ENERGETIC ION-DRIVEN INSTABILITIES ON JET AND ON MAST

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**Appendix of M.Watkins et al., Fusion Energy 2006 (Proc. 21st IAEA Conference, Chengdu, 2006) IAEA (2006)*

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S.E.Sharapov, 48th APS DPP Meeting, Philadelphia, USA, 30 October 2006

Outline of this talk

- Enhanced and new fast ion diagnostics on JET and on MAST
- Experimental study of ‘tornado’ modes and energetic ion redistribution in JET plasmas with monster sawteeth
- Bi-directional tornado modes and TAEs
- Applying X-mode reflectometry to Alfvén eigenmodes
- First observation of Alfvén cascades on spherical tokamak MAST
- Summary

Enhanced and new fast ion diagnostics on JET and on MAST

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JET (2006)

- New scintillator for measuring fast ion losses was installed and is operational now [Cecil et al., APS (2006) NP1 38]
- New set of Faraday cups for measuring fast ion losses was installed and is being commisioned now
- X-mode reflectometry was renewed and provides data on mode localisation and mode amplitude in plasma core
- Far infra-red interferometer was digitised and detects Alfvén modes even in JET discharges with more than 30 MW of input power

These new diagnostics complementary to gamma-ray diagnostics, NPA, O-mode interferometry, and Mirnov coils, significantly expand the JET capability in detecting energetic ion driven instabilities and in assessing energetic ion confinement

MAST (2006)

- MAST is now equipped with magnetic coils with frequency range up to 5 MHz
- Soft X-ray camera with frequency range up to 250 kHz
- Multi-channel (in energy and in lines-of-sight) NPA

These diagnostics, together with super-Alfvénic NBI and wide range of achievable $\beta_{thermal}$ and β_{fast}, make MAST a good test bed for studying Alfvén instabilities

Experimental study of ‘tornado’ modes and energetic ion redistribution in JET plasmas with monster sawteeth

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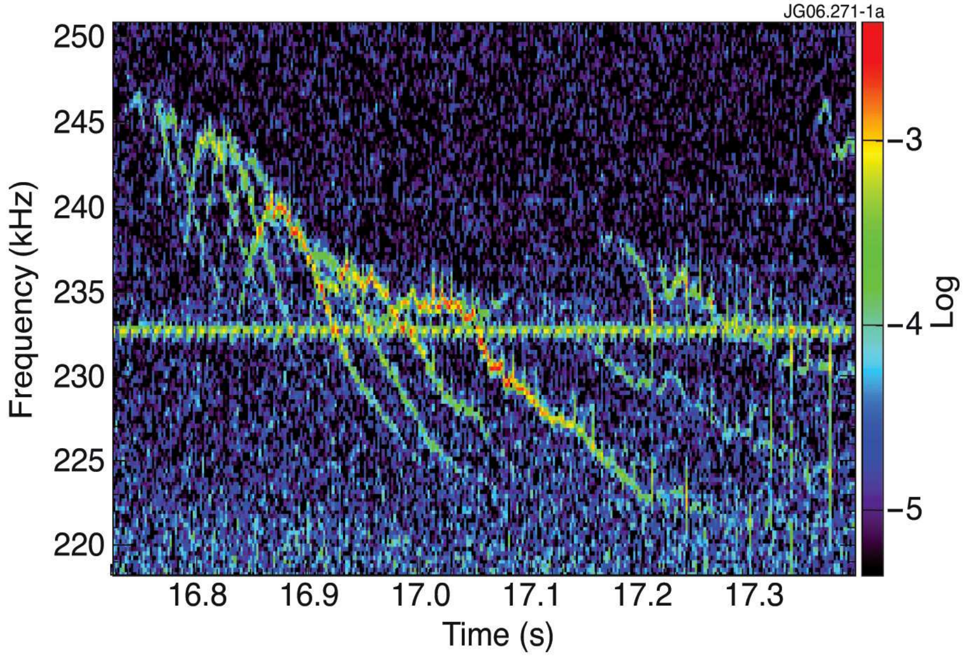
Tornado mode = sweeping frequency mode in plasmas with the q=1 sawteeth. Usually precedes monster sawtooth crash.

Tornado mode ≡ Low-Shear TAE inside the q=1 radius

[Kramer et al., PRL (2004)]



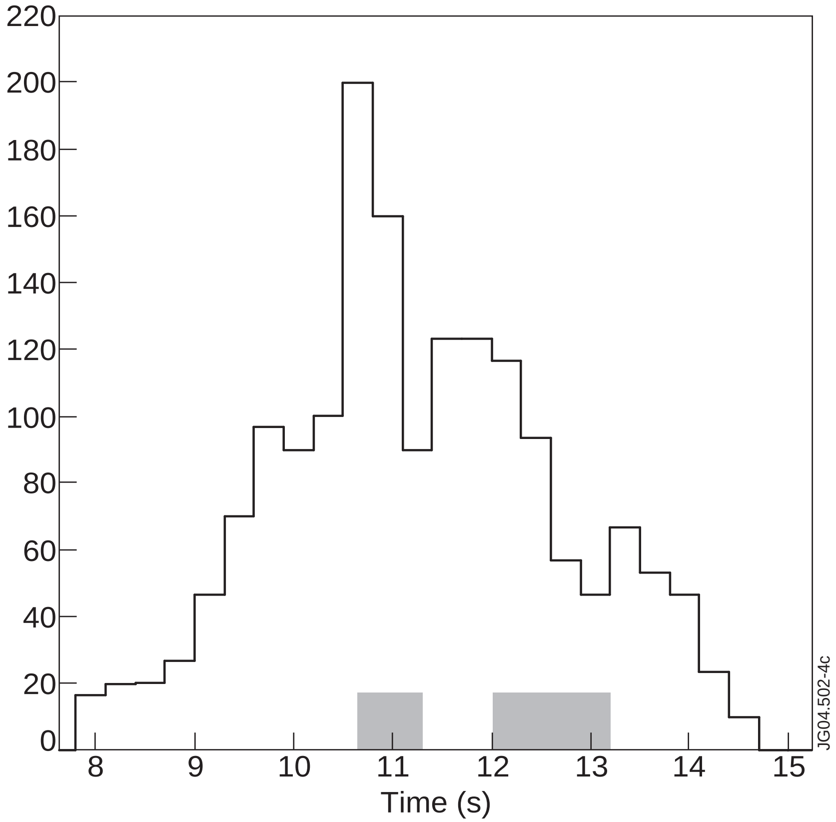
The only mode in TAE frequency range which affects confinement of energetic ions in the q=1 high-performance plasmas.

- Degradation of confinement of fast ions inside q=1 caused by tornado modes has been previously reported:

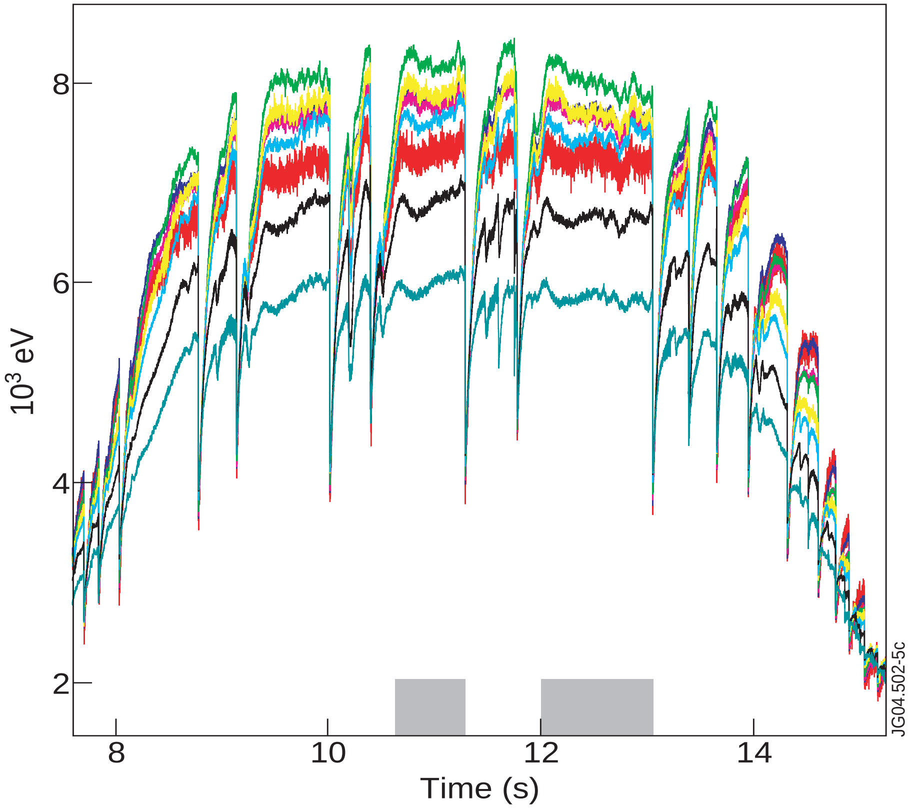
  JT-60U: Saigusa et al., PPCF 40 (1998) 1647
  TFTR: Bernabei et al., Phys. Rev. Lett. 84 (2000) 1212
  DIII-D: Heidbrink et al., Nuclear Fusion 39 (1999) 1369
  JET: Sharapov et al., Nuclear Fusion 45 (2005) 1168

- Tornado modes are considered to be possible reason for expelling fast ions from the q=1 region and causing monster sawtooth crash due to the loss of fast ion stabilisation

JET (2004): Gamma-ray intensity from 5MeV protons decreases 0.5–1 sec before sawtooth crashes



γ-rays from reactions $^{12}C(p, p'\gamma)^{12}C$



T_e at different radii show sawteeth at t=11.4, t=13 s occuring after decreases of γ-intensity

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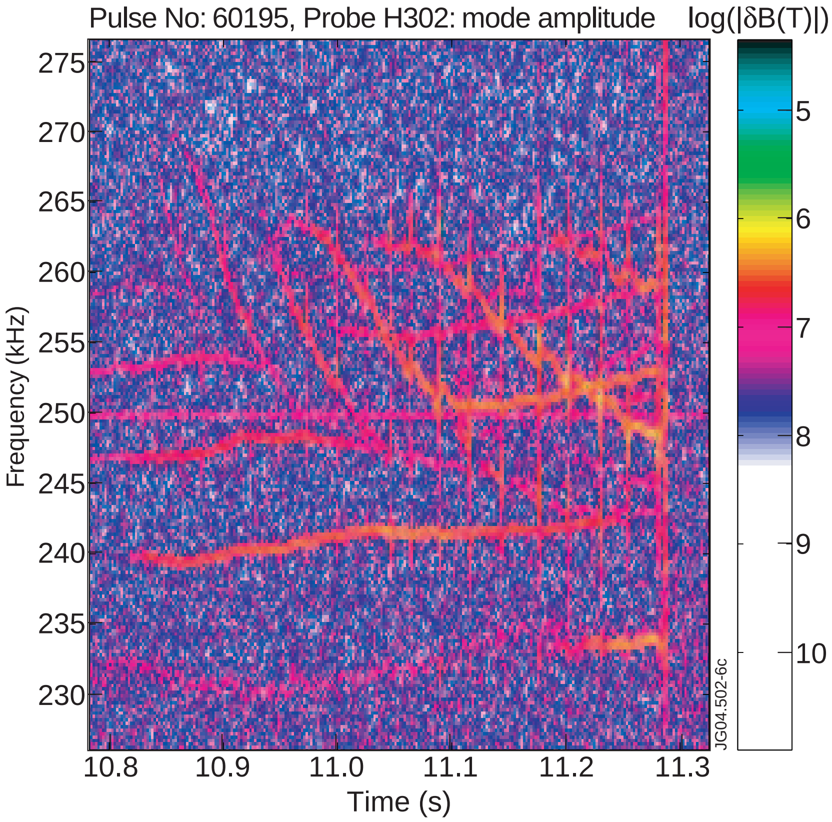
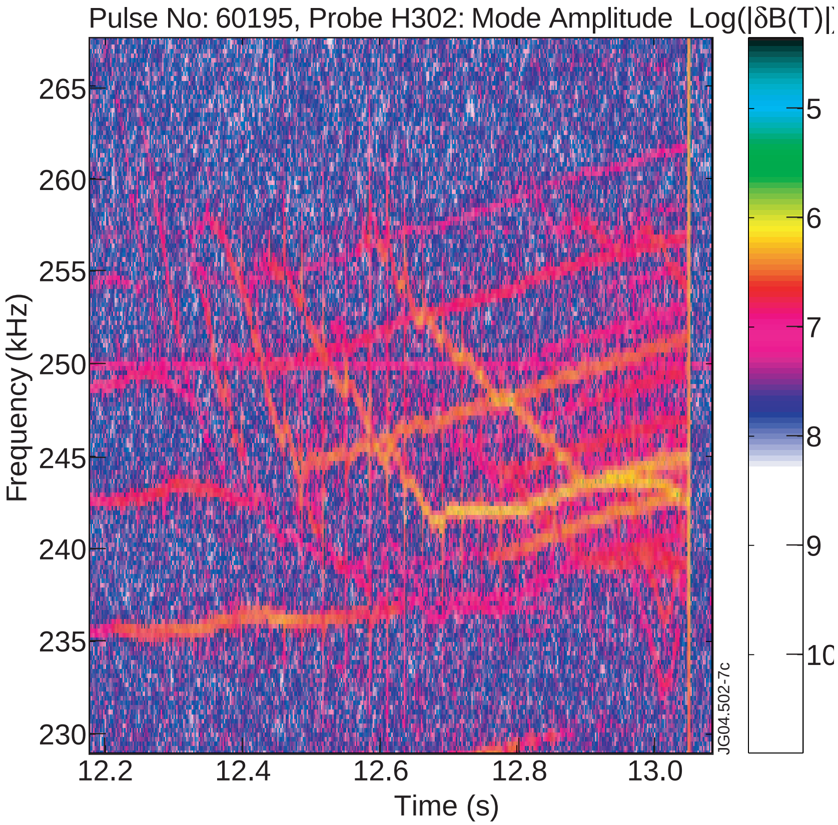
Observed Gamma-ray Decrease Happens when TAEs within q<1 (tornado modes) and TAEs outside q=1 coexist

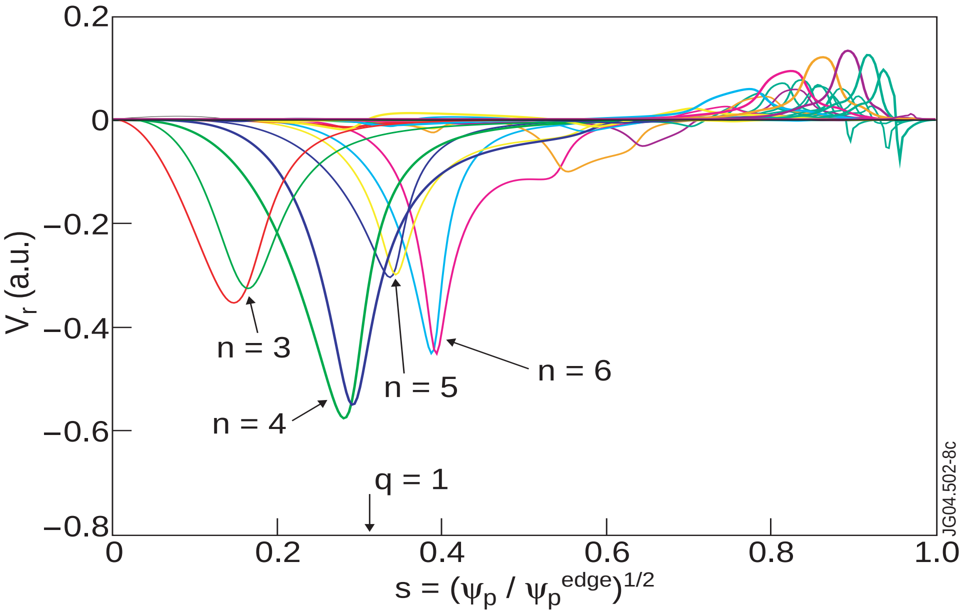


TAEs & tornadoes during first shaded time interval

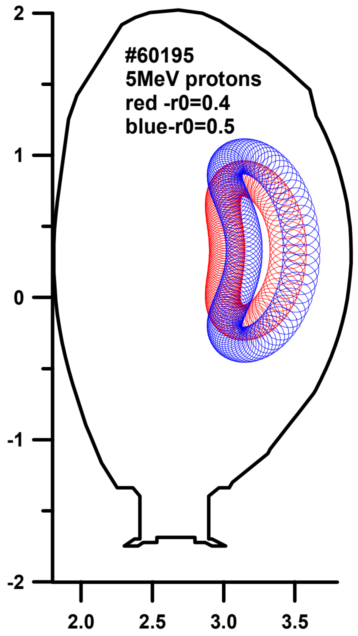


TAEs & tornadoes during second shaded time interval

Observed Gamma-ray Decrease Happens when TAEs within q<1 (tornado modes) and TAEs outside q=1 coexist



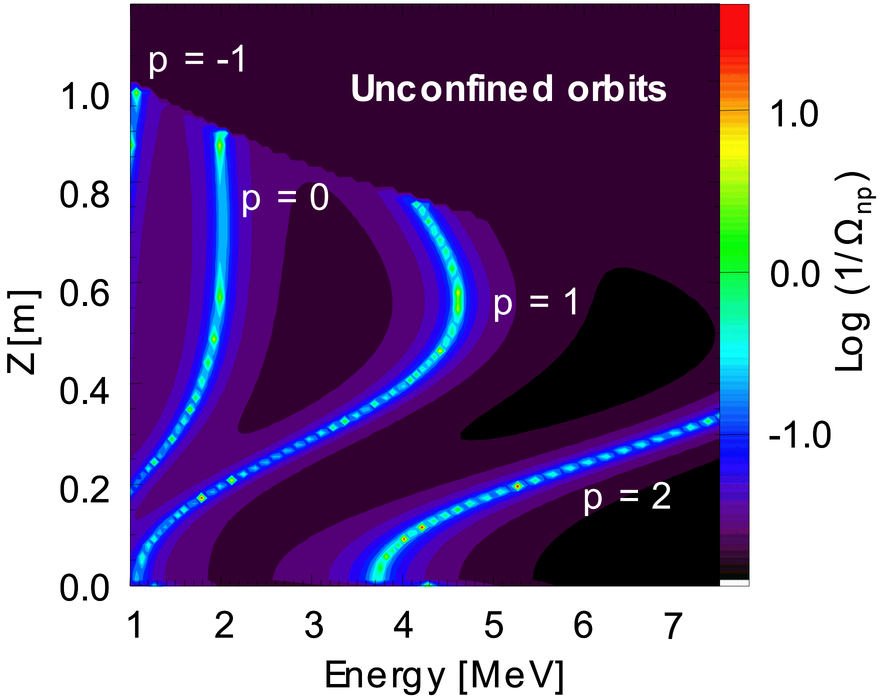
TAEs with n=3, 4 within the q=1 radius (tornado), and n=5,6 TAEs outside the q=1 radius



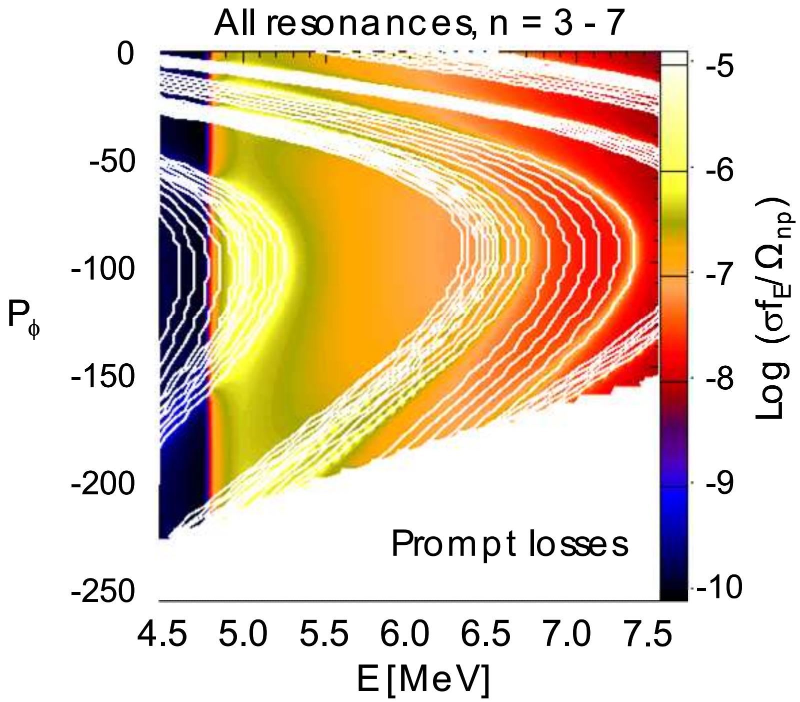
Orbits of 5 MeV protons

- Ideal MHD code used for computing these modes in JET with monotonic q-profile
- Redistribution of protons from the q=1 radius by tornadoes considered main cause of the decrease in gamma-ray intensity

HAGIS modelling of tornado modes shows the importance of frequency sweep (S.Pinches)

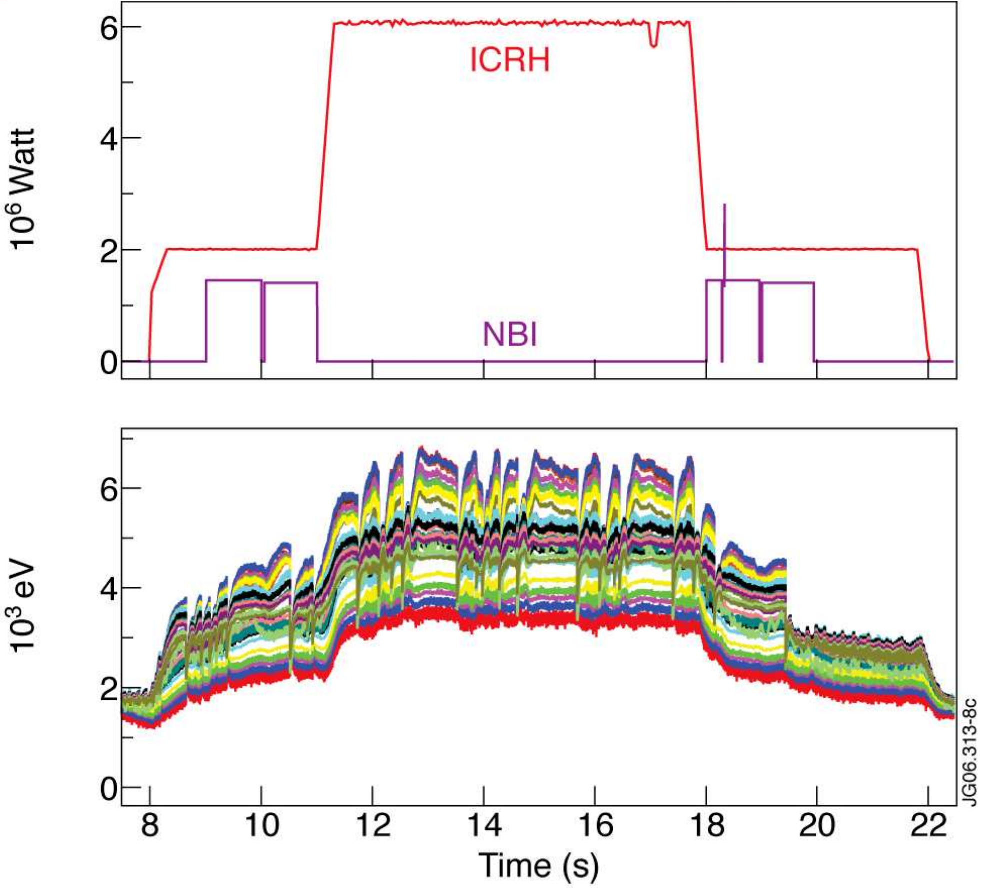


***Regions of phase space where ICRH-accelerated ions resonate with** n=3 tornado mode,* $\Omega_{np} = n\omega_{\phi} - p\omega_{\theta} - \omega = 0$



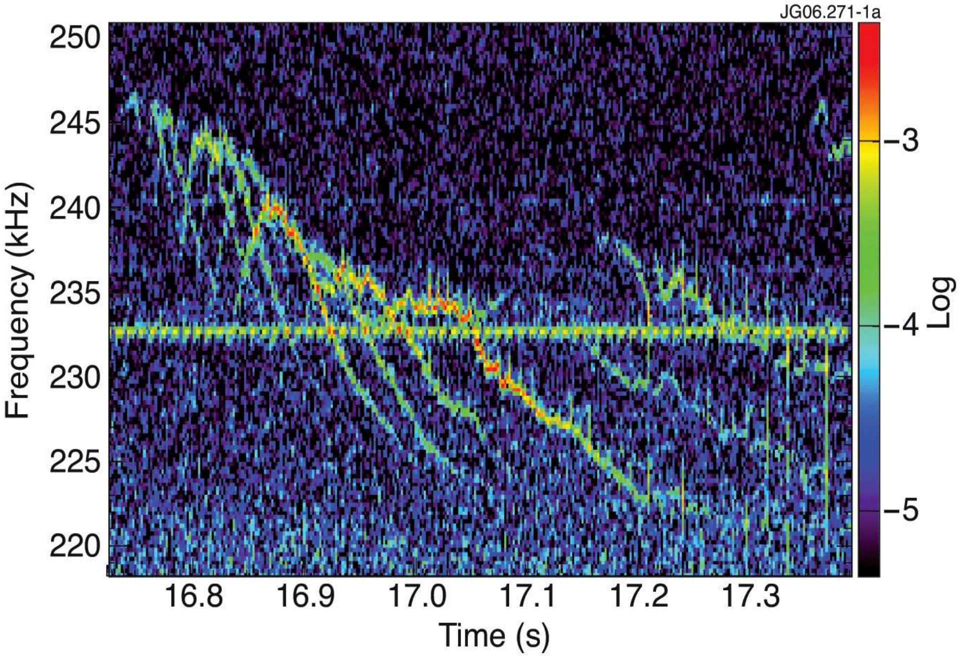
***Movement of resonant lines due to** ALL tornado modes by sweeping frequency in 3% steps over 15%.*

JET (2006): experiment with a more complete set of diagnostics

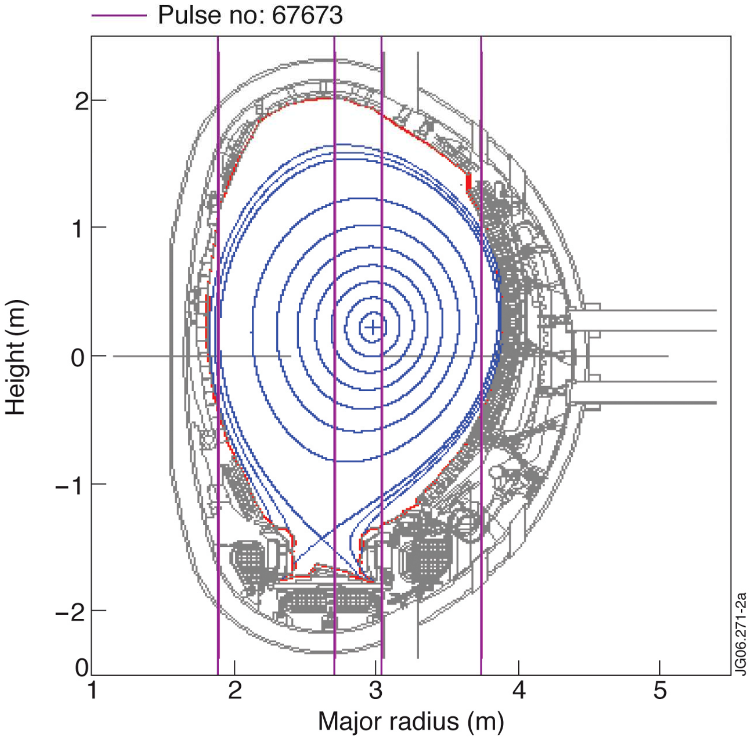


ICRH (hydrogen minority) and NBI power waveforms and T_e measured with multi-channel ECE diagnostics in typical tornado mode discharge on JET (pulse #67673)

New high-quality detection of core-localised modes with far infra-red interferometry (JET discharge #67673)



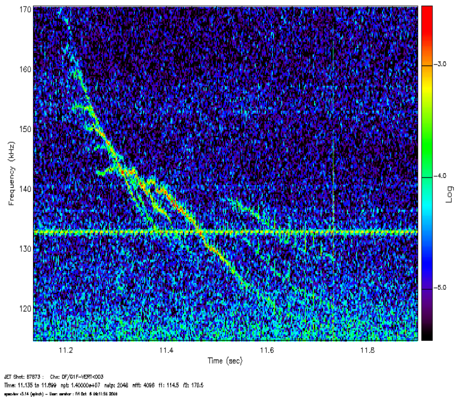
Tornado modes detected with vertical channel passing through the magnetic axis of the JET interferometer

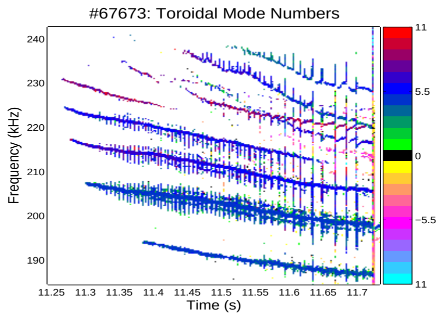


Geometry of JET interferometer with vertical lines-of-sight

Four sets of tornado modes precede four monster crashes in #67673:

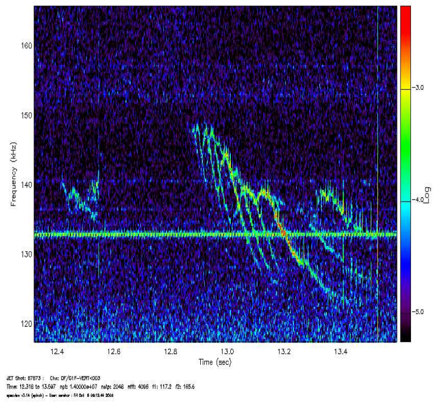
t=11.25 – 11.75 sec

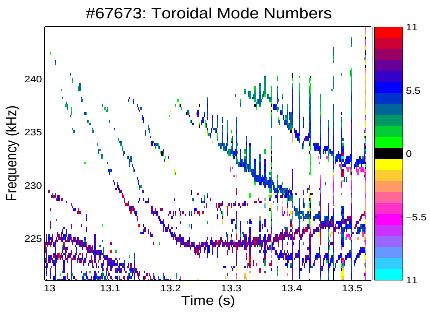




n decreases one-by-one:
n= 8→7→6

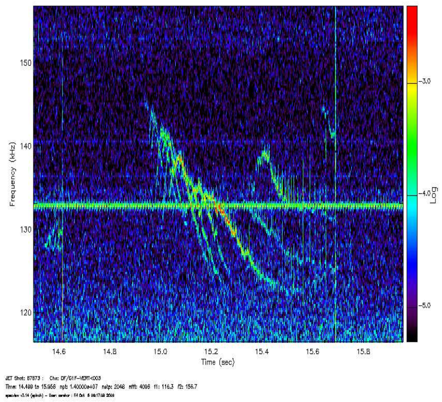
t=13.0 – 13.53 sec

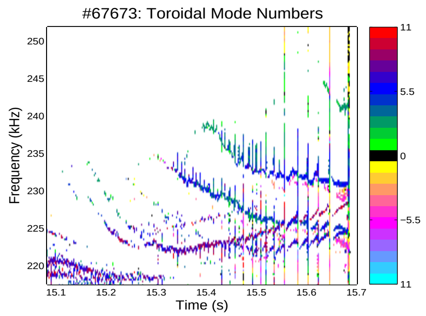




n decreases one-by-one:
n=9→8→7→6→5→4

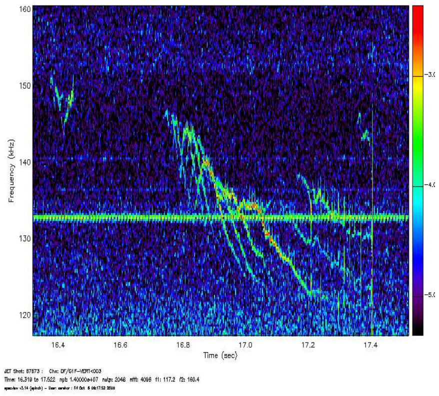
t= 15.1 – 15.68 sec

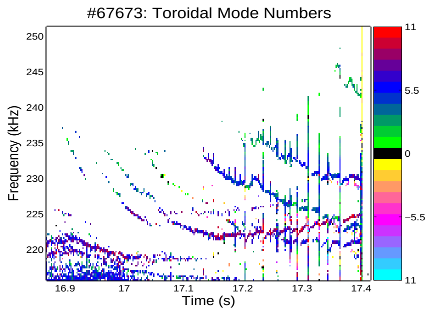




n decreases one-by-one
n=8→7→6→5→4→3

t = 16.9 – 17.4 sec





n decreases one-by-one
n=9→8→7→6→5→4→3

Energetic ion confinement is investigated as follows:

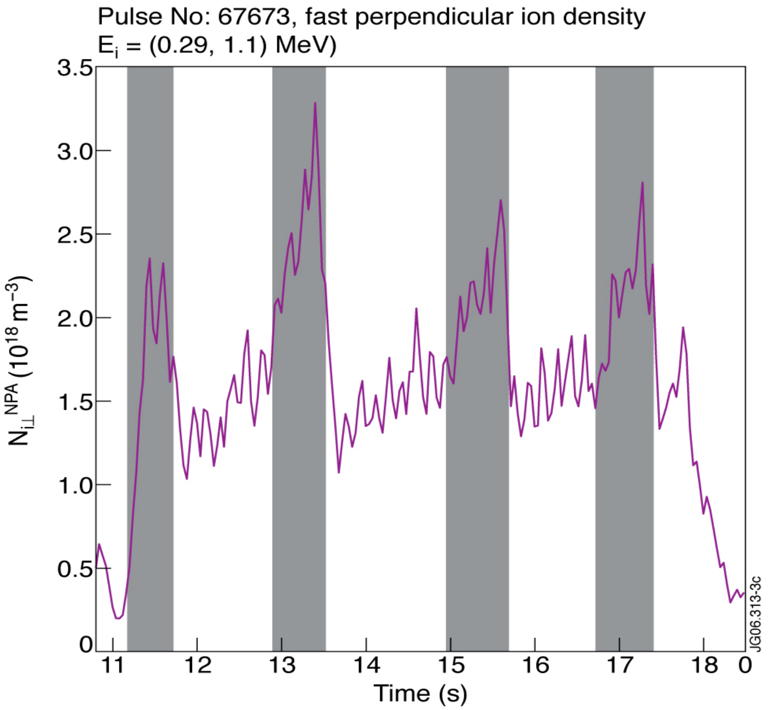
Confined energetic ions:

- Hydrogen minority ICRH-accelerated protons (NPA)
- 2nd harmonic ICRH-accelerated deuterons (gamma-ray spectrometry)

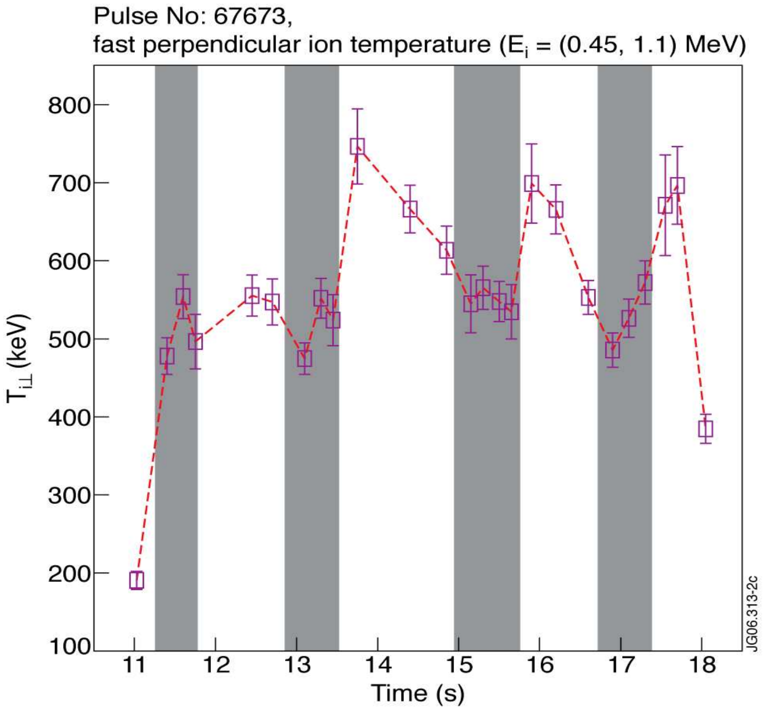
Lost energetic ions:

- Fusion-born protons (3 MeV) and tritons (1 MeV), ICRH-accelerated protons and deuterons (scintillator)

On NPA, density of fast protons starts to decrease just before sawtooth crashes (C.Schlatter)



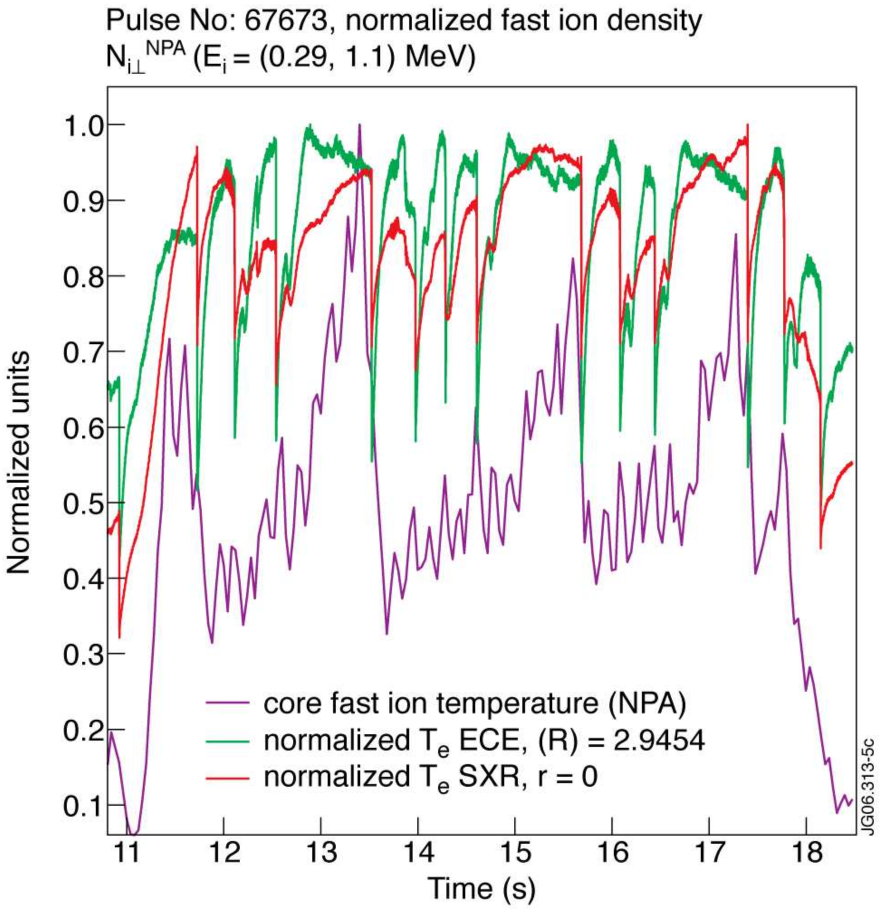
Density of energetic protons

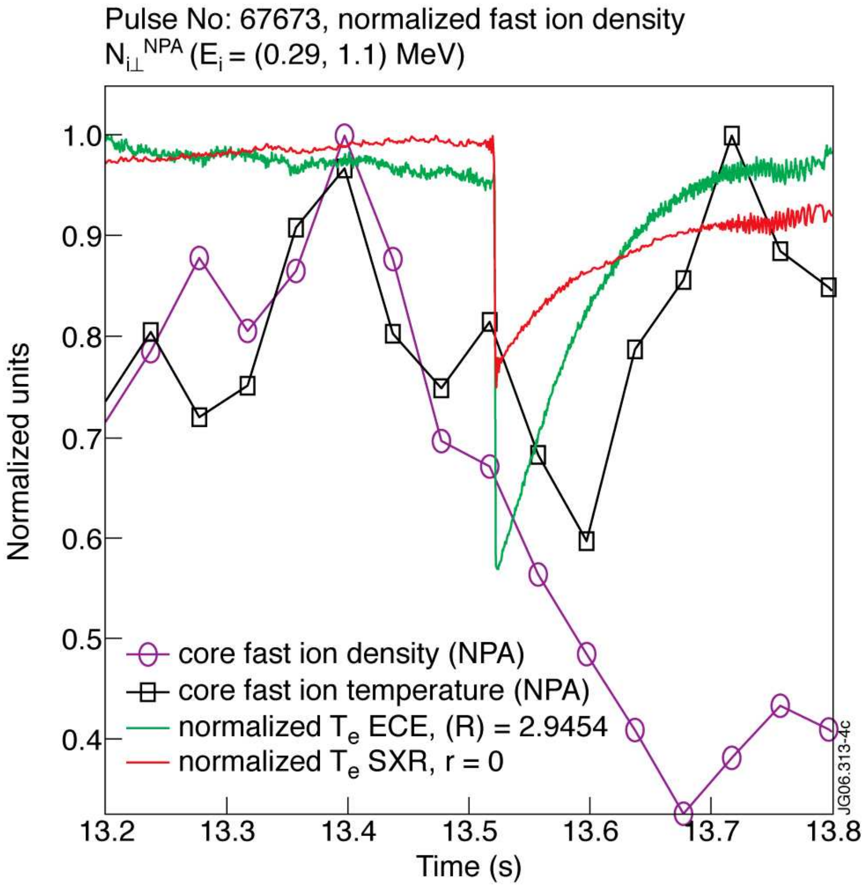


Temperature of energetic protons

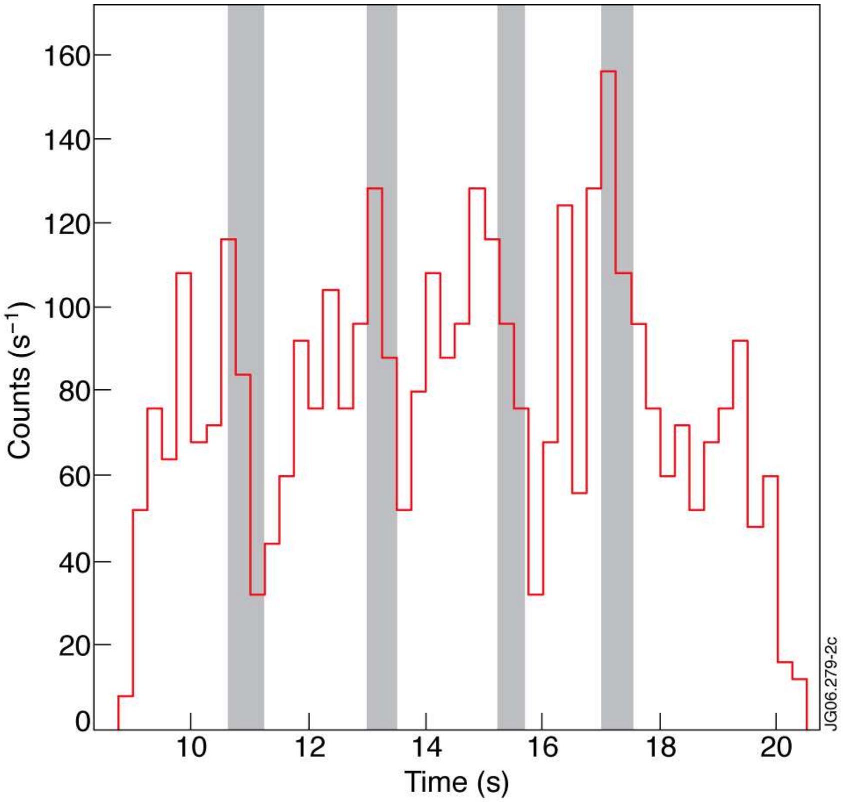
Density of ICRH-accelerated protons decreases when low-n, n=4, tornado mode appears; Temperature of ICRH-accelerated ions is not affected by tornadoes, but seemingly increases after monster sawtooth crashes.

Density and temperature of fast protons from NPA

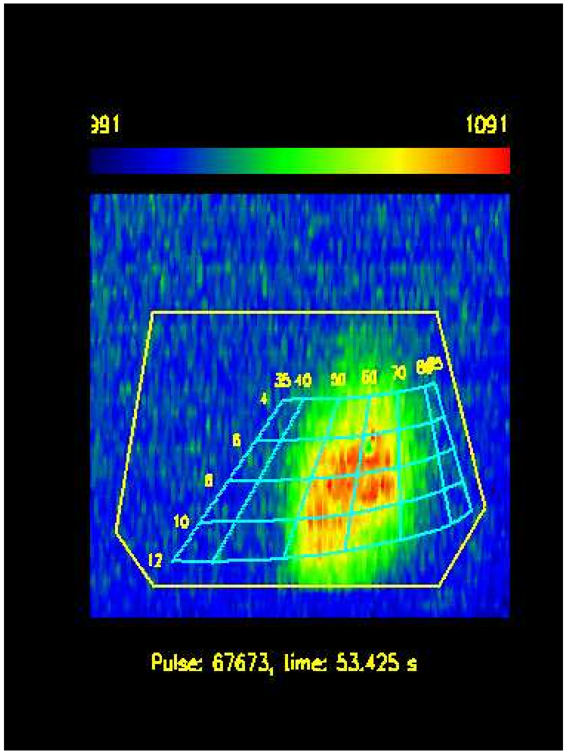




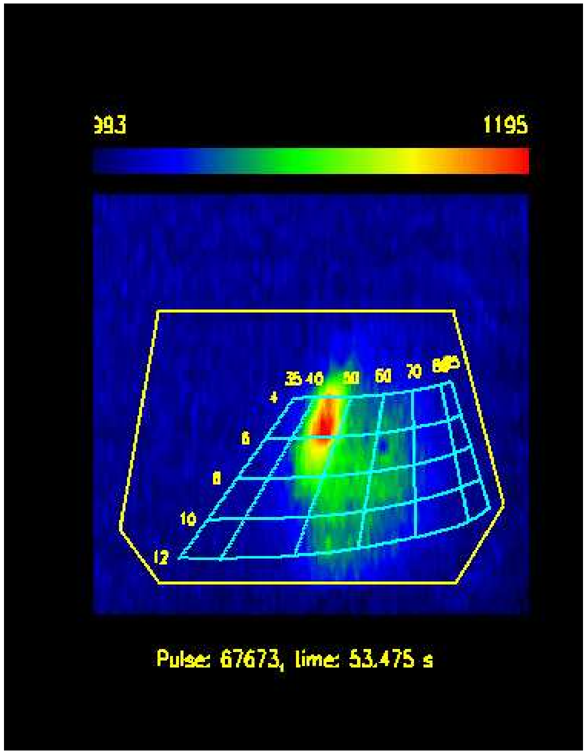
Gamma-ray emission from deuterons (E>500 keV) colliding with carbon, $^{12}C(d,p\gamma)^{13}C$ decreases before crashes (V.G.Kiptily)



Losses of energetic ions measured with scintillator outside plasma are different before and during sawtooth crashes



Ions with gyro-radii 6-10 cm are lost before sawtooth crash



Ions with gyro-radii 4-6 cm are lost during sawtooth crash

Losses of energetic ions measured with scintillator are very different before and during sawtooth crashes

Larmor radii 6-10 cm:

- Protons in the energy range 1.3-5 MeV
- Tritons in the energy range 0.4-1.7 MeV
- Deuterons in the energy range 0.6 – 2.5 MeV

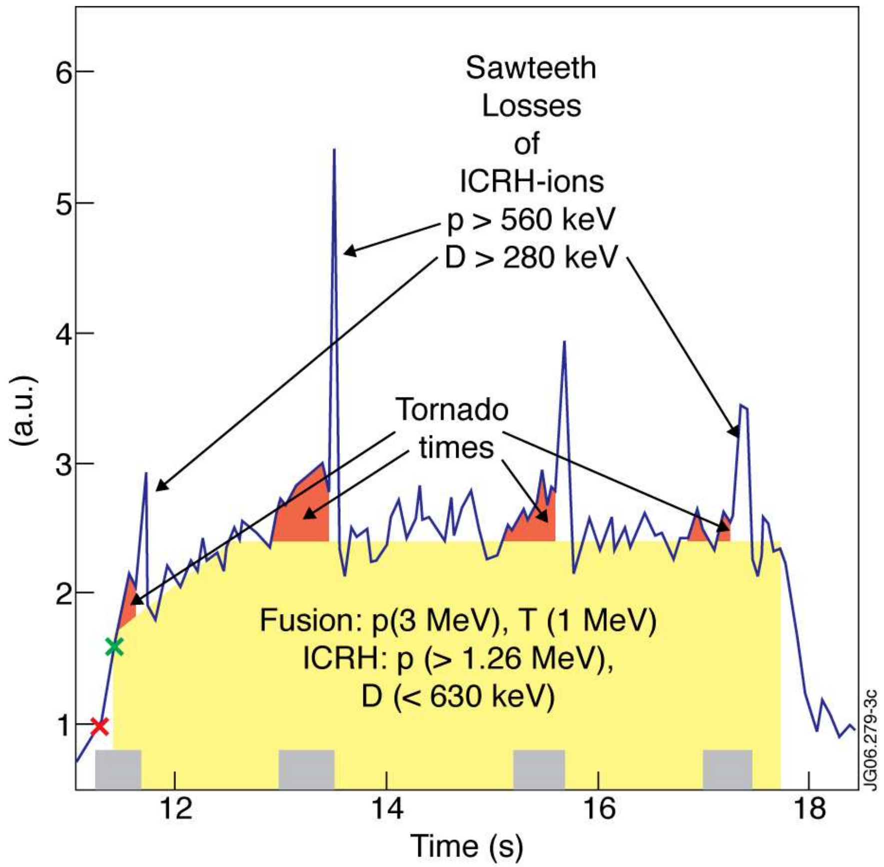
Protons and Tritons are born in reaction D + D → p (3 MeV) + T (1 MeV) with a significant spread coming from ICRH-accelerated deuterium.
Protons with E>1.3 MeV and Deuterons with E>600 keV accelerated by ICRH

Larmor radii 4-6 cm:

- Protons in the energy range 0.5-1.3 MeV
- Deuterons in the energy range 0.3-0.6 MeV

These ions are accelerated with ICRH

Loss measurements indicate increase during tornado activity



- Modelling to be performed for correlating fast ion re-distribution outside q=1 radius and the flux of lost ions measured outside plasma

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Bi-directional tornado modes and bi-directional TAEs on JET

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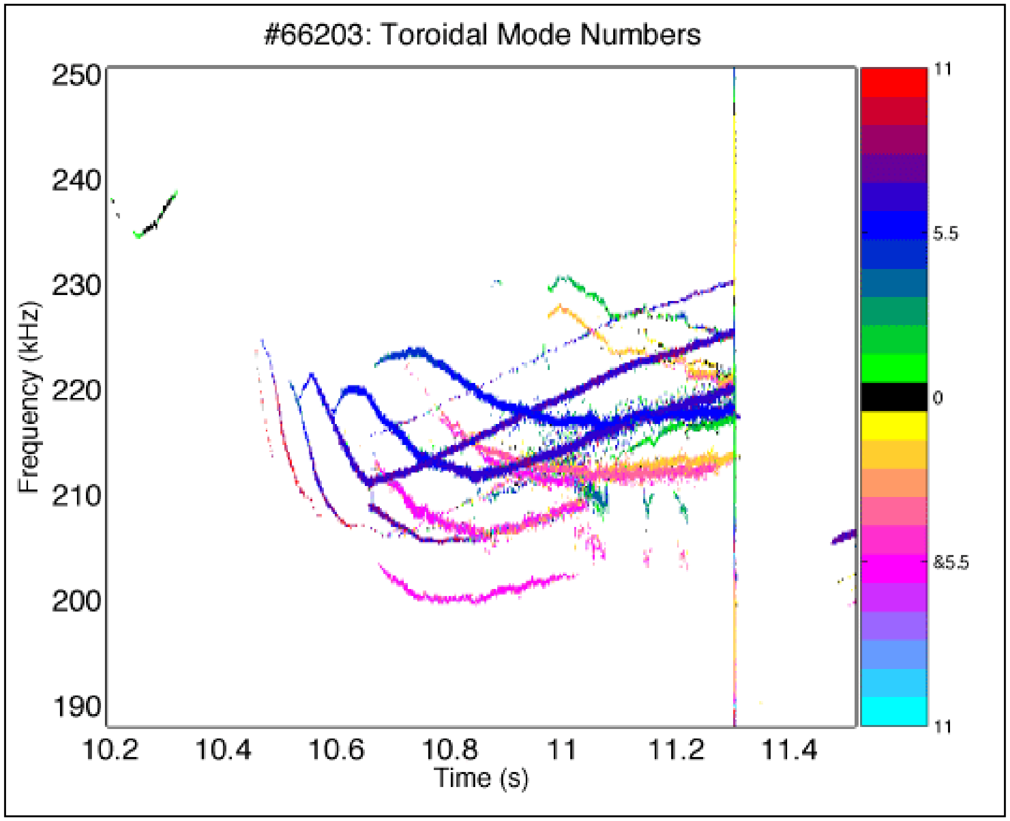
Bi-directional tornado modes observed on JET



Tornado modes with BOTH positive and negative toroidal mode numbers observed at the same time

Bi-directional tornado modes previously reported from JT-60U

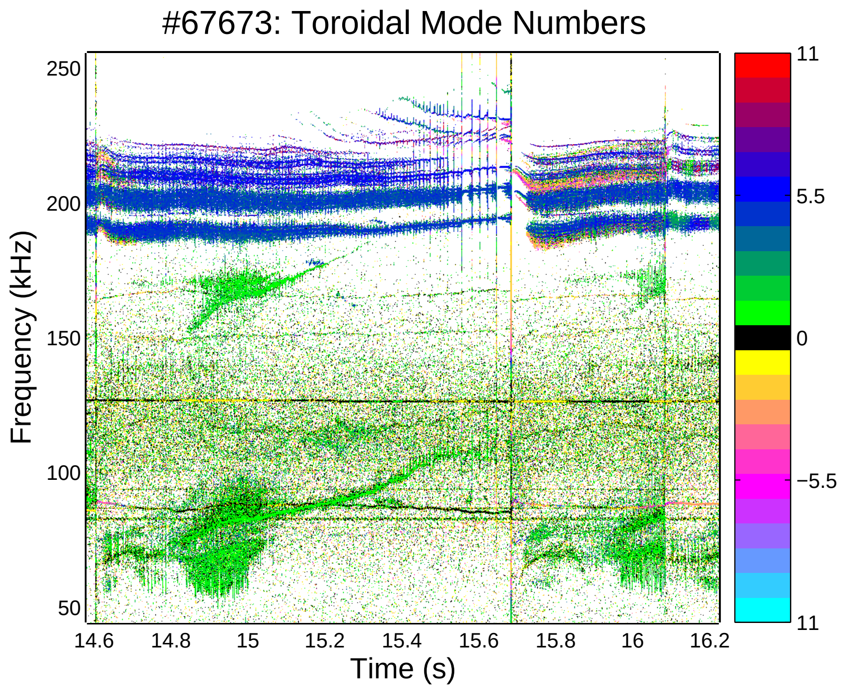
- Saigusa et al.,1998: drive comes NOT from a radial hollow fast-particle profile but is thought to be either a nonlinear coupling between bi-directional modes or caused by velocity space drive

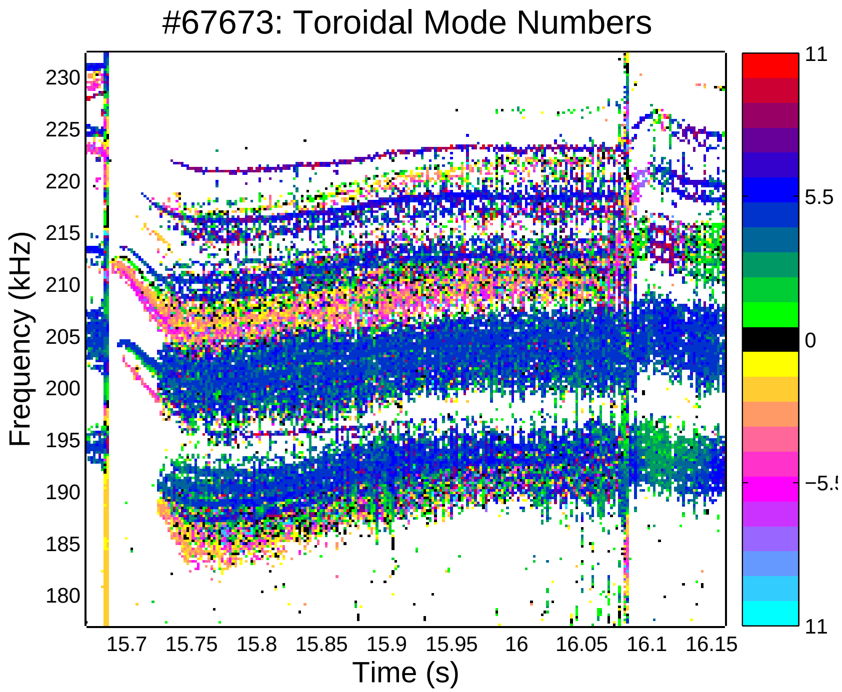
- Wong and Berk 1999: fast ion anisotropy provides destabilization of counter-propagating modes in ICRF-heated plasmas

$$\frac{\gamma}{\omega} \propto \left[\frac{1}{T}\left(\frac{n\omega_{*hot}}{\omega} - 1 \right) F_{hot} - \frac{\lambda}{H}\frac{\partial F_{hot}}{\partial \lambda} \right] \cdot \delta\left(\Omega_{resonance}\right)$$

- Modelling of ICRH distribution function for JET with FIDO code (T.Johnson) shows no hollow fast ion profile. However, temperature anisotropy is large indeed, $T_{Perp} / T_{Parallel} \sim 5$ and may be the reason for the anisotropy drive

Bi-directional TAEs are observed *after sawtooth crashes* for the first time. Possibly they are caused by increase in fast ion anisotropy





n's for TAEs are only positive before sawtooth crash at t=15.7 s but positive and negative after it

Zoom of Figure showing toroidal mode numbers for TAEs after the crash

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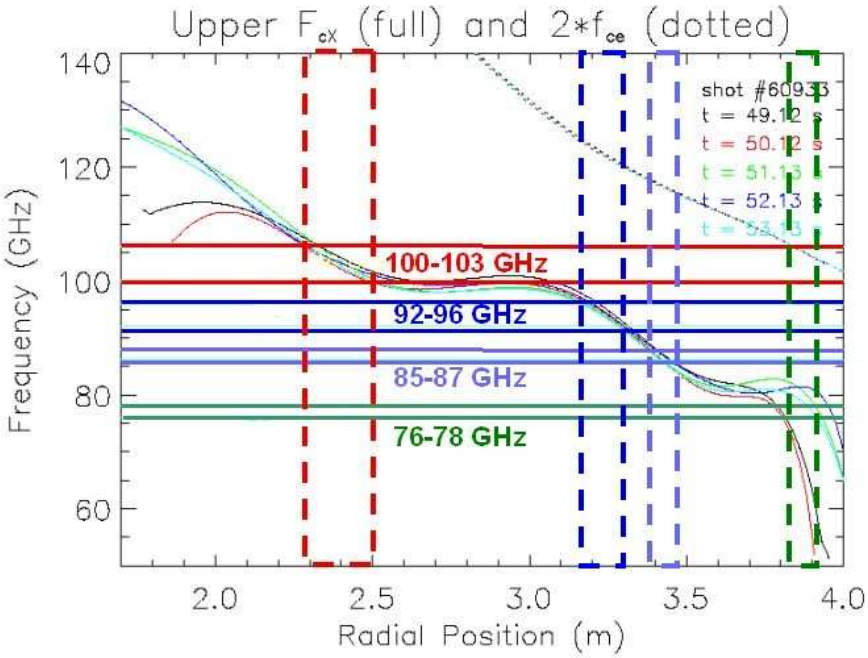
Applying X-mode reflectometry to Alfvén eigenmodes on JET

Renewed X-mode reflectometry for fast ion instabilities on JET

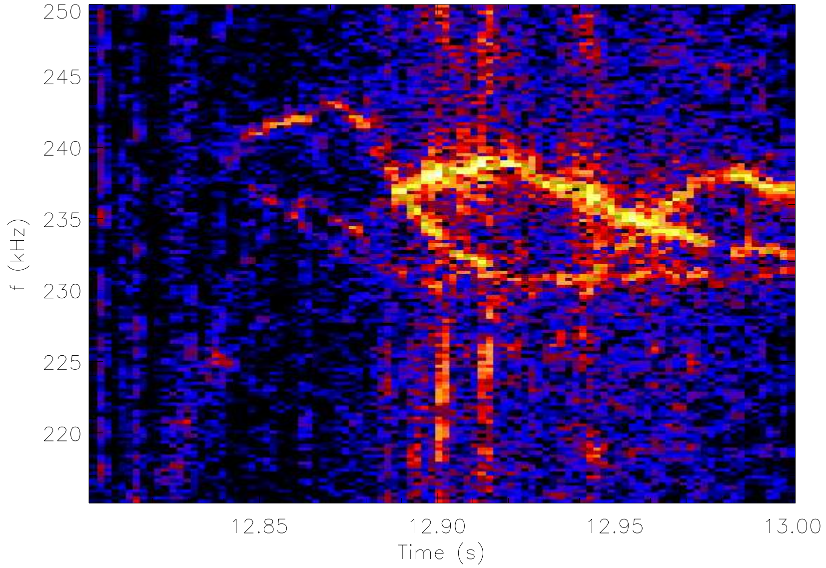
- **X-mode reflectometry** **was renewed and is operational now:**
  - 4 radial correlation reflectometers (76-78, 85-87, 92-96, 100-106 GHz ranges) upgraded with **new low-attenuation transmission lines** (20dB improvement)
  - localised measurement of $\delta n_e(r)$ from $\delta\varphi(f)$ of the reflected signal



Upgraded X-mode reflectometry detects tornado modes well

- Provides data on the mode localisation (e.g. the tornado modes in JET #66205 were found to be localised in the plasma core at ~3.2 m);

- Provides absolute mode amplitude from phase fluctuations of signal



See also [Kramer et al., APS (2006) NP1 36]

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FIRST OBSERVATIONS OF ALFVÉN CASCADES ON SPHERICAL TOKAMAK MAST

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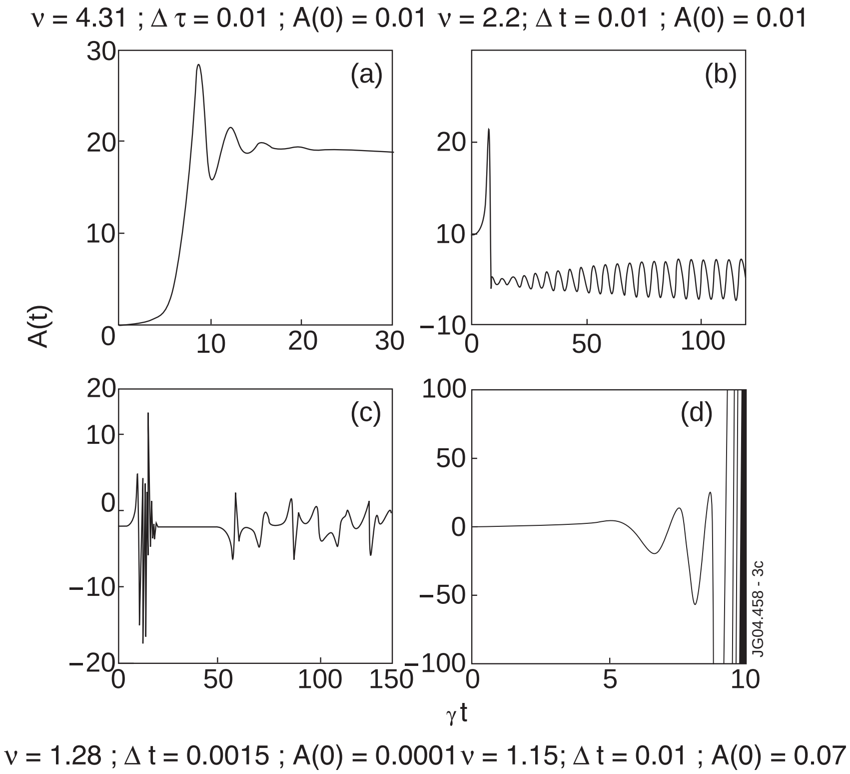
THE PROBLEM

- **Alfvén Cascades (ACs) were observed in almost all present day conventional tokamaks: JET, JT-60U, TFTR, C-MOD.**
- **However, neither NSTX nor MAST have ever reported AC observations although ITB scenarios are being developed on both STs.**
- **Why? Are there any special circumstances preventing AC excitation and the use of ACs for developing ITB scenarios in STs? Is there a problem with obtaining reversed shear equilibrium in general?**

Nonlinear Evolution of a Single TAE



Nonlinear equation for amplitude A(t)

$$\frac{dA}{dt} = A - \exp(i\phi)\int_0^{t/2}\tau^2\int_0^{t-2\tau}\exp\left[-\nu^3\tau^2\left(2\tau/3+\tau_1\right)\right]$$

$$\times A(t-\tau)A(t-\tau-\tau_1)A^*\left(t-2\tau-\tau_1\right)d\tau_1 d\tau$$

derived in [*] describes four different regimes of TAE amplitude A:

- **Steady-state A=const;**
- **Periodically modulated (observed as ‘pitchfork-splitting’ effect);**
- **Chaotic;**
- **Explosive regime as ratio $\nu \equiv \nu_{eff}/\gamma$ decreases (was investigated for MAST in S.Pinches et al., PPCF 46 (2004) S55**

[*] H.L.Berk, B.N.Breizman, and M.S.Pekker, Plasma Phys. Reports 23 (1997) 778

THE HYPOTHESIS

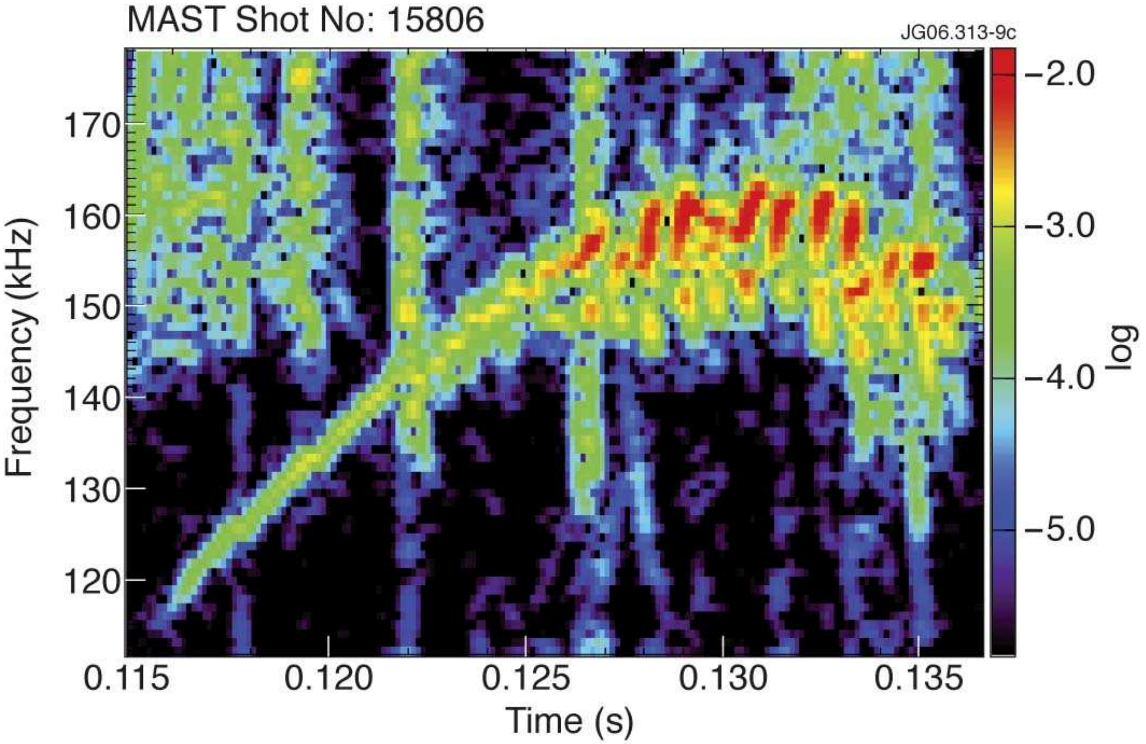
- Due to higher ratios $\beta_{hot} / \beta_{Therm}$ and V_{NBI} / V_A in NSTX and MAST, the beam drive and thermal plasma damping are not in the regime of exciting TAEs and ACs with a steady-state amplitude

⇓

Decrease NBI power for obtaining weaker-driven ACs with a better quality spectral line

SCAN IN NBI POWER ON MAST

- A scan in NBI power from 1.5 MW down to 0.5 MW was performed in order to reduce the energetic ion drive and to get rid of the chirping modes. It was found that the optimum NBI power required for driving ACs with clear spectroscopic signal is about 1.3 MW.



Aim of reversed shear MAST discharges: sustaining shear reversal for as long as possible. Investigate ITB.

Two main scenarios:

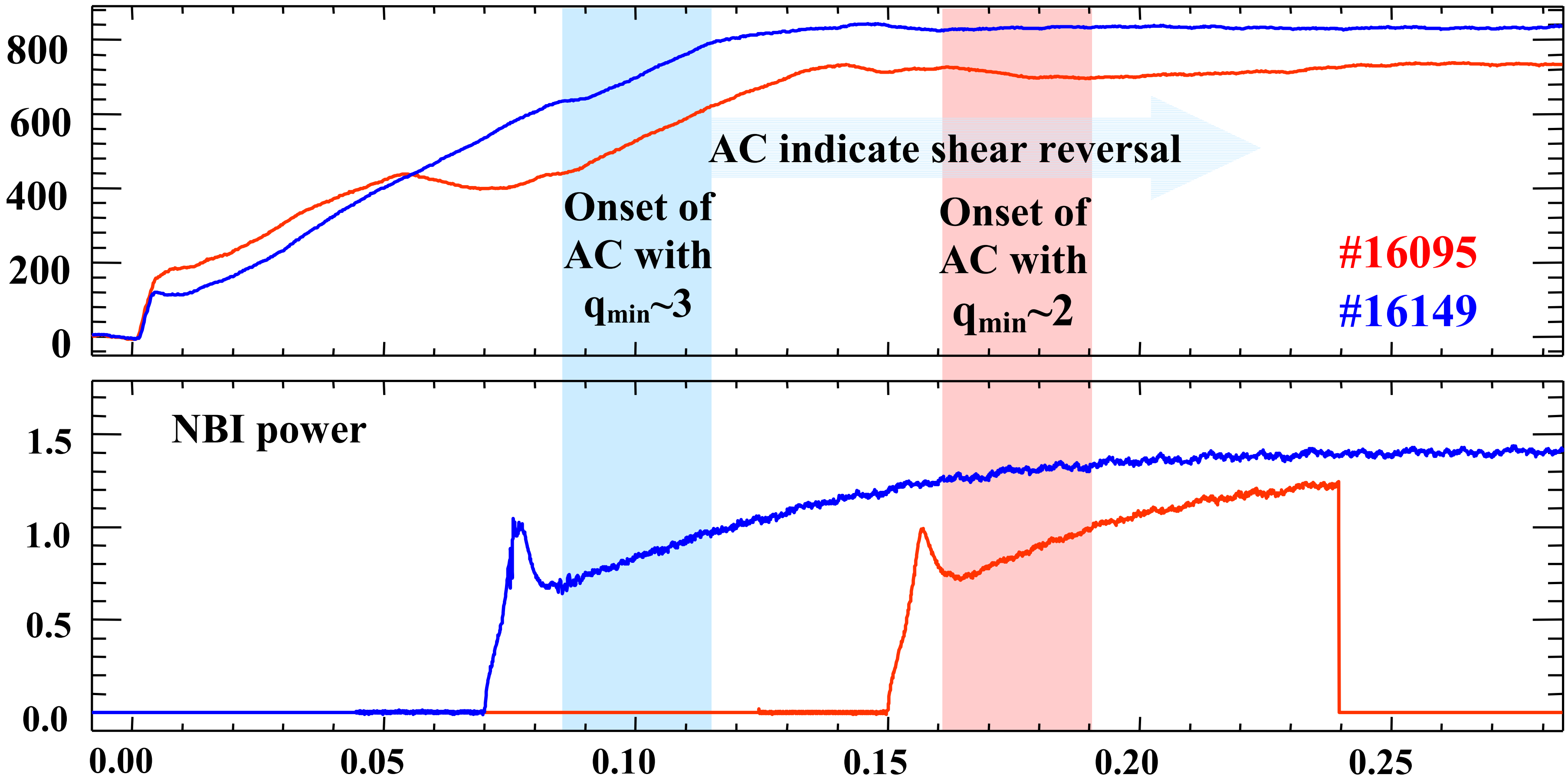
1. **scenario with a two-step current ramp-up and NBI applied late, at 130 msec, and**
2. **a scenario with fast, about 5 MA/s, ramp-up of the current and NBI applied early, e.g. at 70 ms**

The first scenario was aimed at studying ACs and ITBs at the time of $q_{\min} = 2$ appearing in the plasma.

The second scenario was aimed at ACs and ITBs associated with the magnetic surface $q_{\min} = 3$ entering the plasma.

Both scenarios show ACs and, occasionally, ITBs, with somewhat higher temperature, $T_i \approx T_e \approx$ 1.2 keV, in the first scenario.

TEMPORAL EVOLUTION OF CURRENT IN TWO SCENARIOS

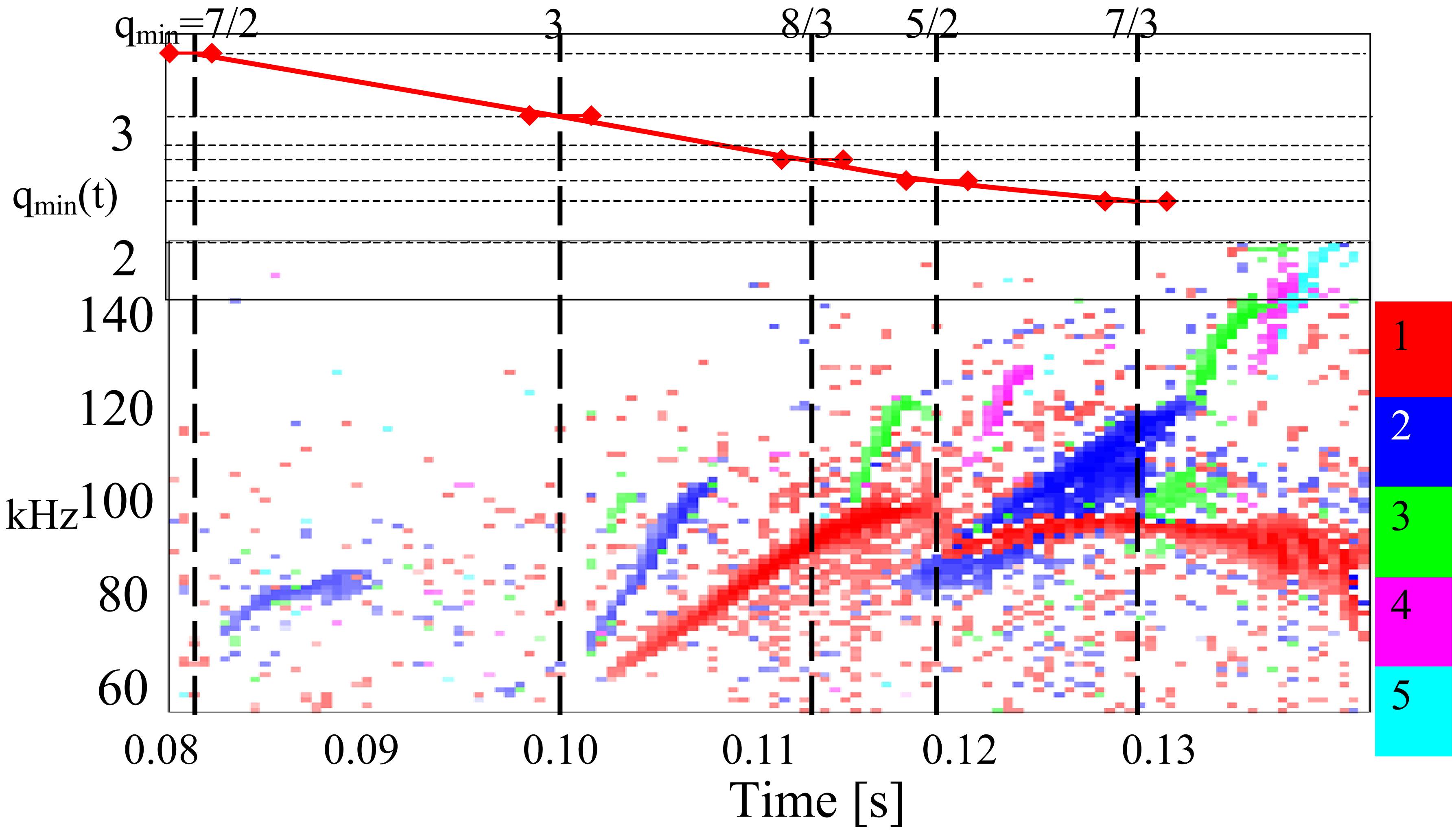


AC indicate shear reversal

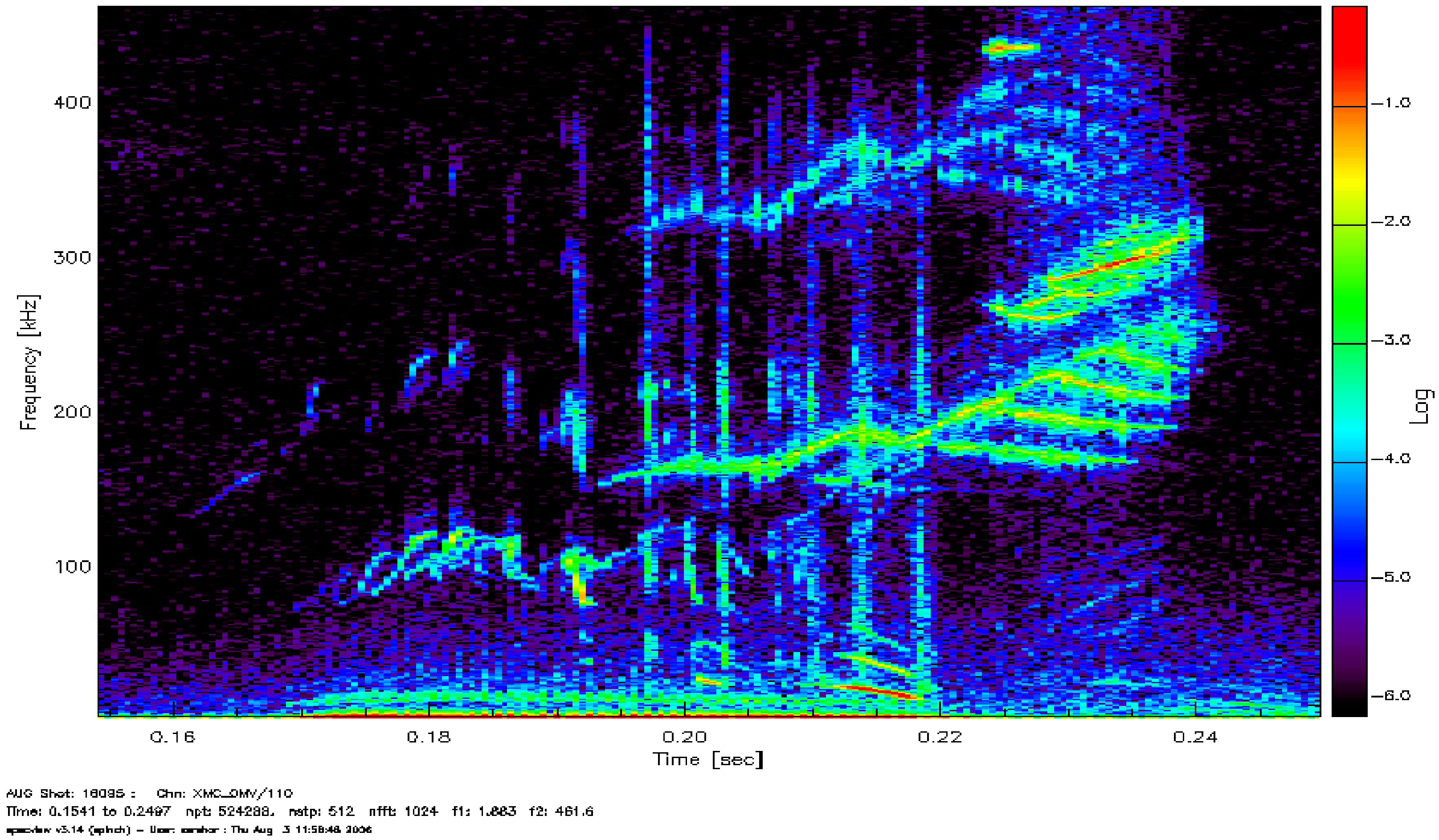
Onset of AC with q_{min}~3

Onset of AC with q_{min}~2

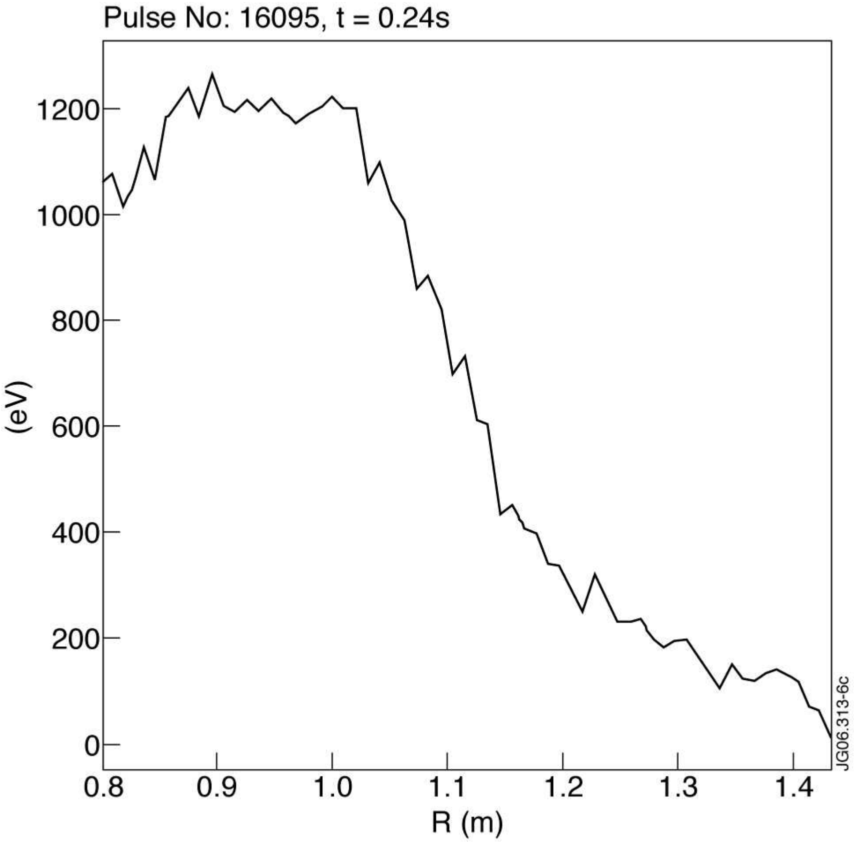
Alfvén cascades and $q_{min}(t)$ in fast current ramp case (#16149)



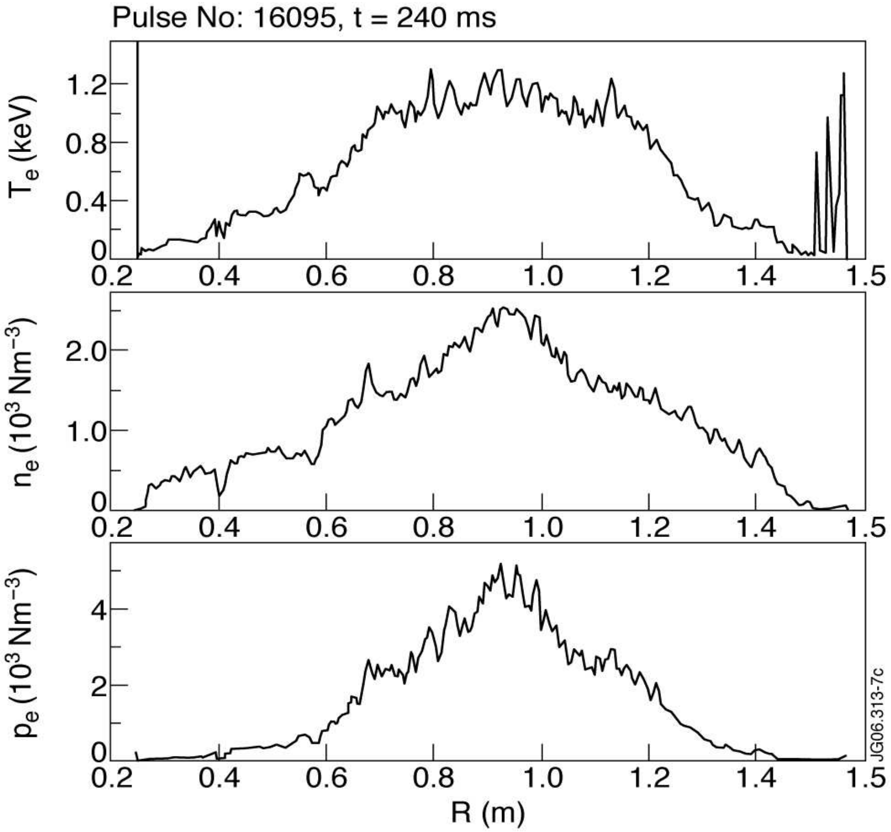
ACs and TAEs in “current double ramp-up” discharge



ITB FORMATION SEEN IN T_i PROFILE, LESS CLEAR IN T_e, n_e



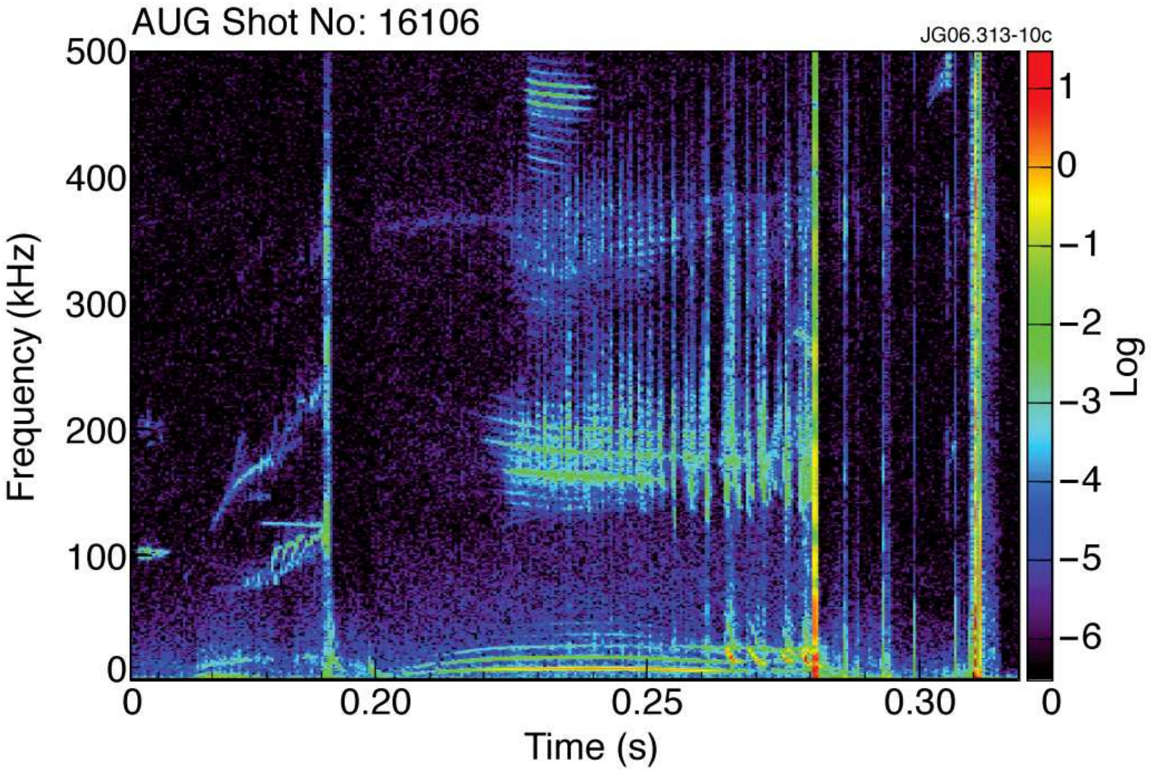
Ion temperature profile



Profiles of electron temperature, density, and pressure

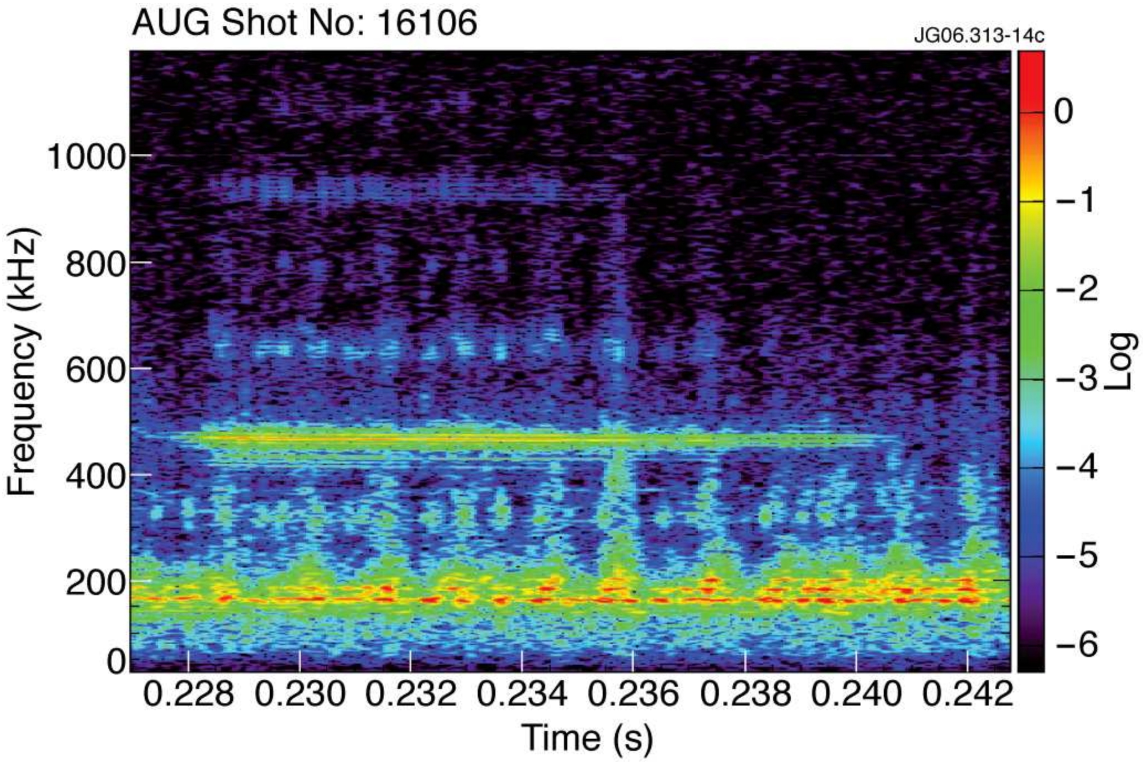
HIGH-FREQUENCY MODES DETECTED

- **At current ramp-up exceeding 5 MA/sec, MHD event prevents AC existence indicating non-sustained shear reversal**



HIGH-FREQUENCY MODES DETECTED

- High-frequency modes are observed then with the new high-frequency magnetic coils
- Analysis under way to identify the modes



SUMMARY

- Confinement of energetic trapped ions arising from hydrogen minority ICRH was investigated in the presence of tornado modes on JET

- NPA data show that density of confined ICRH-accelerated protons with energy E in the range 290 keV – 1.1 MeV decreases when low-n (n<4) tornado mode appears just before monster sawtooth crash. Temperature of energetic protons increases somewhat after sawtooth crashes.

- Measurements of confined deuterons with E>500 keV (accelerated by 2nd harmonic ICRH) using gamma-ray spectrometry shows a decrease of such deuterons during tornado mode activity

- Flux of lost energetic ions from JET plasma measured with new scintillator has some increase of losses during tornado modes. These are most likely to be protons with E>1.2 MeV and deuterons with E>0.6 MeV; more accurate analysis is under way.

- Tornado modes with both positive and negative toroidal mode numbers (bi-directional) are observed in some JET discharges. Modelling of the ICRH distribution function shows monotonic profiles of energetic ions and indicates that the excitation of bi-directional modes may be associated with a significant temperature anisotropy in these discharges.

- Bi-directional TAEs are also observed after some monster sawtooth crashes.

- Alfvén cascades have been observed for the first time on the Spherical Tokamak MAST.

- Best conditions for observing ACs on MAST are established to be associated with a moderation of NBI power driving the modes.

- Two advanced ST scenarios are developed with AC excitation revealing evolution of q_{min}. In both cases, ACs are observed well into the current flat-top phase showing the sustained shear-reversal until $q_{min}=1$ occurs. ITBs are present in some of these discharges.

INTERFEROMETRY ON MAST ALSO SEES ACs, BUT NOT BETTER THAN MAGNETICS