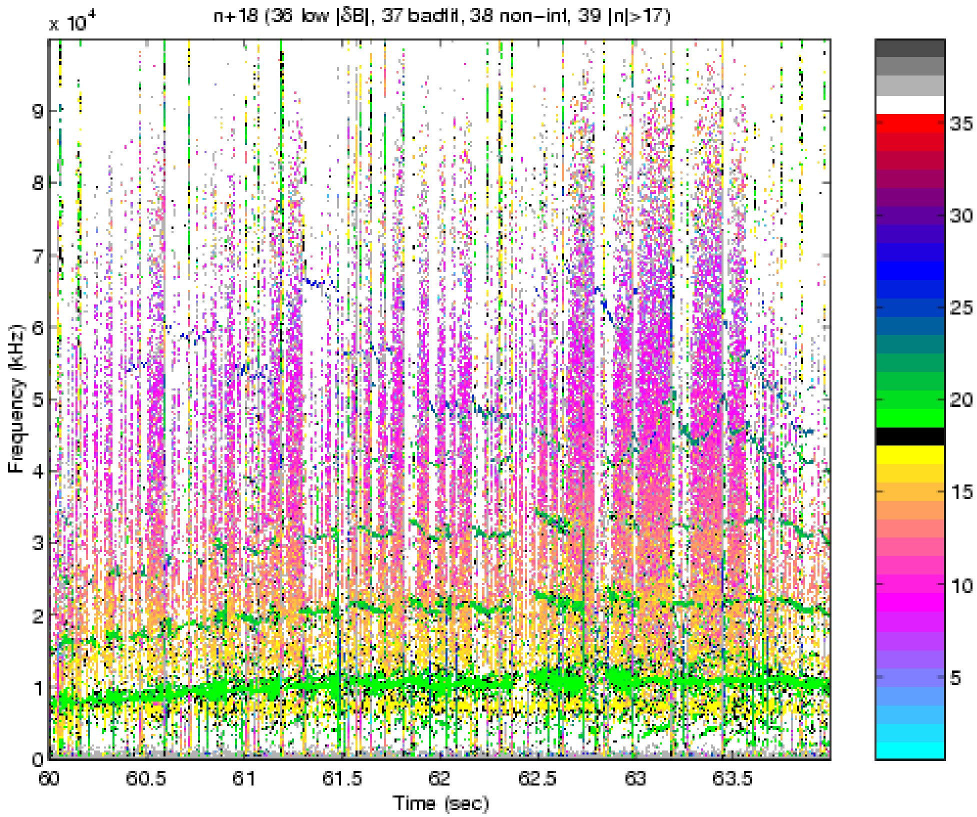
Reference discharge: D_2 gas puff only, H-mode, #50475



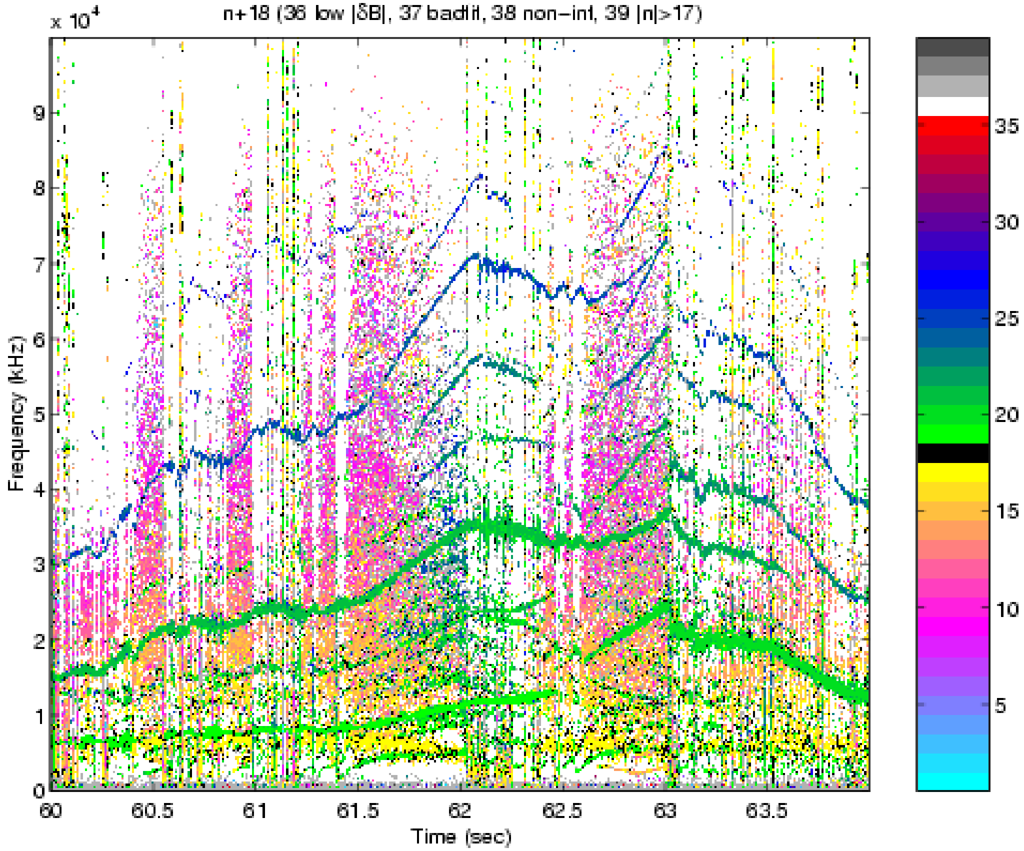
- **Magnetic turbulence propagating *counter-current* and peaked at n=-8 is observed**

Ne puff, H-mode, #50474



- **Some noise-free time intervals appear after ELMs**

Ar puff only, H-mode, #50475



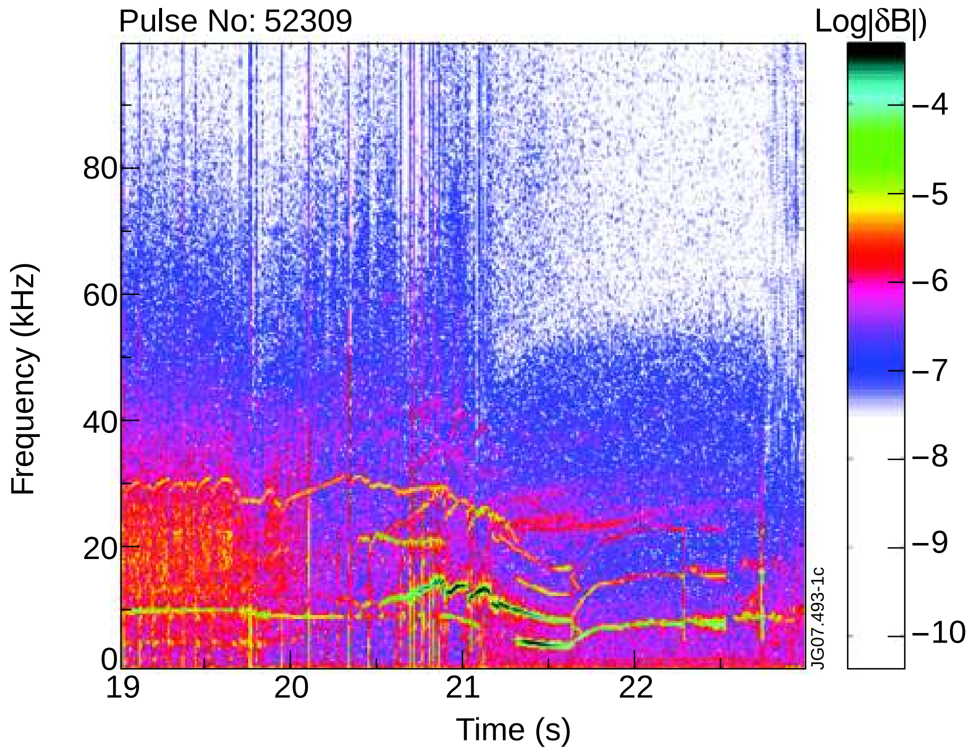
- **Longer noise-free time intervals appear after ELMs**

SUMMARY FOR RI IMPROVED CONFIEMENT REGIMES

- No change in the sign of magnetic turbulence was observed
- Turbulence-free time windows were found to increase significantly with the change from D to Ne to Ar gas puffs
- Possible explanation of the RI improved confinement may be associated with a lower time-integrated level of turbulence rather than with the change in the turbulence sign

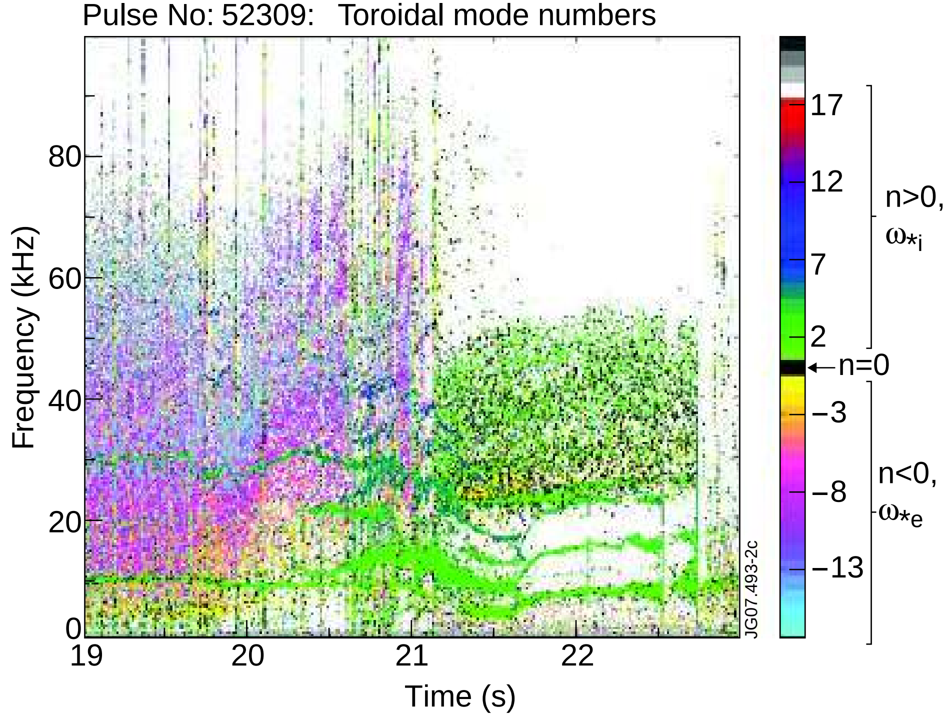
DO WE EVER SEE CHANGE OF THE SIGN IN THE MAGNETIC TURBULENCE?

Amplitude magnetic spectrogram



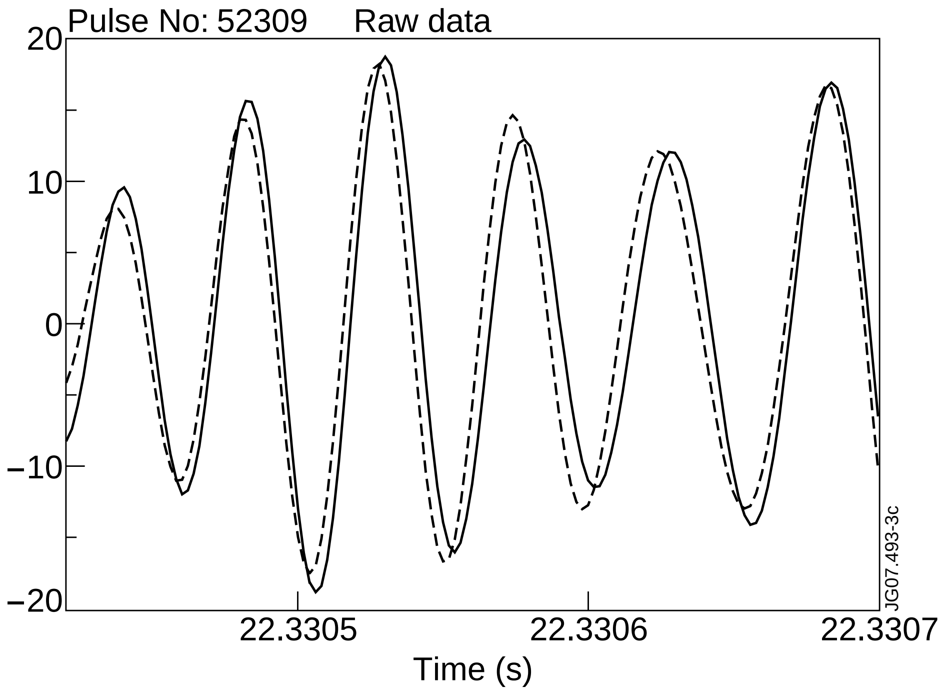
- *Single* Mirnov coil provides info on *amplitude and frequency* of MHD modes and broad-band, up to 80 kHz, magnetic noise

Phase magnetic spectrogram showing toroidal mode number n



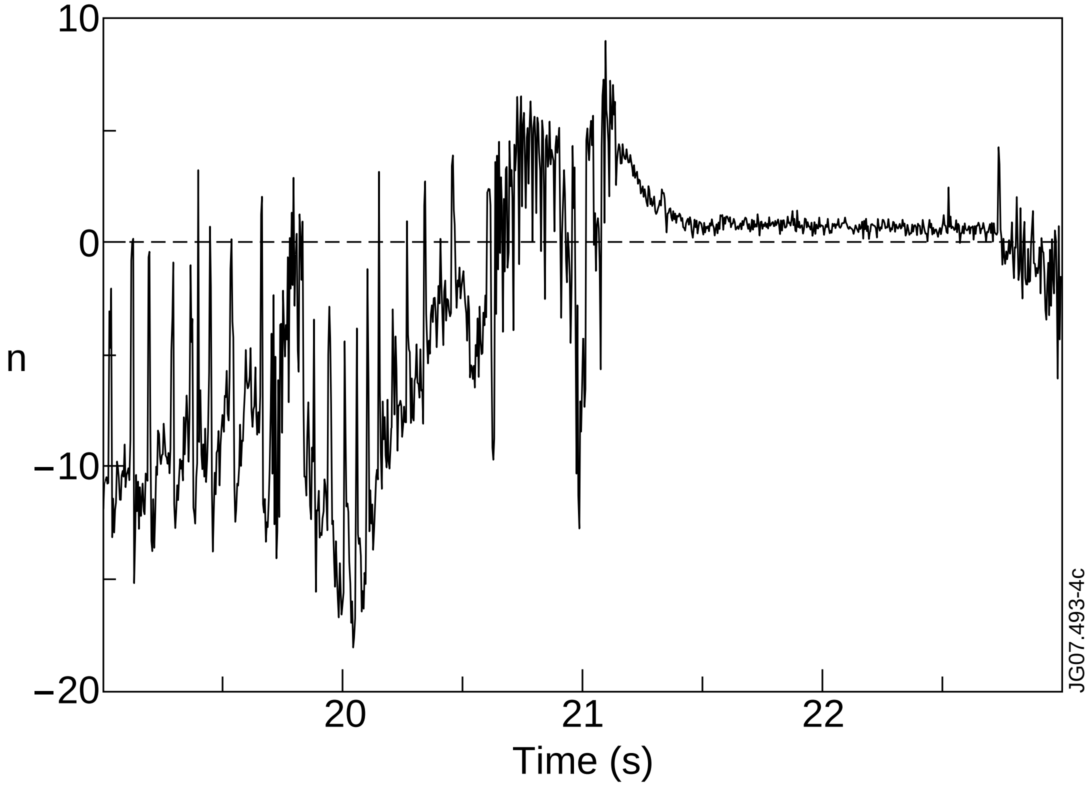
- **Phase spectrogram showing phase shifts of the modes between toroidally separated probes. An abrupt change from counter-current, n<0 (pink-blue), n=-2 to -12, to co-current, n>0 (green), n=1 to 2, magnetic turbulence is seen at t ≈ 21 s. The n>0 turbulence ends at t ≈ 22.75 s.**

Change in sign of prevalent magnetic modes of the magnetic turbulence: raw data at 40 kHz



- Mirnov coils H303 ($\varphi_2 = 13.11^0$) – solid and H304 ($\varphi_3 = 18.74^0$) – broken. This phase shift means ion drift direction of the wave propagation and n=1.

Change in sign of prevalent magnetic modes:
More sophisticated wavelet analysis consistent with Fourier



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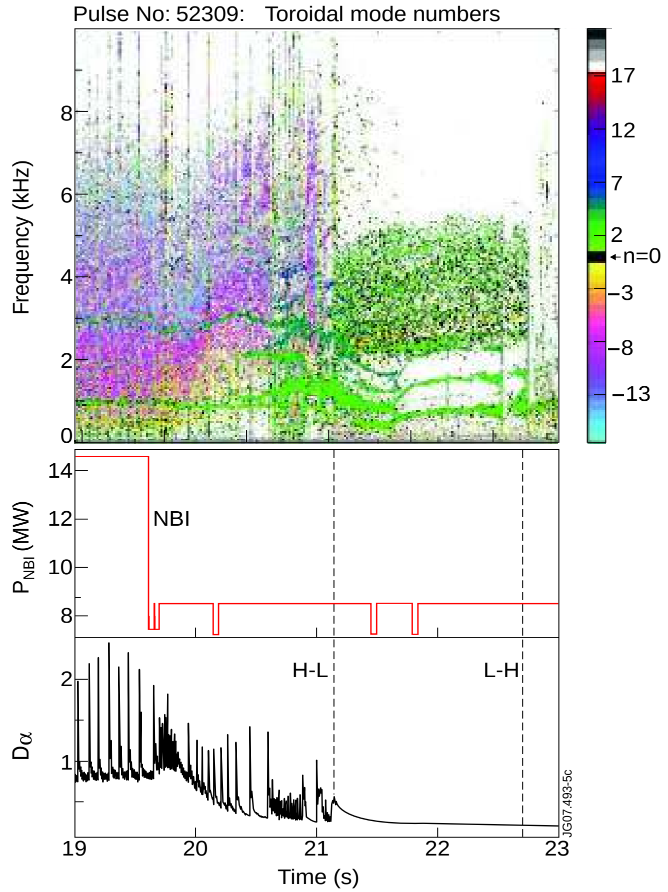
The abrupt change in *sign* correlates in time with H-L transition !



← Phase spectrogram of magnetic perturbations showing abrupt change of magnetic broad-band turbulence from n<0, n=-2 to -12 to n>0, n=1 to 2, at the H-L transition at ~21 s.

← NBI power step-down waveform (top) and D_α signal (bottom). JET #52309. B=2.7 T, I_P=2.5 MA. H-L transition occurs at ~21 s.

The change in sign correlates in time with H-L transition

- In addition to the abrupt change in the sign from n<0 to n>0 the other changes are:
- The width of n-spectrum also changes abruptly from n = -2 to n=-12 with average n= -7 to a single-n broadband spectrum, n=1 only
- The frequency range drops from 80 kHz to 50 kHz
- The change in toroidal mode number cannot be explained by any plasma rotation
- Did anyone predict a change of the turbulence from ion-drift to electron-drift during L-H transitions?

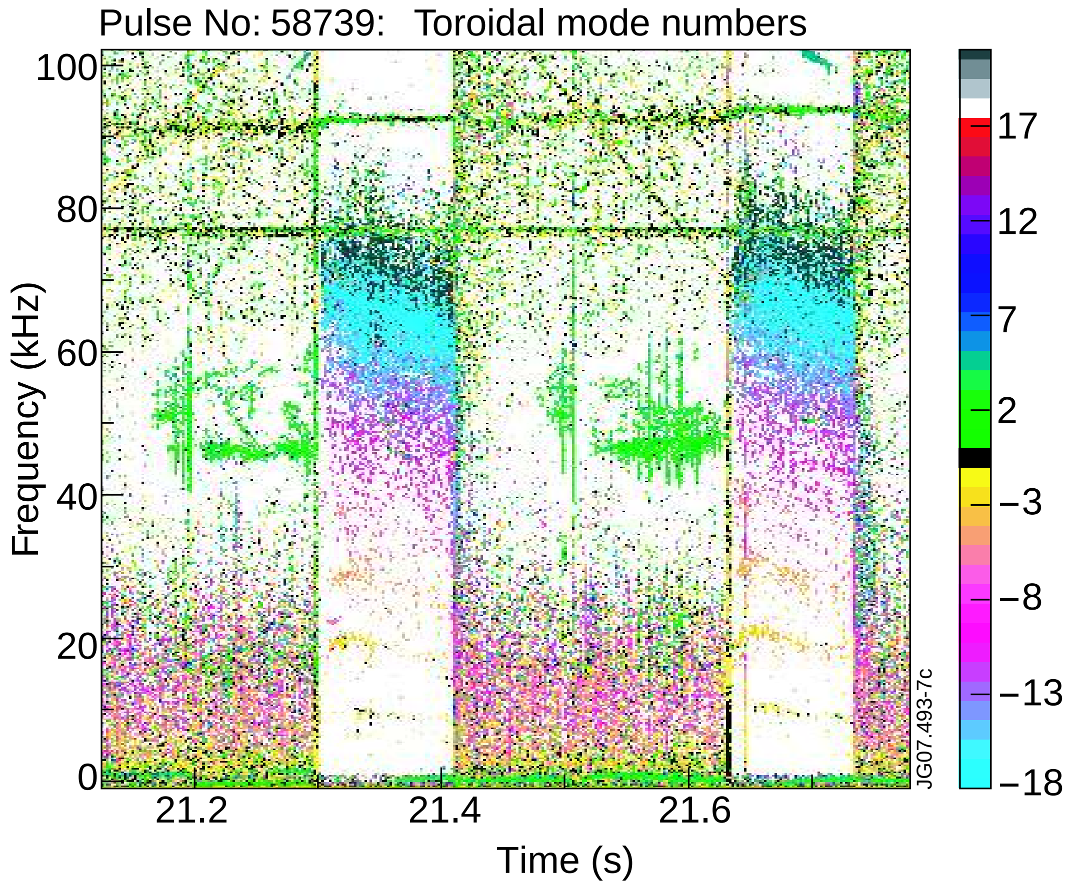
COPPI's THEORY FOR SPONTANEOUS PLASMA ROTATION

- **Alcator C-MOD ICRF heated plasmas have shown a significant "spontaneous" toroidal rotation, sign of which changes *during L-H transition* [J.E. Rice et al., Nucl. Fusion 39 (1999) 1175]**

- **Accretion theory of "spontaneous" toroidal rotation explained experiments above [B.Coppi, Nucl. Fusion 42 (2002) 1] suggesting that edge fluctuations of plasma *scatter particles in the direction of the phase velocity* of the prevalent modes, thus transferring angular momentum in the phase velocity direction to the wall, and *accelerating plasma in opposite direction*.**

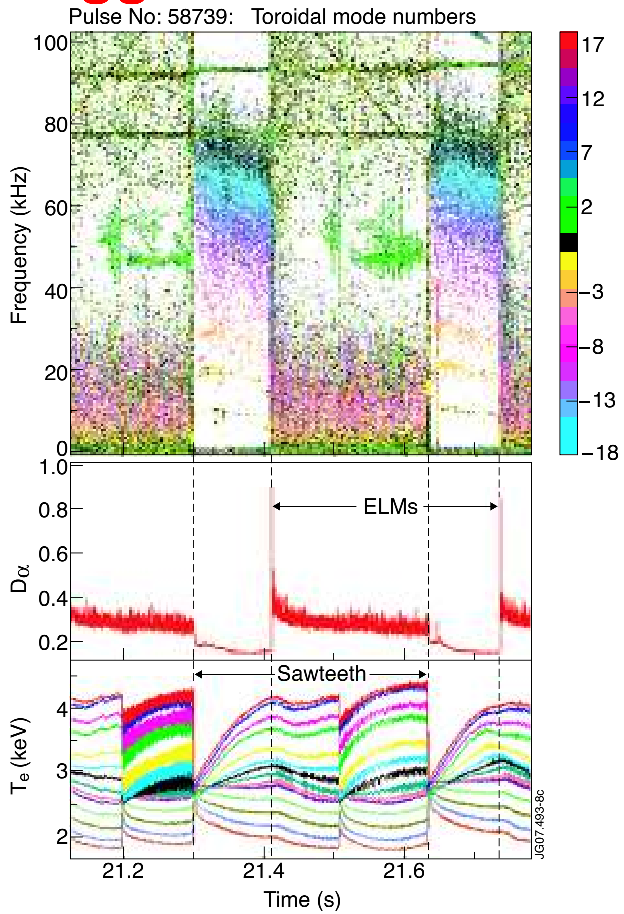
- ***Change in sign of phase velocity* of the prevalent mode from co-current (n>0, or ω_{*i} direction) to counter-current (n<0, or ω_{*e} – direction) *during L-H transition* predicted by B.Coppi resulting from dn/dr – suppression of ITG when density pedestal is formed in H-mode**

Abrupt changes during transitions from III type ELM to I type ELM

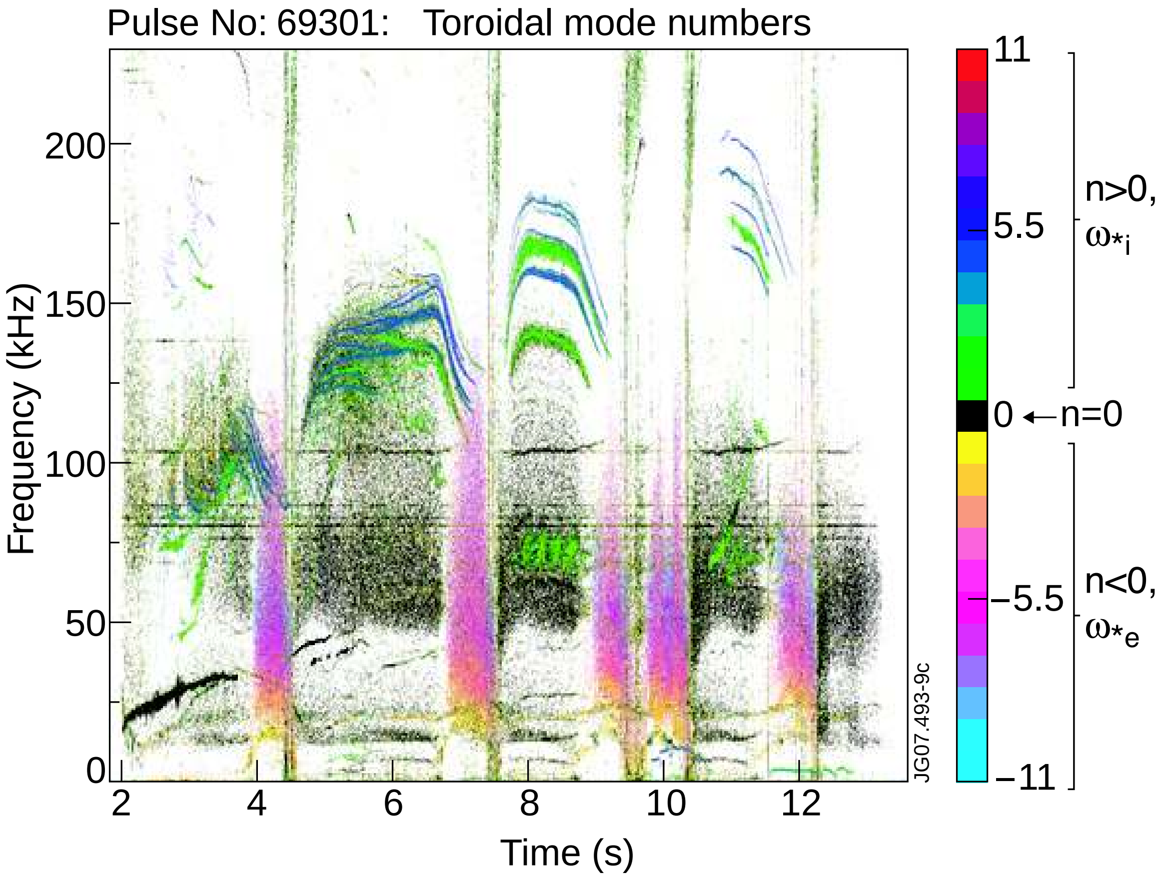


- **In this case, dominant toroidal mode number changes from n = -10 to n= -18**

Sawtooth/ ELM triggered III ELM → I ELM transitions

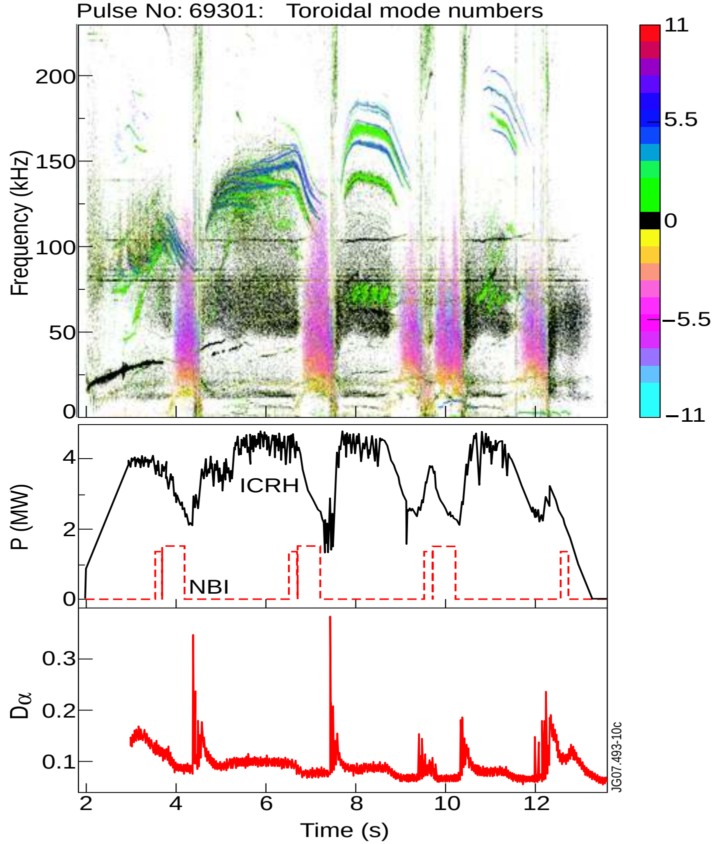


Other example of transitions to ELM-I H-modes: off-axis ICRH+NBI



- **Transitions from n<0, n=-1 to -8 (yellow-pink) to n=0 (black) broad-band noise**

Other example of transitions to ELM-I H-modes: off-axis ICRH+NBI



- **The changes in magnetic turbulence correlate with confinement transitions to H-mode with I-type ELMs triggered by low-power NBI blips**

Magnetic turbulence in ITB discharges

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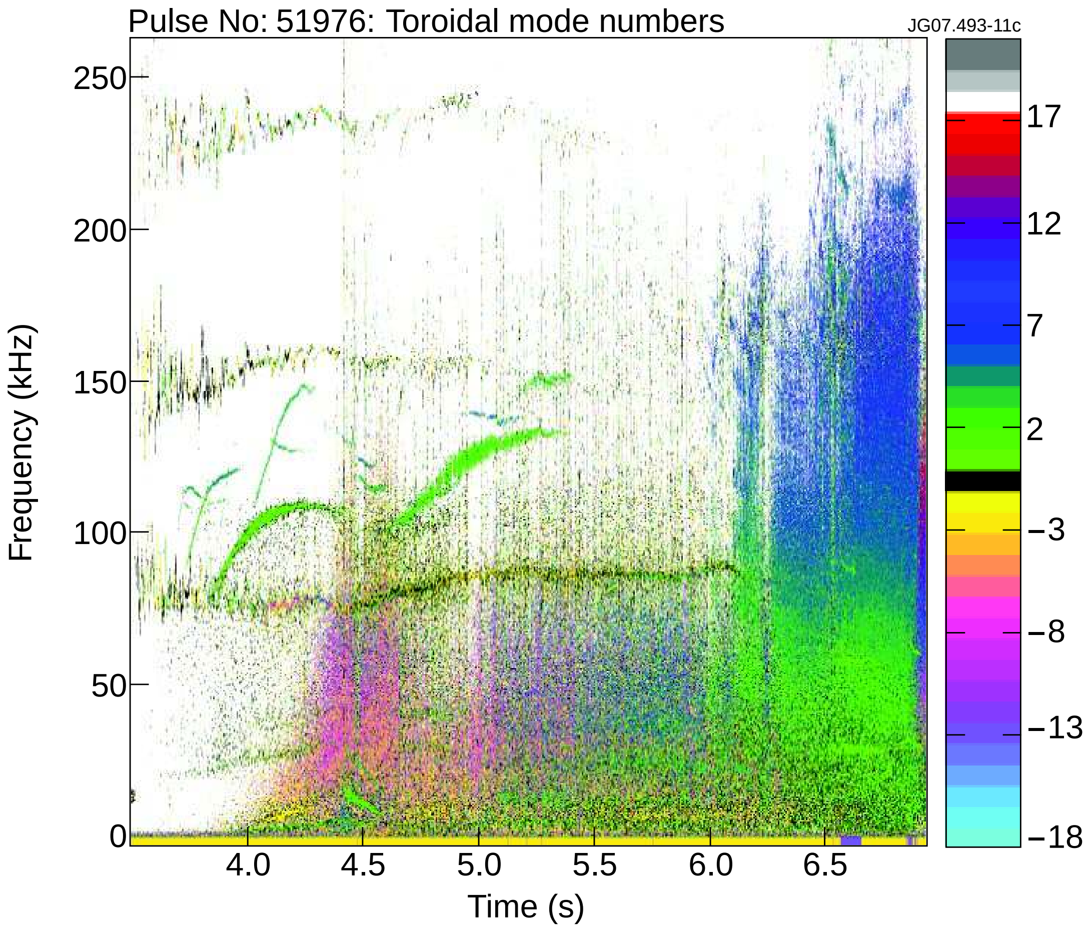
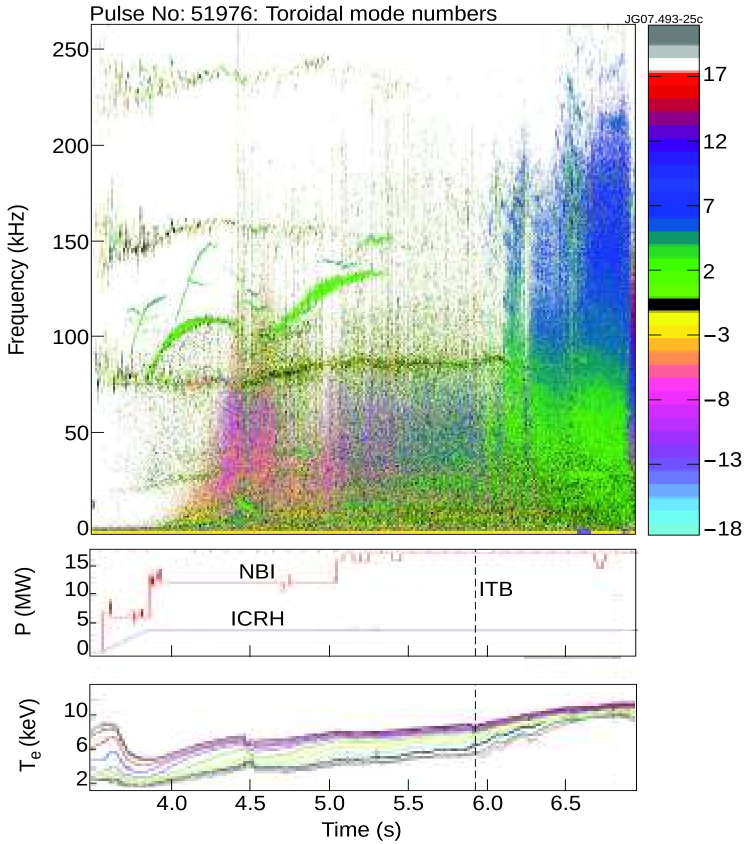
Magnetic turbulence builds up to 250 kHz around 6.0 s- why?



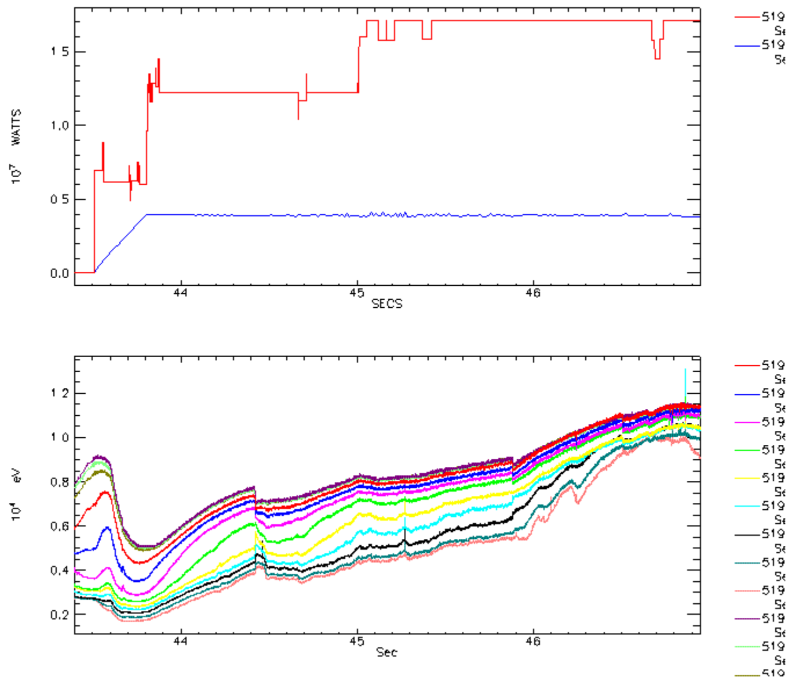
This time corresponds to ITB formation!



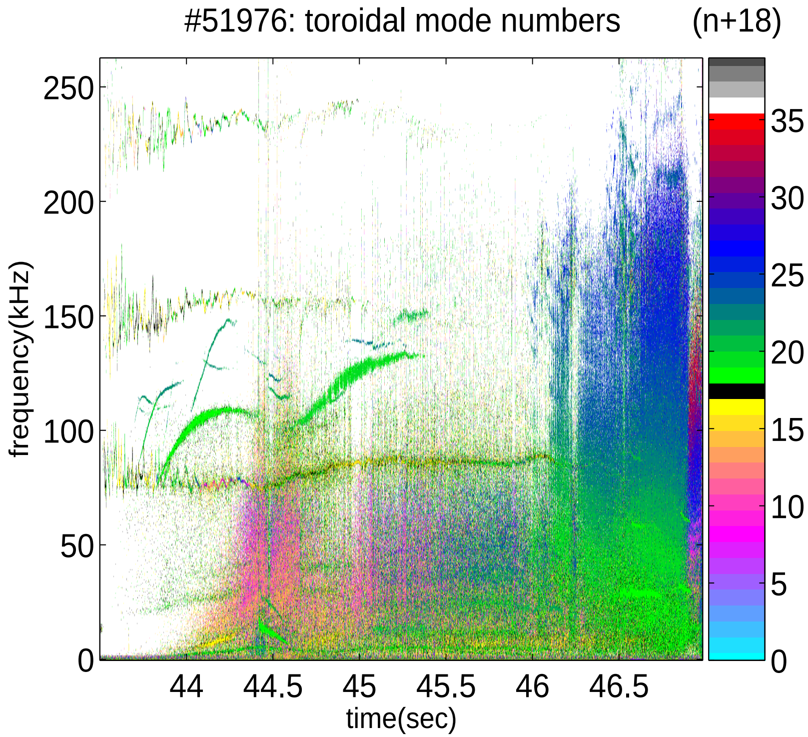
← Phase spectrogram of magnetic perturbations shows a build-up of n>0, n=1-10 broad-band magnetic turbulence at ≈ 6 s when ITB is formed

← NBI and ICRH (top) and T_e measured with multi-channel ECE (bottom) in JET #51976. B=3.4 T, I_P=2.2 MA, ITB is formed at ≈ 6 s as T_e traces show .

Co-current, n>0, magnetic noise arises during ITB formation

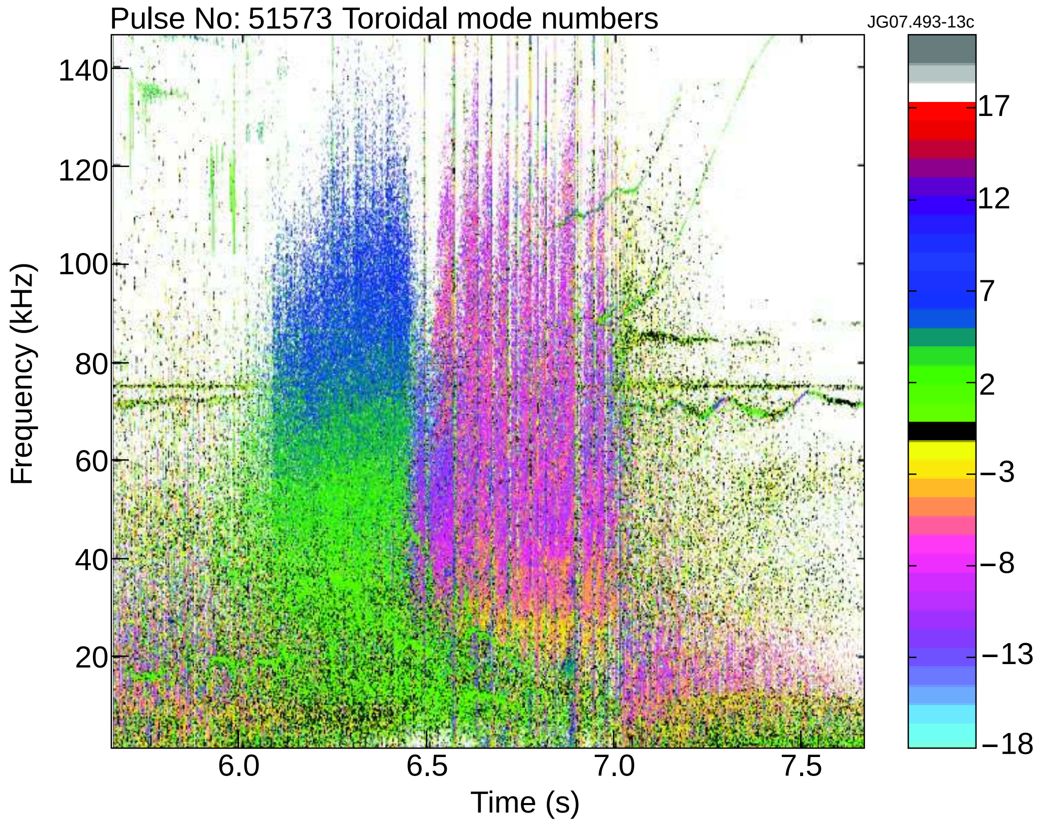


NBI and ICRH (top) and T_e measured with multi-channel ECE (bottom) in JET #51976. B=3.4 T, I_P=2.2 MA, ITB is formed at t=46 s.

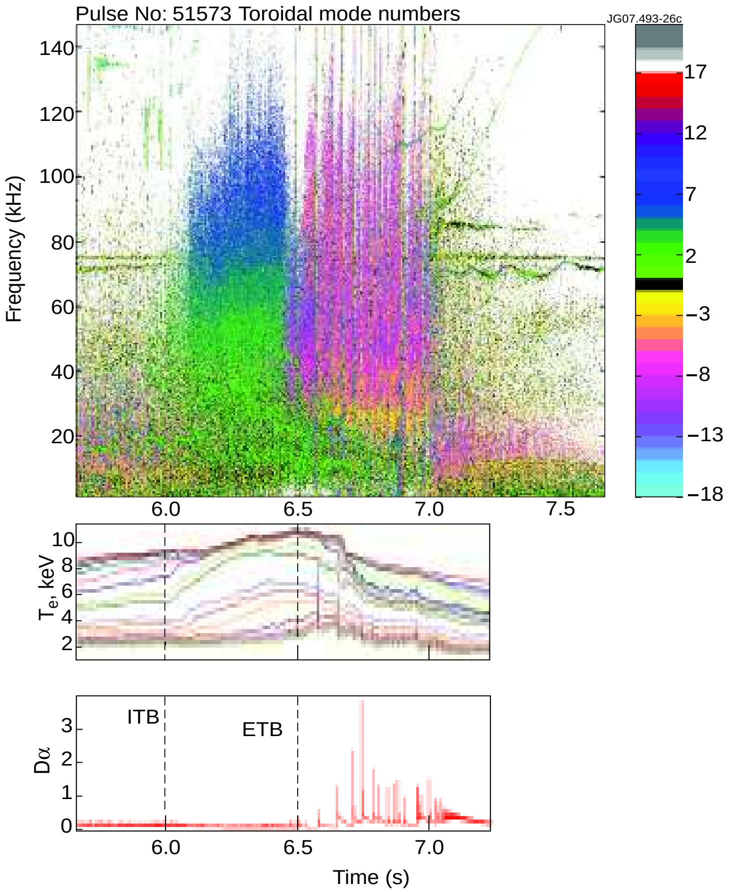


Phase spectrogram of magnetic perturbations shows a build-up of n>0, n=1-10 broad-band magnetic turbulence at 46 s when ITB is formed

Magnetic turbulence builds up at 6 s, changes sign at 6.5 s- why?



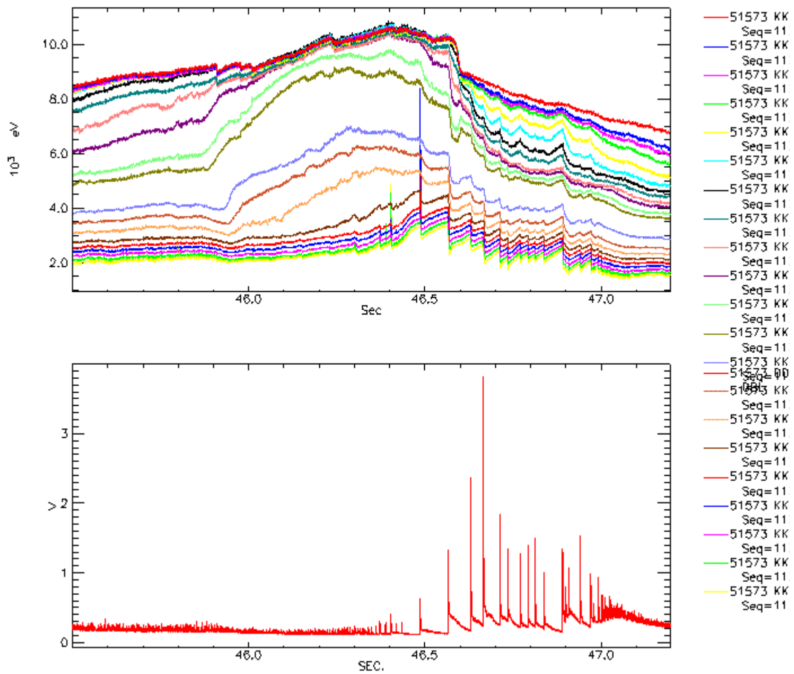
ITB followed by ETB and transition to H-mode with I type ELMs



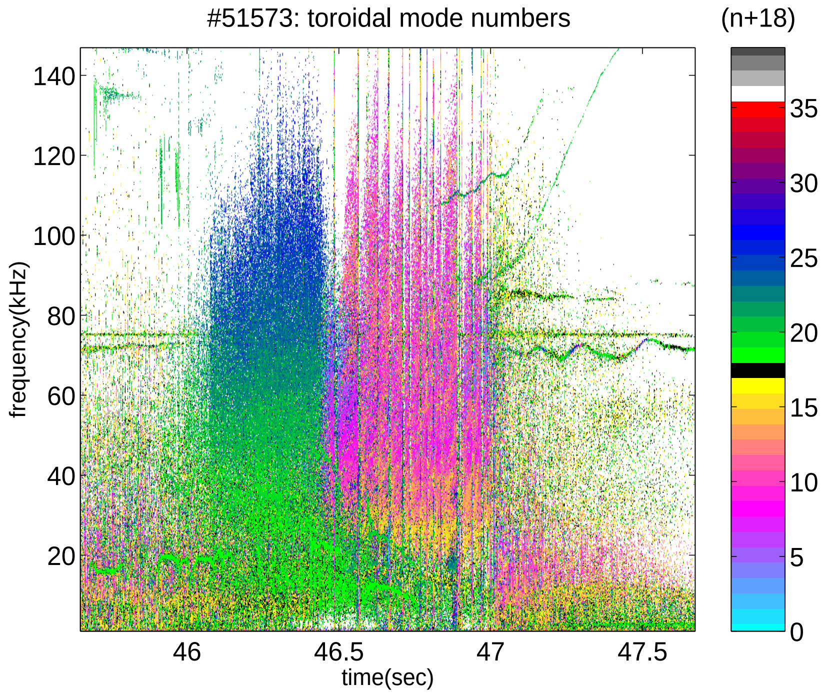
← Phase spectrogram of magnetic perturbations showing a build-up of n>0, n=1-10 broad-band turbulence at 5.9 s (ITB formed) and the abrupt chan of the phase to n<0, n=-3 to -10, at the ETB formatior 6.5 s.

← T_e measured with multi-channel ECE (top) and D_α signal (bottom). JET #51573. B=2.6 T, I_P=2.2 MA, P_{NBI}=11.5 MW, P_{ICRH}=5 MW)

ITB followed by L-H transition



T_e measured with multi-channel ECE (top) and D_α signal (bottom). JET #51573. B=2.6 T, I_P=2.2 MA, P_{NBI}=11.5 MW, P_{ICRH}=5 MW)



Phase spectrogram of magnetic perturbations showi a build-up of n>0, n=1-10 broad-band noiseat 45.9 s (ITB formed) and the abrupt change of the phase to n<0, n=-3 to -10, at the L-H transition at 46.5 s.

Electrostatic versus magnetic turbulence in ITB scenario

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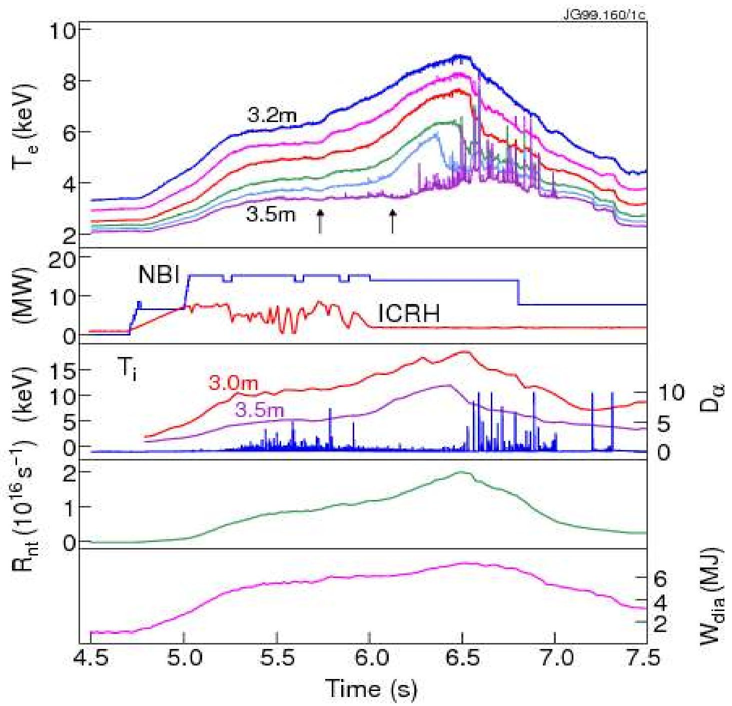
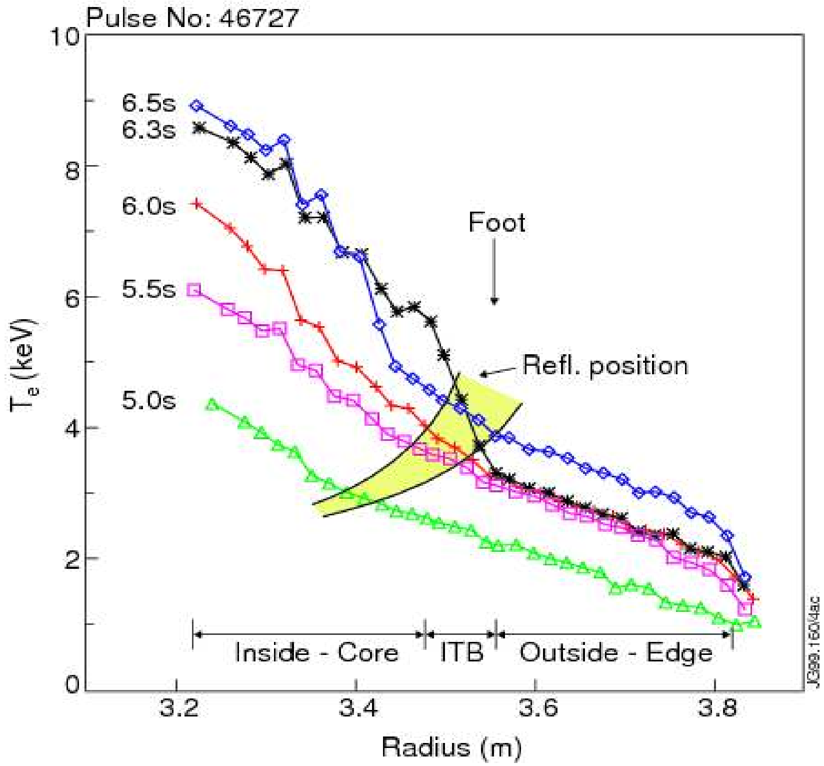
MEASUREMENT OF ELECTROSTATIC TURBULENCE AT ITB

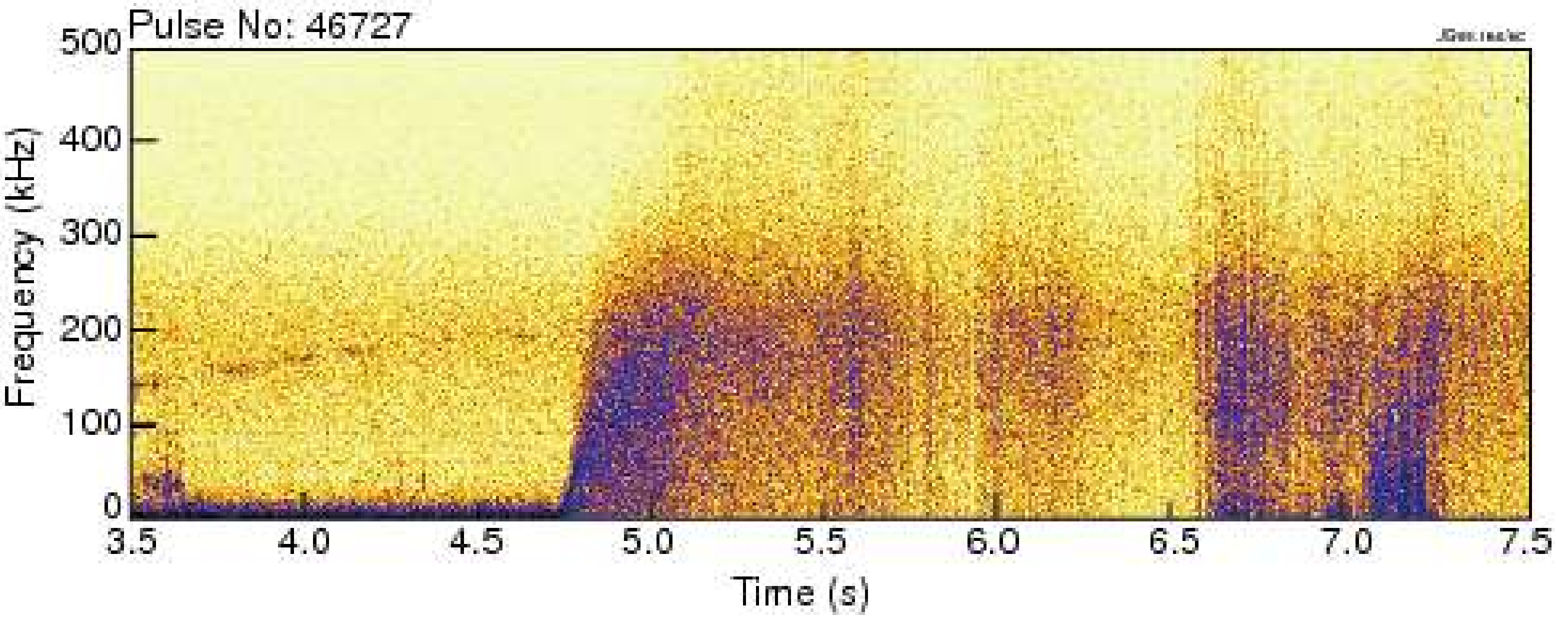


T_e measured with multi-channel ECE, NBI and ICRH power waveforms, T_i and D_α signas, neutron rate and diamagnetic energy in #46727



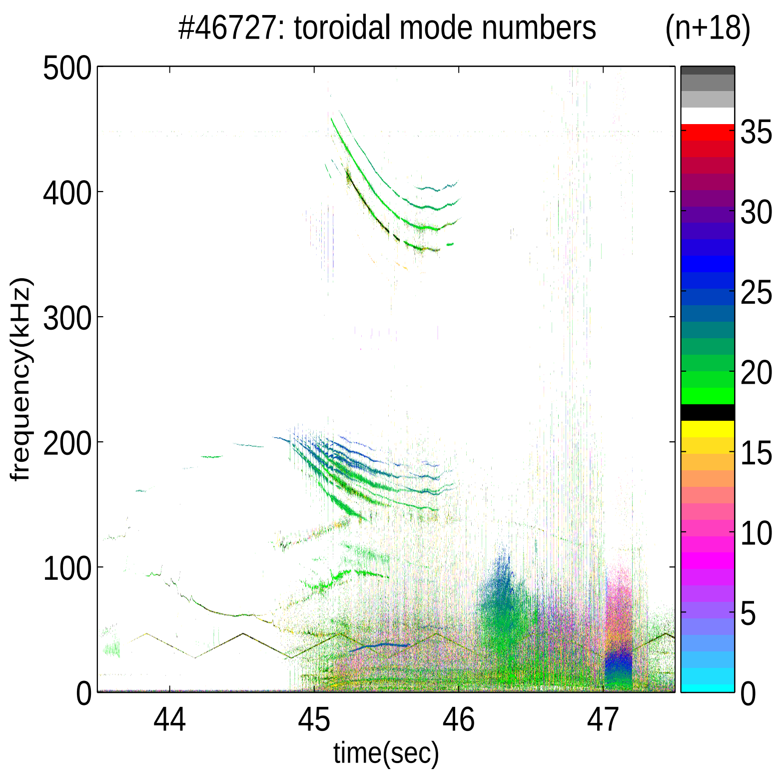
Profiles of $T_e(R)$ varying in time and the evolution of 92 GHz swept frequency X-mode reflectometer position (G.D. Conway et al., PRL 84 (2000) 1463)

Electrostatic turbulence is suppressed during ITB formation (G.D. Conway et al., PRL 84 (2000) 1463)

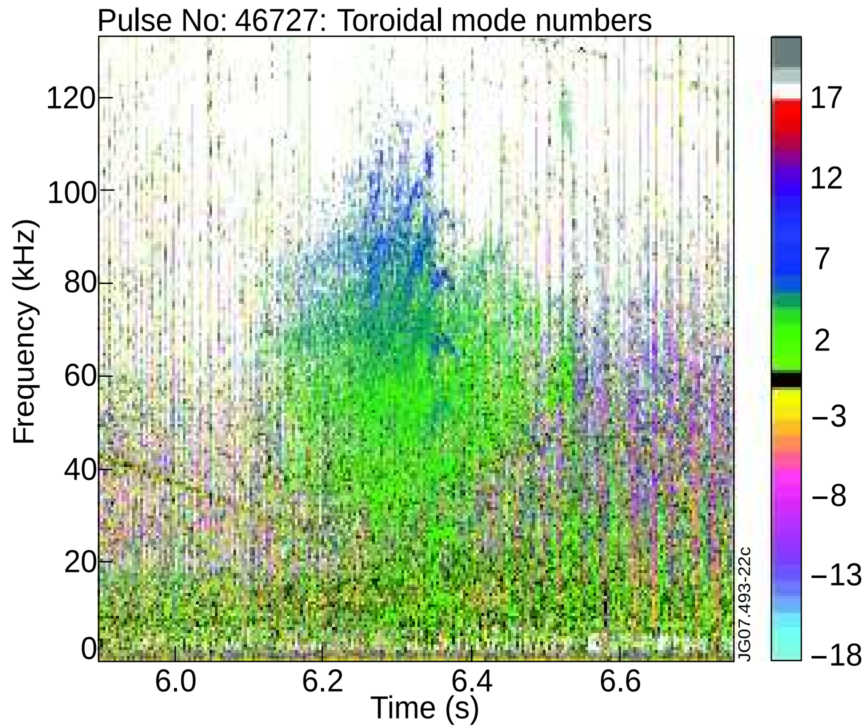


- As main heating with total power exceeding 15 MW is applied at 4.7 s, the spectrum of the high frequency density turbulence increases scaling in amplitude with heating power
- As ITB is formed at 6.2 s and lasts to 6.5 s, at precisely these two times the density turbulence shows a fast collapse and recovery.

Magnetic turbulence during ITB formation



Phase spectrogram of magnetic perturbations showing TAEs, EAE, and a broad-band n>0 magnetic turbulence during ITB (from 6.2 to 6.5 s, time shift 40 s) in #46727



Zoom of the phase spectrogram of magnetic perturbations showing a broad-band n>0 magnetic turbulence during ITB (from 6.2 to 6.5 s) in #46727

Electrostatic versus magnetic turbulence in ITB scenario

- **The experimentally observed suppression of density turbulence at exactly the same time coincides with a sharp increase in magnetic turbulence**

↓

- **ITB formation may be associated with a transition from a turbulence with dominant electrostatic potential φ to turbulence with dominant vector potential $A_{||}$ rather than with an overall decrease in the wave energy**

Summary

- The broad-band magnetic noise is not a "white" noise! It consists of MHD perturbations with well-determined toroidal mode numbers $1 \leq |n| \leq 15$ and broad band frequency range (up to ≈250 kHz in ITB discharges) in LAB reference frame
- In RI mode on JET, no change in sign of the magnetic turbulence was detected. Turbulence-free time windows were found to depend on gas species.
- In H-modes, the magnetic turbulence has $n<0$ (electron drift direction), while in L-mode, the magnetic turbulence has positive n, i.e. propagates in ion drift direction
- Transitions from III type ELMs to I type ELMs are associated with abrupt changes in frequency and toroidal mode numbers without change in sign
- In discharges with ITB, the magnetic turbulence builds up at the time of ITB formation, it has n>0 and it spreads up to a very high frequency ≈250 kHz
- Magnetic turbulence increases while density turbulence is suppressed during ITB. May be interpreted as an ITB formation associated with $\varphi \rightarrow A_{||}$ transition in turbulence.