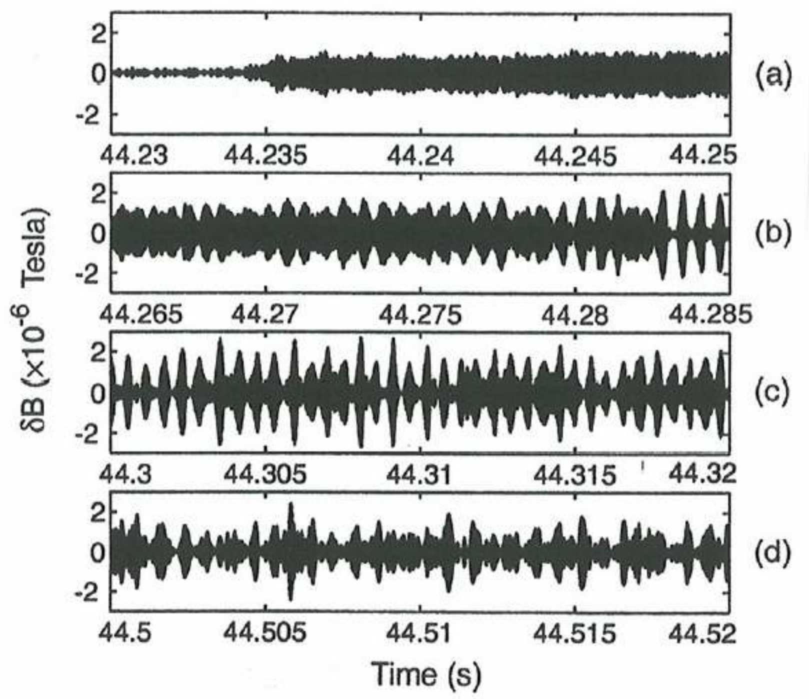
EXPERIMENTALLY OBSERVED NONLINEAR SCENARIOS OF ENERGETIC ION DRIVEN ALFVÉN EIGENMODES

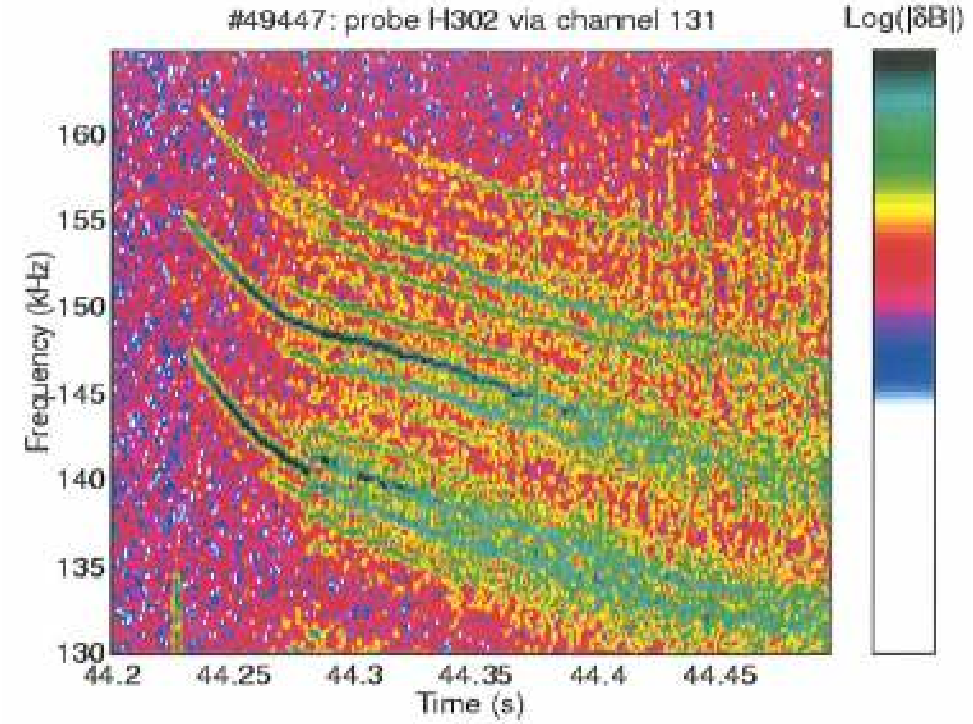
S.E. Sharapov and M.P. Gryaznevich

Euratom/CCFE Fusion Association,
Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK

TAEs DRIVEN BY ICRH AND NBI HAVE DIFFERENT TEMPORAL EVOLUTION

ICRH-GENERATED F$_{HOT}$ DRIVES NEARLY STEADY-STATE TAE

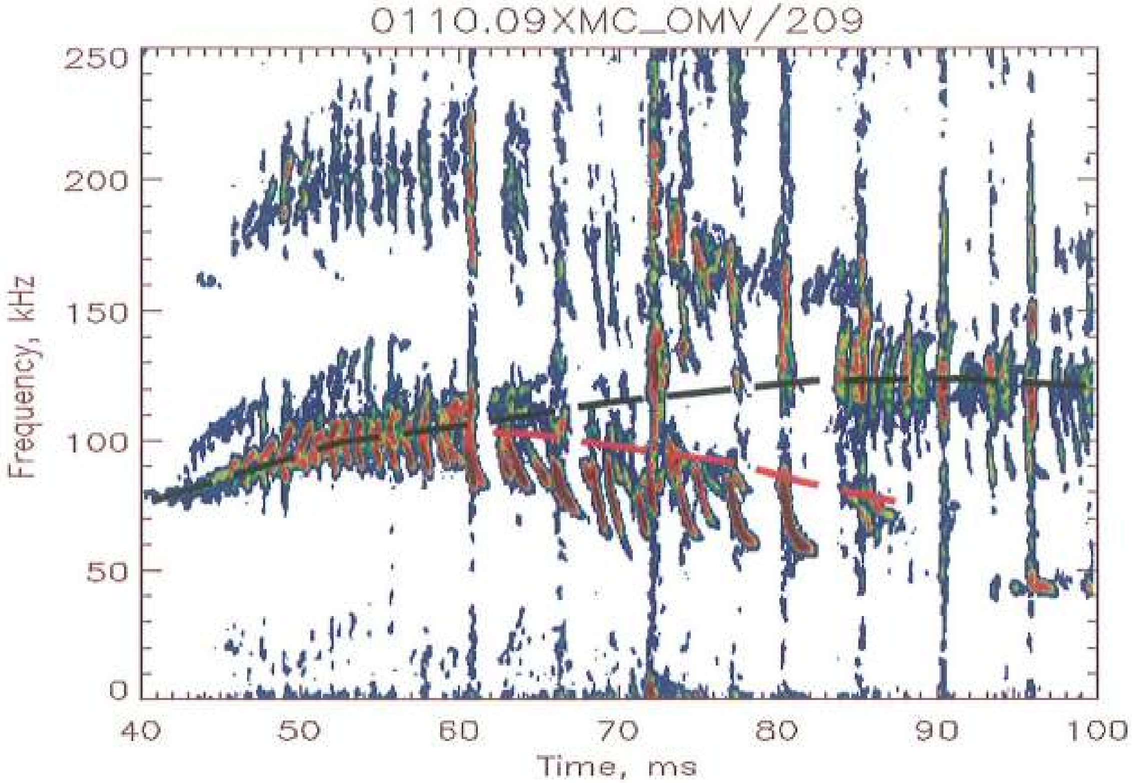




At gradually increasing ICRH power, TAEs exhibit steady state, periodically modulated, and chaotic regimes (JET)

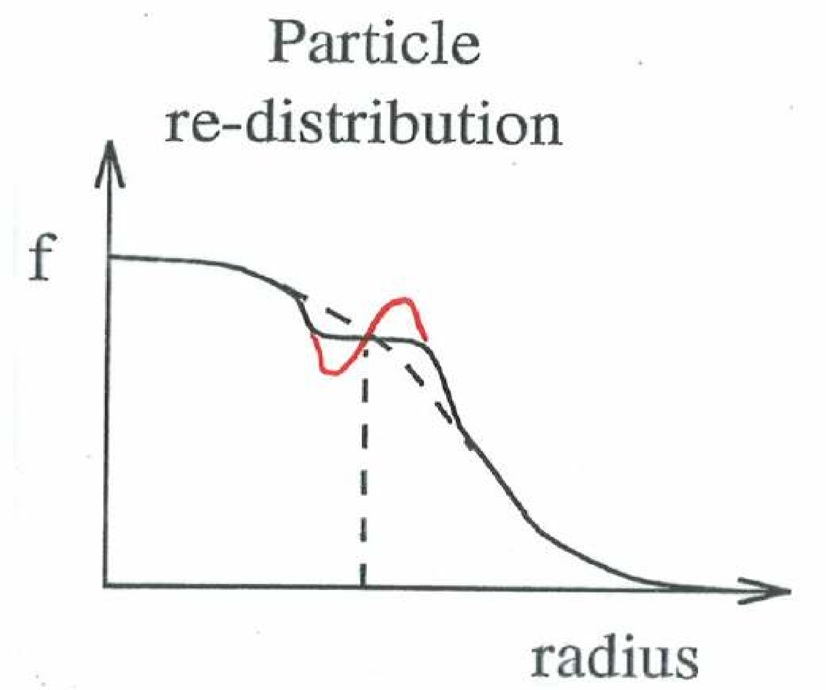
Magnetic spectrogram corresponding to the left Figure with raw data. Steady state, periodically modulated (pitchfork splitting), and chaotic regimes are seen

NBI-PRODUCED F$_{HOT}$ DRIVES BURSTING AE



Majority of NBI-driven AEs on MAST have bursting amplitudes and significant frequency sweeping

NONLINEAR EVOLUTION OF TAE INSTABILITY



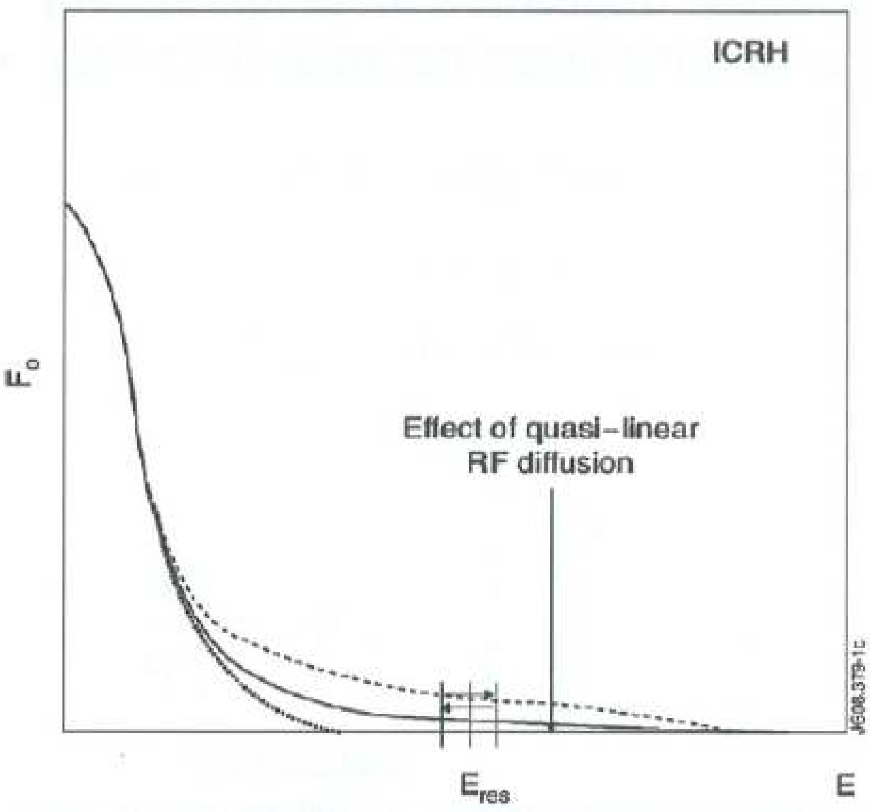
- **Non-linear TAE evolution near the instability threshold is determined by the competition between *the field of the mode* that tends to *flatten* distribution function near the resonance (effect depends on $\gamma \equiv \gamma_L - \gamma_d$) and *the collision-like processes* that constantly *replenish* it (effect depends on ν_{eff})**

1-D BUMP-ON-TAIL MODEL WITH COLLISIONAL OPERATOR

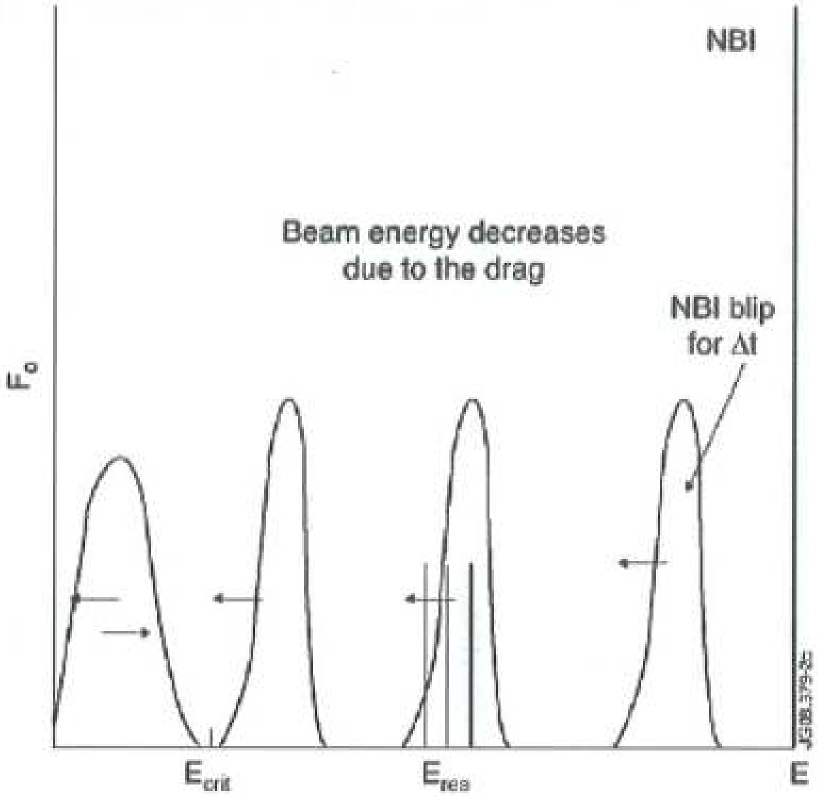
- **Nonlinear near-threshold model *for the "bump-on-tail"* problem in a *1D velocity* space with collisions has successfully reproduced the main qualitative features of the experimentally observed data [M.Lilley's talk].**

- **The nonlinear temporal evolution is determined by dominant diffusion or drag effects restoring the unstable F_{HOT}**

EFFECTS RESTORING F_{HOT} NEAR THE RESONANCE



ICRH REPLENISHES FAST ION DISTRIBUTION
VIA QUASILINEAR RF-DIFFUSION



NBI RESTORES FAST ION DISTRIBUTION
VIA COULOMB DRAG AND DIFFUSION

1-D BUMP-ON-TAIL MODEL WITH COLLISIONAL OPERATOR

- However, the 1D bump-on-tail model shows also some qualitatively new nonlinear modes occurring as a result of the competing diffusion and drag:

  1) holes with a constant frequency;

  2) “hook”-type frequency evolution;

  3) “snaking”-frequency holes.

- Search for similar experimental phenomena on present-day machines is important for validating the theory

- Possible anomalies found in the mode evolution could indicate the applicability conditions and the directions for further studies.

NBI-DRIVEN TAE ARE BETTER SUITED FOR COMPARING THE DRAG AND DIFFUSION EFFECTS

ASSESSING DRAG VS DIFFUSION FOR TAE

- **Introduce the resonance**

$$\Omega_l \equiv \omega - n < \dot{\varphi} > - l < \dot{\vartheta} >= 0$$

where

$$< \dot{\varphi} >= \omega_\varphi \left(E,\ P_\varphi,\ \mu\right)\ , < \dot{\vartheta} >= \omega_\vartheta \left(E,\ P_\varphi,\ \mu\right)$$

- **NBI distribution function can be assessed from Fokker-Plank equation with Coulomb collisional operator:**

$$\frac{\partial f}{\partial t} = \frac{V_0^3}{\tau v^2} \left\{ \frac{\partial}{\partial v} \left[\frac{V_0^2 a(v)}{2v} \frac{\partial f}{\partial v} + b\left(v\right) f \right] + \frac{c\left(v\right)}{V_0} \cdot \frac{1}{\sin \vartheta} \frac{\partial}{\partial \vartheta} \left[\sin \vartheta \frac{\partial f}{\partial \vartheta} \right] \right\} - \nu f + pF$$

- **We are interested in evolution of distribution function *across* the TAE resonance**

$$\left.\frac{dF}{dt}\right|_{coll} = \frac{\partial}{\partial \mathbf{v}} \cdot \mathbf{D} \cdot \frac{\partial f}{\partial \mathbf{v}} + \frac{\partial}{\partial \mathbf{v}} \cdot \mathbf{b} f = \left\langle \frac{\partial P_\phi}{\partial \mathbf{v}} \cdot \mathbf{D} \cdot \frac{\partial P_\phi}{\partial \mathbf{v}} \right\rangle \left(\frac{\partial \Omega}{\partial P_\phi} \right)^2 \frac{\partial^2 f}{\partial \Omega^2} + \left\langle \frac{\partial P_\phi}{\partial \mathbf{v}} \cdot \mathbf{b} \right\rangle \left(\frac{\partial \Omega}{\partial P_\phi} \right) \frac{\partial f}{\partial \Omega}$$

DRAG VS DIFFUSION FOR TAE DRIVEN BY PASSING NBI IONS

- **The comparison of the drag and diffusion terms can be express via resonance width:**

$$\frac{(\Delta\Omega_{\rm Diff})^6}{(\Delta\Omega_{\rm Drag})^6} \approx \left\langle \frac{\partial P_\phi}{\partial \mathbf{v}} \cdot \mathbf{D} \cdot \frac{\partial P_\phi}{\partial \mathbf{v}} \right\rangle^2 \left(\frac{\partial \Omega}{\partial P_\phi} \right) \left\langle \frac{\partial P_\phi}{\partial \mathbf{v}} \cdot \mathbf{b} \right\rangle^{-3}$$

- **Substitute physics parameters at $V_{\parallel\,\rm beam} = V_A$ and obtain**

$$\frac{(\Delta\Omega_{\rm Diff})^6}{(\Delta\Omega_{\rm Drag})^6} \approx mS\tau \frac{c}{eB_0} \frac{E_{\rm A}}{r^2} \frac{\theta_b^4}{2} \frac{27}{64} \left(\frac{\pi m_b}{m_e} \right)^{3/2} \left(\frac{T_e}{E_{\rm A}} \right)^{9/2}$$

- **The competition between electron drag and diffusion due to Coulomb collisions in the TAE resonance region is essentially determined by T_e/E_A ratio**

MAST IS WELL-SUITED FOR STUDYING NONLINEAR REGIMES OF NBI-DRIVEN AEs WITH DOMINANT DRAG EFFECT AT $V_{llbeam} = V_A$ RESONANCE

MAST PARAMETERS

R, m	a, m	κ	I_{pl}	B_{tor}, T	E_{NBI}, keV	P_{NBI}, MW	$\tau_{NBIpulse}$, s	β_t, % (*)	β_{fast}, % (**)	β_{fast} / β_t (**)	τ_{SD}, s (**)	n_e / n_e^G	τ_{pulse}, s
0.8	0.6	≤ 2.8	≤ 1.35	0.4 – 0.7	40 – 65	≤ 3.3	≤ 0.4	≤16	≤ 5	≤ 0.8	≤ 0.2	≤ 2	≤ 0.7

(*) – EFIT analysis;
(**) – TRANSP/LOCUST analysis [Gryaznevich et al., Nucl. Fusion 2006]

Due to the low magnetic field, Alfvén velocity on MAST is low

$V_A = (1-3)\times 10^6\ \ m/s$ (JET has $V_A = 7\times 10^6\ \ m/s$),

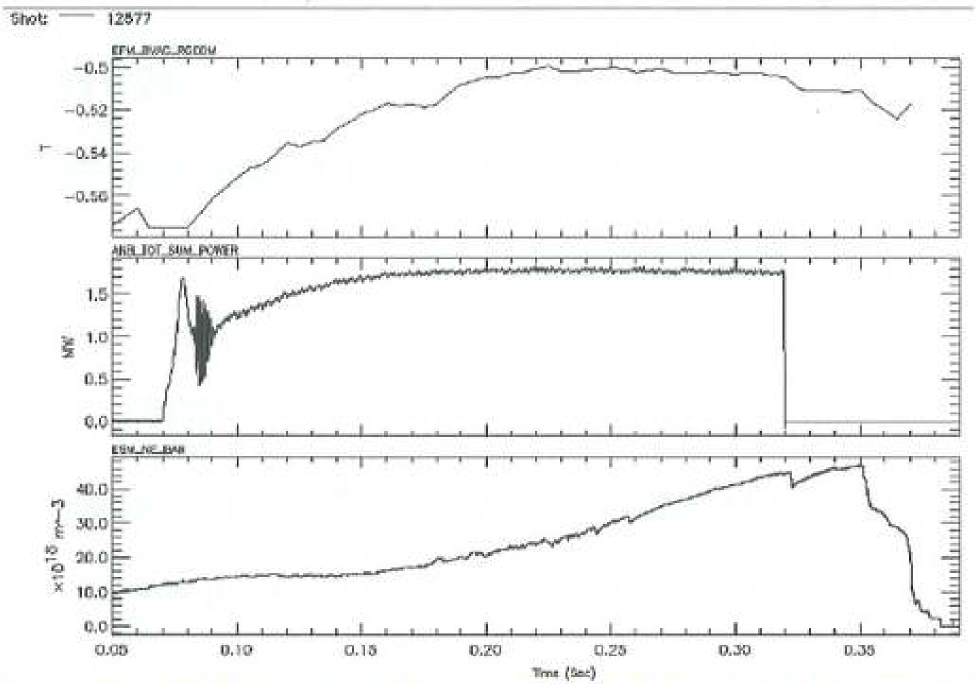
so that NBI is usually super-Alfvénic,

$V_{NBI} > V_A$,

and the drag may globally dominate at the resonance

$$E_A = \frac{m_D V_A^2}{2} >> E_{crit} = 16.5 T_e$$

TEMPORAL EVOLUTION OF PLASMA PARAMETERS

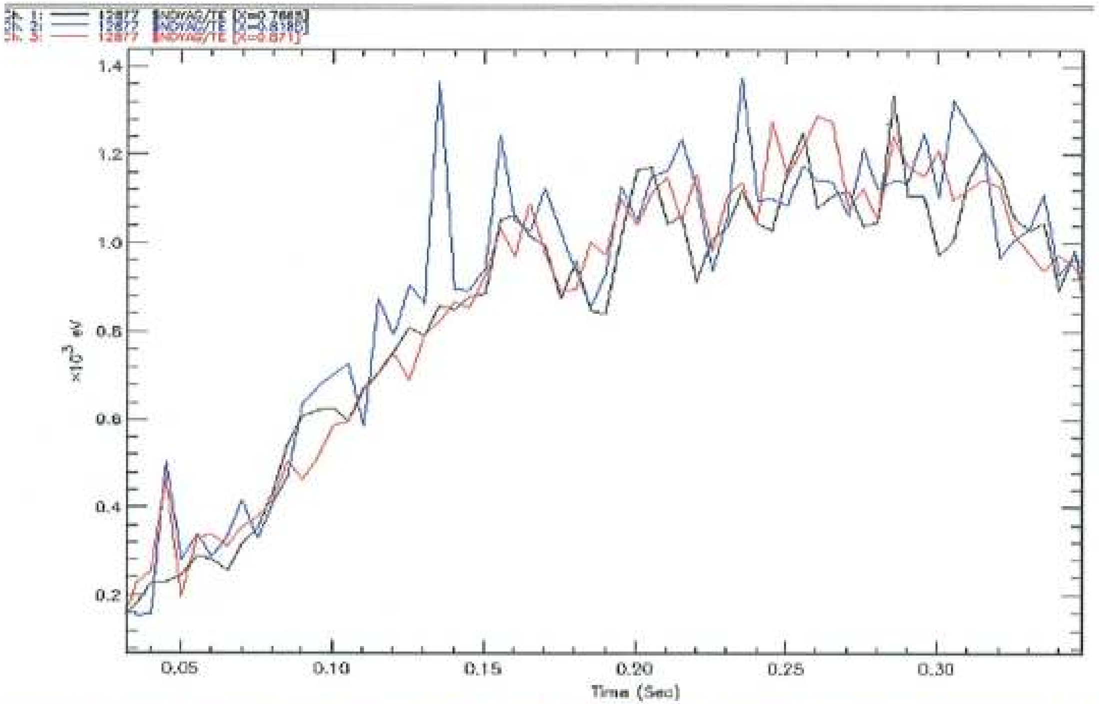


Magnetic field (T), NBI power (MW), and on-axis electron density (m^{-3}) in MAST discharge #12877

- At the start of NBI, electron density is quite low,

$$n_e(0) \approx (1-1.5)\times 10^{19}\, m^{-3}$$

TEMPORAL EVOLUTION OF ELECTRON TEMPERATURE



Electron temperature measured at 3 points near magnetic axis

- **At the start of NBI, electron temperature is also low,**
  $$T_e(0) \approx (0.4 - 0.6)\ keV$$

THE START OF NBI IS THE BEST OPTION FOR THE SEARCH:

$$n_e(0) \approx (1-1.5)\times 10^{19}\, m^{-3};$$

$$T_e(0) \approx (0.4-0.6)\ keV$$

$$\downarrow$$

$$E_A \equiv \frac{1}{2} m_D V_A^2 \approx 40\ \ keV >> E_{crit} = 16.5 T_e \approx 8\ \ keV$$

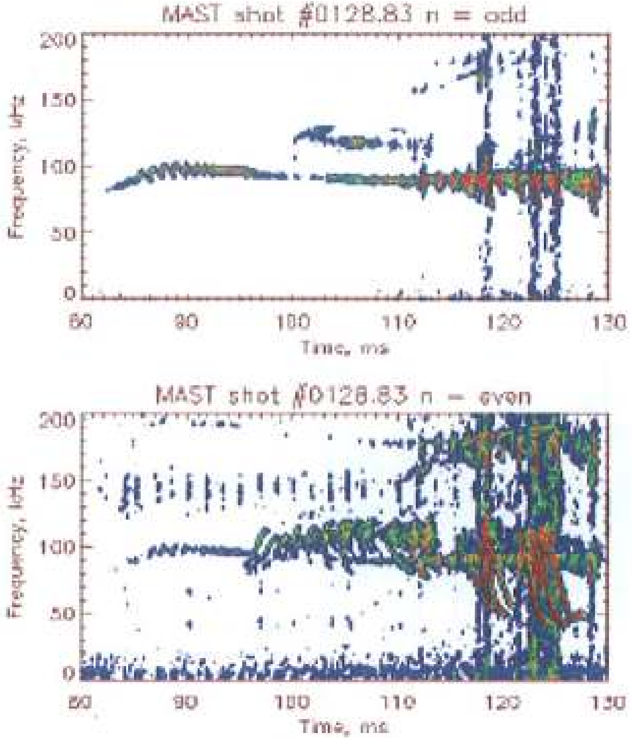
$$\frac{(\Delta\Omega_{\mathrm{Diff}})^6}{(\Delta\Omega_{\mathrm{Drag}})^6} \approx mS\tau \frac{c}{eB_0} \frac{E_{\mathrm{A}}}{r^2} \frac{\theta_b^4}{2} \frac{27}{64} \left(\frac{\pi m_b}{m_e}\right)^{3/2} \left(\frac{T_e}{E_{\mathrm{A}}}\right)^{9/2}$$

$$\downarrow$$

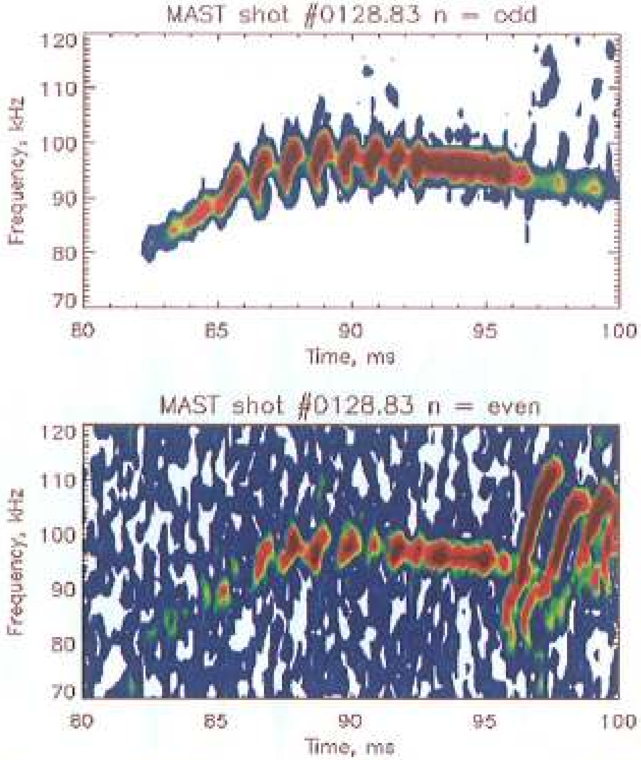
$$\frac{\Delta\Omega_{Diff}}{\Delta\Omega_{Drag}} \approx 0.1 \div 0.8$$

HIGH AMPLITUDE TAE WITH STEADY-STATE FREQUENCY FOUND IN THE EARLY PHASE OF DISCHARGES

STEADY-STATE TAE: POSSIBLE OBSERVATION OF STEADY-STATE BGK MODE SIMILAR TO M.LLILLEY's MODELLING

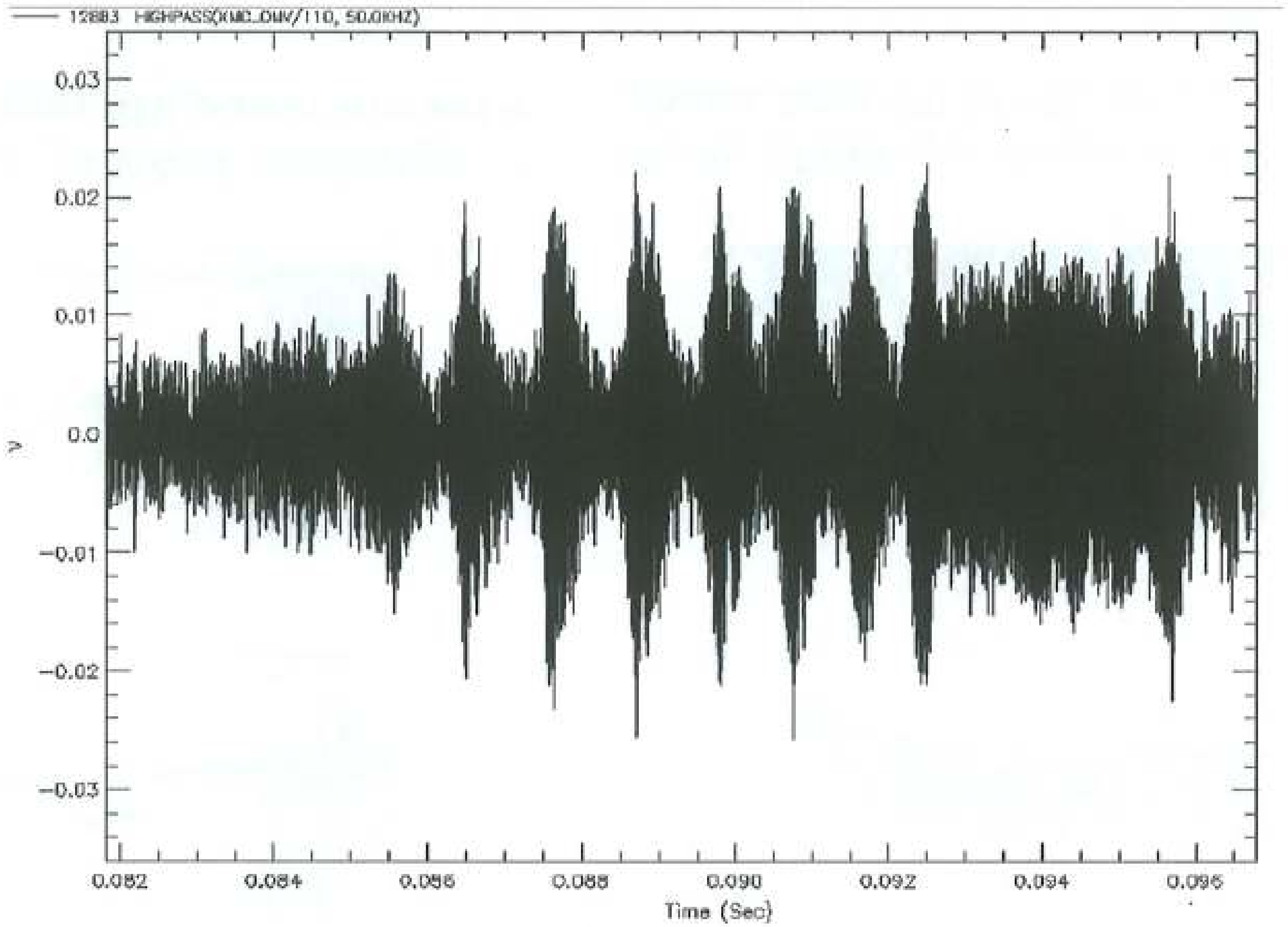


TAE excited in MAST discharge #12883 during NBI power increase



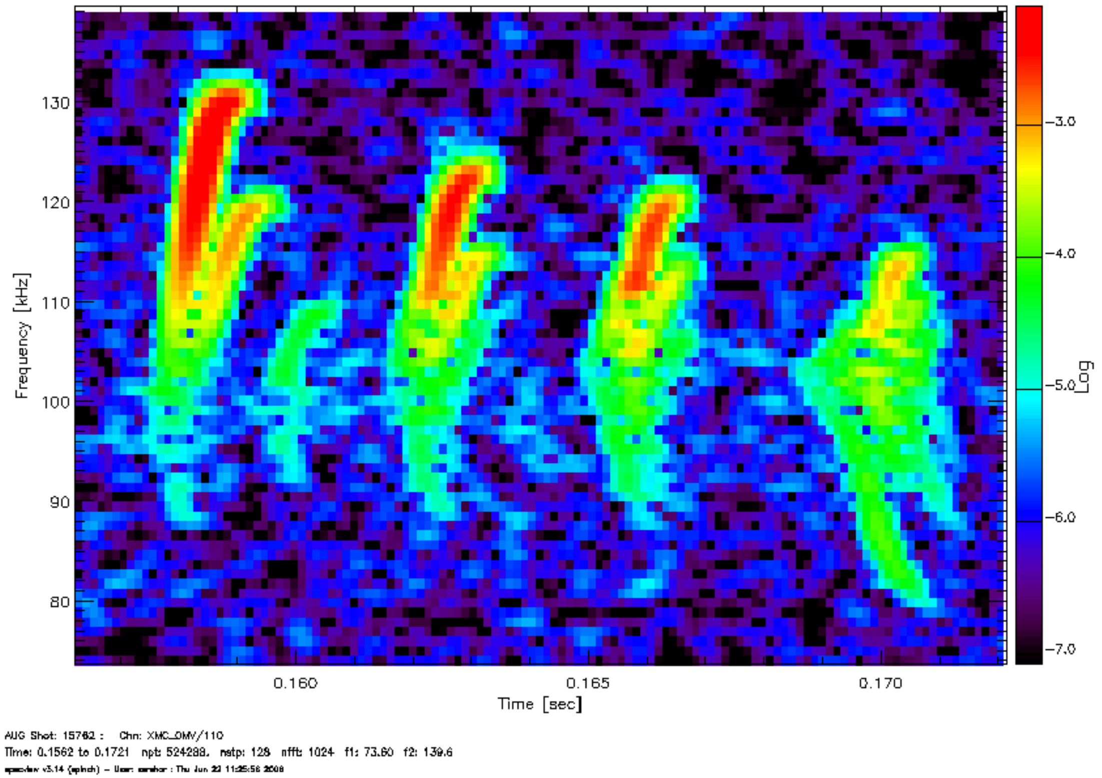
Zoom of the spectrogram in the early phase, from 80 to 100 msec

HIGH AMPLITUDE STEADY-STATE TAE IN THE DRAG CASE



TAE WITH A HOOK TYPE FREQUENCY EVOLUTION ARE SEEN AT SOMEWHAT HIGHER RATIO OF $\Delta\Omega_{Diff}/ \Delta\Omega_{Drag} \approx 0.5$

POSSIBLE CANDIDATE FOR THE HOOK FREQUENCY EVOLUTION

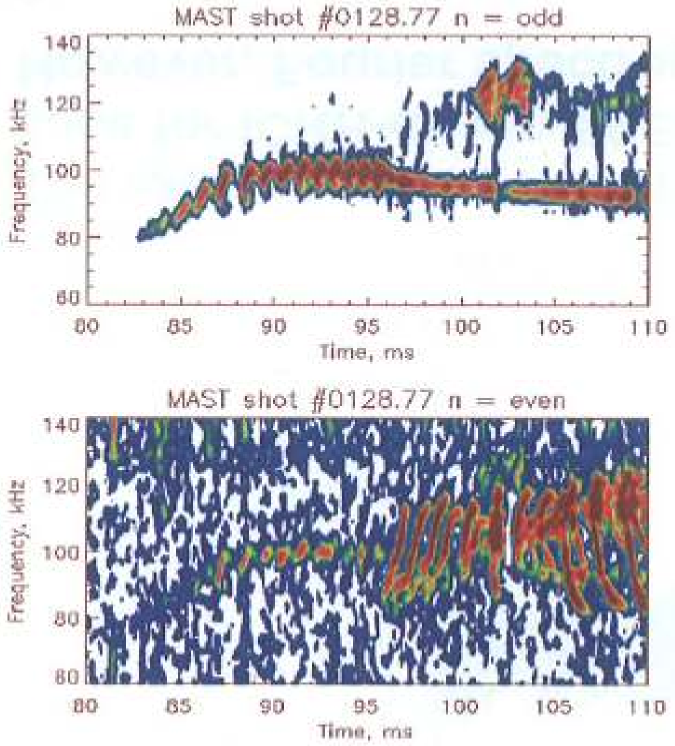


These modes are seen at somewhat higher ratio of $\Delta\Omega_{Diff}/\Delta\Omega_{Drag} \approx 0.5$, in line with the stronger competition between the drag acting to deepen the hole and diffusion that acts to destroy the hole

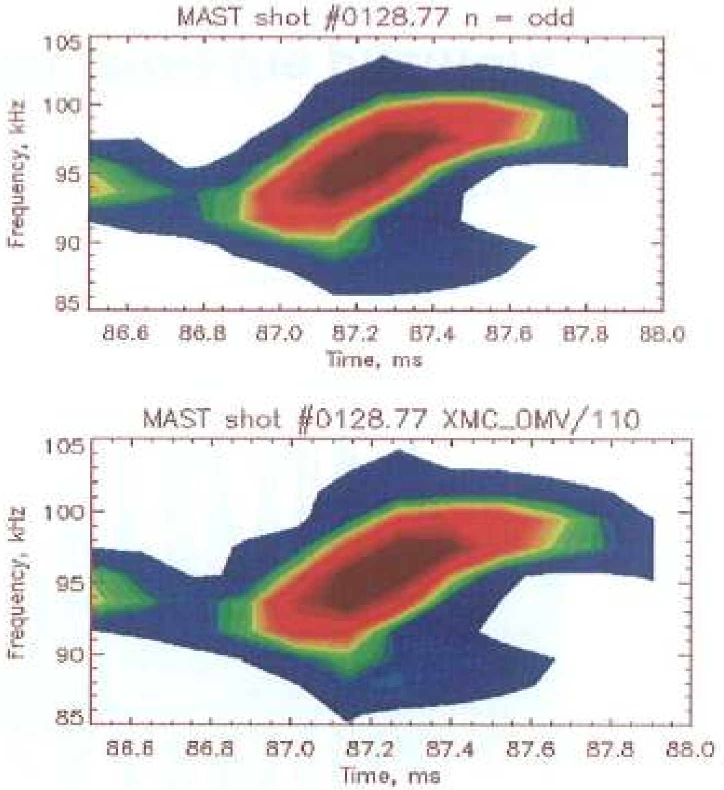
S.E.Sharapov, IAEA TCM on Energetic Particles, Austin, September 6-9, 2011

“SNAKING” FREQUENCY TAE

POSSIBLE CANDIDATE FOR THE "SNAKING" FREQUENCY MODE

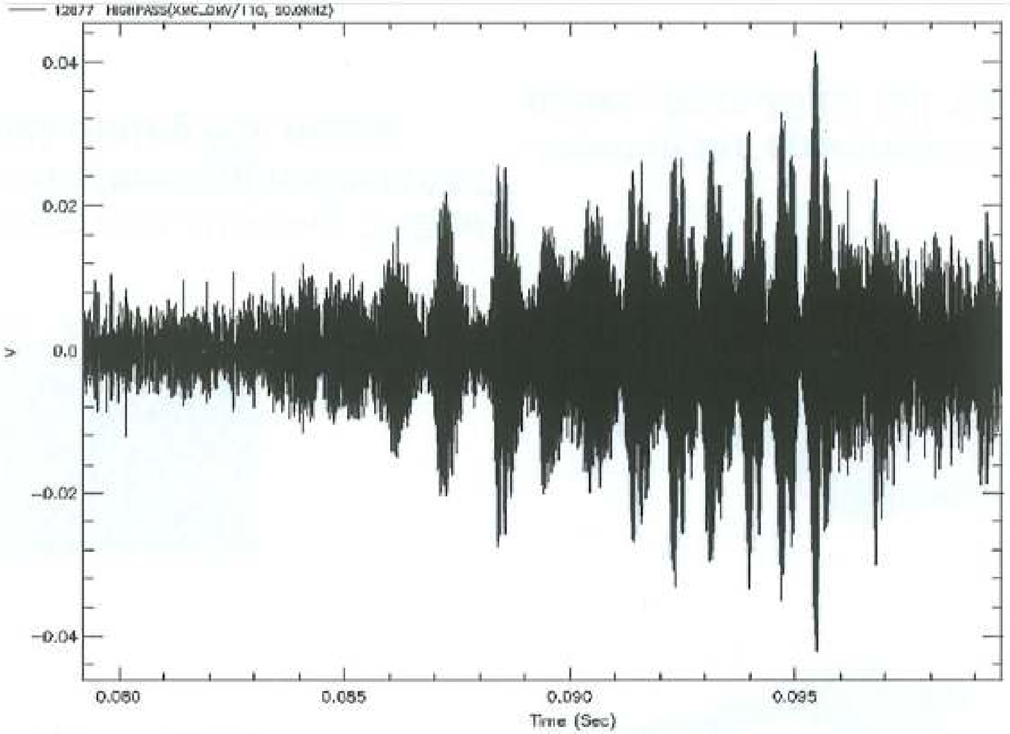


Magnetic spectrograms showing TAE of odd (top) and even (bottom) n's in MAST discharge #12883 during NBI power increase



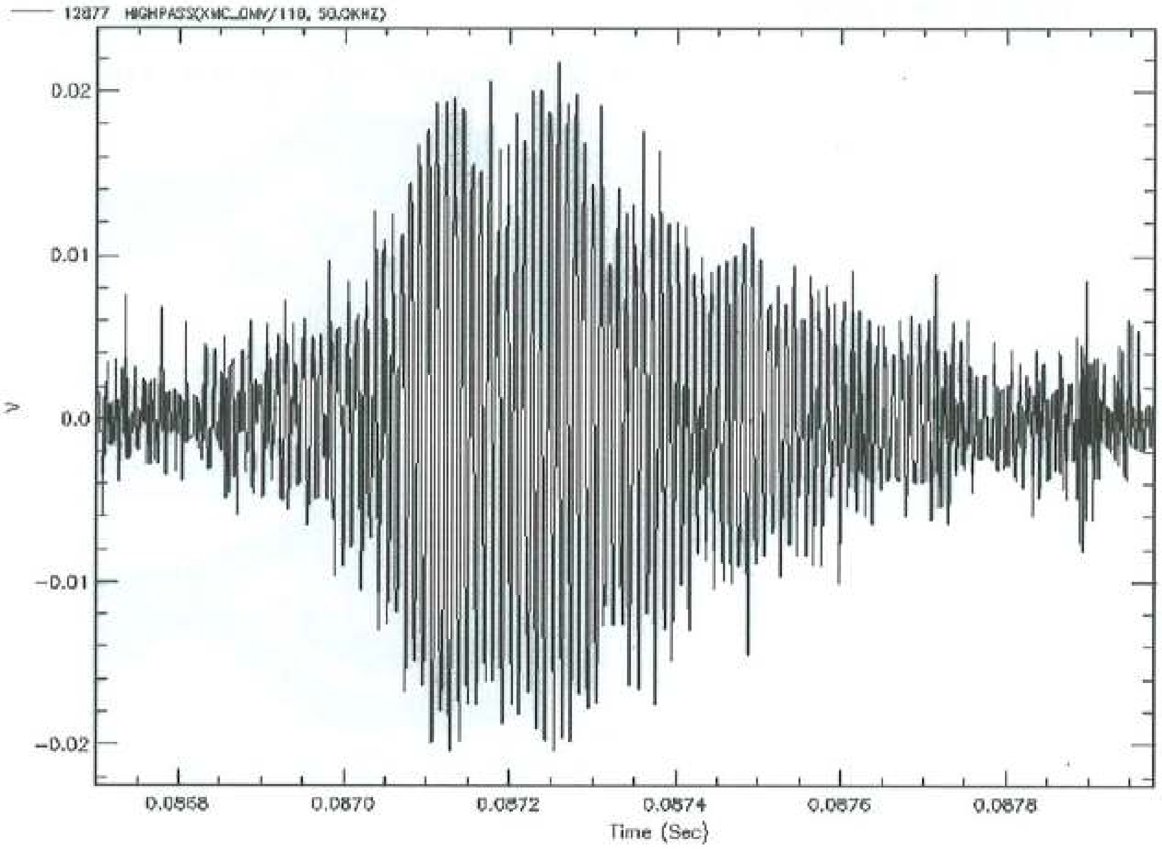
Zoom of the spectrogram in the early phase, from 80 to 100 msec

THE BACK TRANSITION TO LOW AMPLITUDE TAE @ t>95 ms

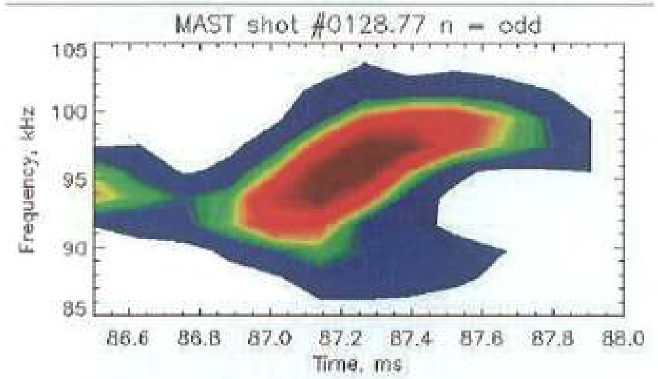


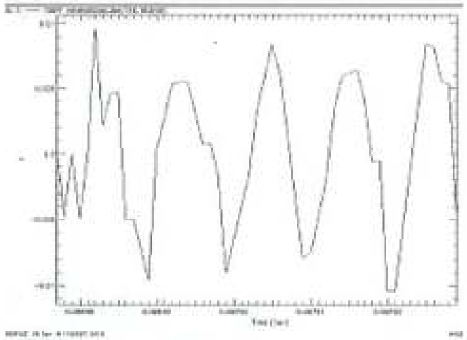
- The raw data looks from first glance very similar to the "pitchfork" splitting case for ICRH-driven TAEs on JET.
- However, Fourier spectrogram does not show the pitchfork. Why?

CONSIDER A SINGLE PERIOD BURST

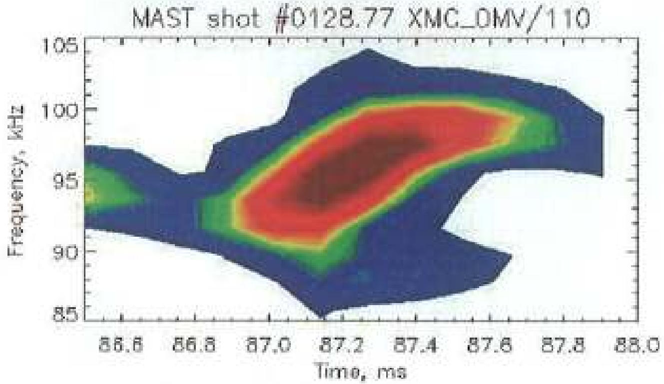


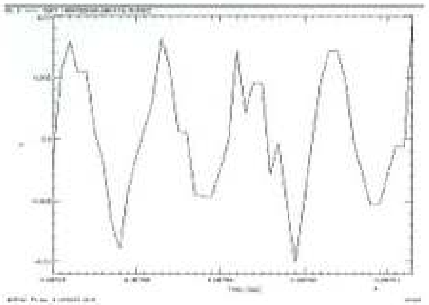
THE FREQUENCY SWEEP CO-EXIST WITH THE AMPLITUDE MODULATION MAKING THE PITCHFORK SPOILED





t = 87.0 ms, 90kHz

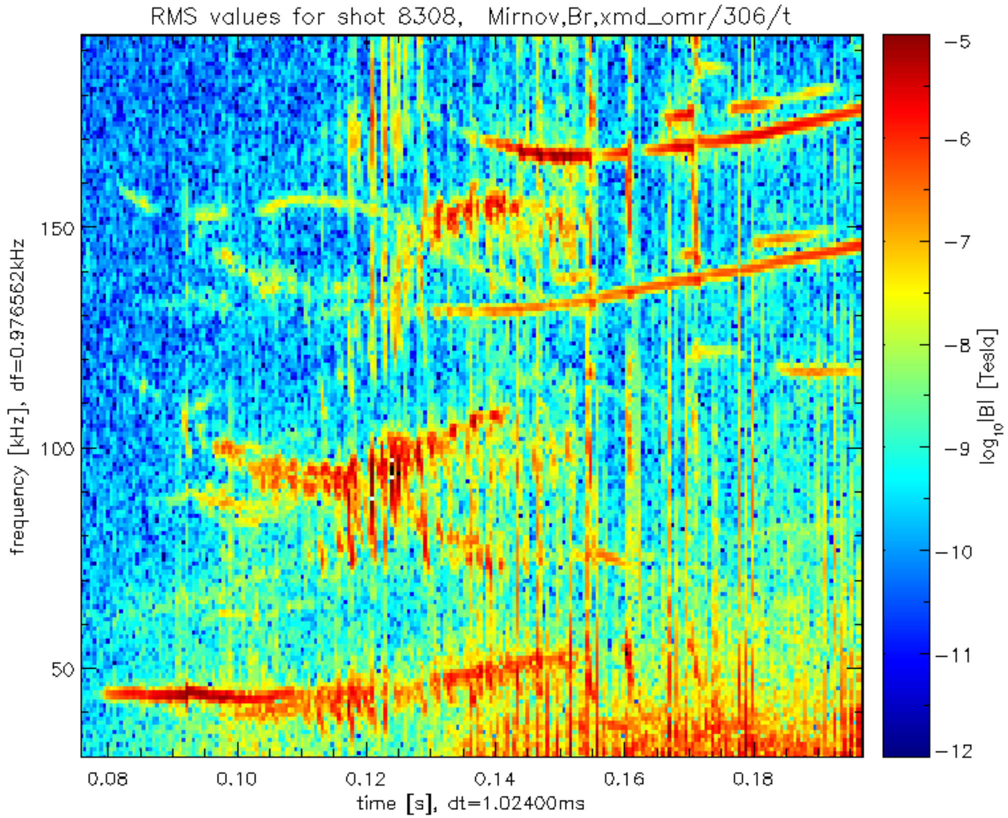




t = 87.6 ms, 100kHz

STEADY-STATE TAE OBSERVED IN PLASMAS WITH COUNTER-INJECTED NBI

STEADY-STATE TAE DRIVEN BY COUNTER-NBI



$B_T(0)$=0.5 T, $T_e(0)$≈650 eV, E_{NBI}≈50 keV > E_A >> E_{crit}

SUMMARY

- NBI-driven AEs in MAST discharges with strongly dominant electron drag at $V_{\parallel \mathrm{beam}}=V_A$ resonance, $\Delta\Omega_{Diff}/\Delta\Omega_{Drag} \approx 0.1 - 0.8$, are found to exhibit:

1) Bursting amplitude TAE with up- and down-sweeping of frequency (absolute majority of cases);
2) High amplitude nonlinear AE with nearly constant frequency;
3) Up-sweeping AE with frequency evolution close to the “hook” evolution;
4) High-amplitude AE with “snaking” frequency evolution.

- Strong interaction between modes is observed in some cases requiring development of the multi-mode theory

- MAST experiments with improved set of diagnostics will be performed for the set of reference discharges above.

- Experimental observation of steady-state TAE in MAST discharges with counter-NBI could be considered as anomaly incompatible with the drag-dominated scenario. Further investigation is required of both the type of the resonance driving AE and the distribution function in the resonance region.