# Energetic particle-driven MHD observations on STs and their relevance to a Next Step Burning Plasma ST.

**M. P. Gryaznevich,** K.G. McClements, S. E. Sharapov and MAST team.
*EURATOM/UKAEA Fusion Association, Culham Science Centre,*
*Abingdon, Oxfordshire, OX14 3DB, UK*
*tel 44-1235-463667; fax. 44-1235-464192*
*E-mail: mikhail.gryaznevich@ukaea.org.uk*

Alfvén eigenmodes [1] excited by supra-thermal ions with velocities comparable to the Alfvén velocity have been extensively studied in magnetic fusion devices since they have the potential to redistribute fusion-born alpha-particles in the core of a fusion reactor, limiting the reactor operational regime [2]. In present-day neutral beam-heated STs the use of low magnetic fields, and plasma densities comparable to those of conventional tokamaks, implies a lower Alfvén speed and hence a lower beam energy threshold for the excitation of Alfvénic instabilities (via the fundamental $v_{\mathrm{beam}} = v_A$ resonance, where $v_A \sim B_T\, n_e^{-0.5}$ is the Alfvén speed). The experimental study of these modes in STs provides an opportunity to test theoretical models [3], which could then be applied to alpha-particles physics predictions for a burning plasma and reactor-scale tokamaks.

Several types of high frequency MHD activity were observed on START during the first experiments with neutral beam injection [4,5]. Already during the first MAST and NSTX campaigns, a rich variety of high frequency MHD activity that may be associated with toroidal Alfvén eigenmodes (TAEs) [1,9] and energetic particle modes (EPMs) [6], has been observed. Rapid chirping activity has been observed in most neutral beam heated shots. Finally, high-frequency broad-band activity has been observed in many ohmic discharges on MAST, often preceding an increase in low-frequency MHD. Typical examples of different types of activity observed are shown in Figures 1 and 2, where Mirnov coil spectrograms and a Fourier power spectrum for two neutral beam heated MAST discharges are presented.

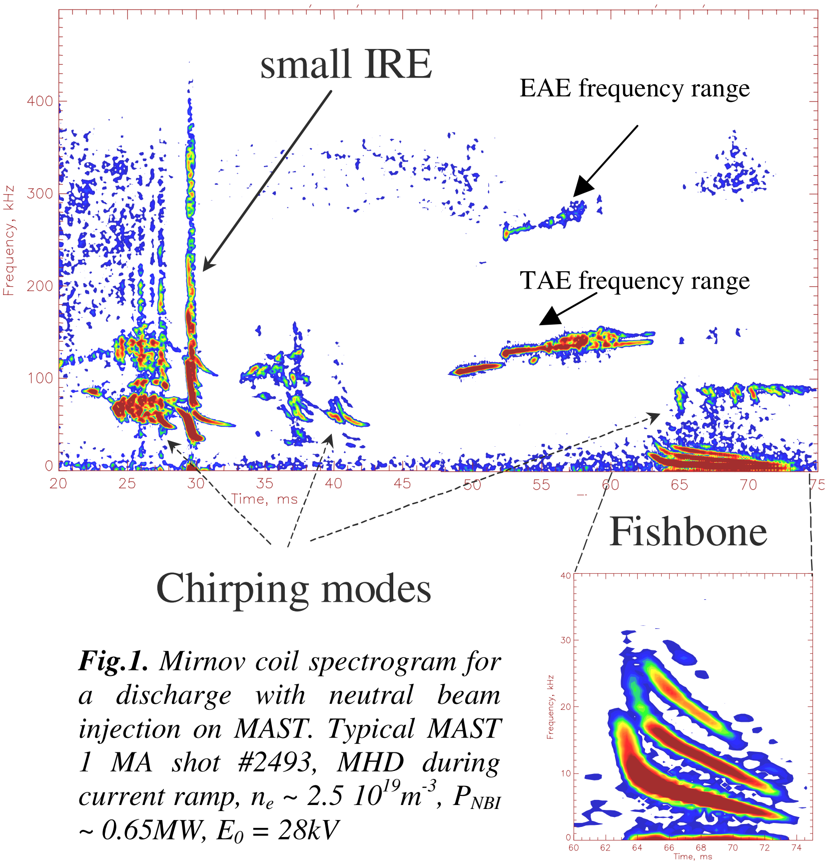

***Fig.1.*** *Mirnov coil spectrogram for a discharge with neutral beam injection on MAST. Typical MAST 1 MA shot #2493, MHD during current ramp,* $n_e \sim 2.5\ 10^{19} m^{-3}$, $P_{NBI} \sim 0.65 MW$, $E_0 = 28kV$

This activity includes discrete, closely-spaced modes, believed to be TAEs and EAEs [9], occurring during neutral beam injection (Fig.1, t = 48 – 63 ms; Fig.2, t = 55 – 90 ms). The appearance of high frequency ($f$ ~ 100 - 300$kHz$) modes with a TAE-like spectrum has been previously observed in NBH discharges on START [4,5] over a range of different conditions at moderate NBI powers. There is also evidence of fast particles in the NPA spectrum and Alfvénic mode activity following sawtooth crashes in both NBI and ohmic heated discharges on MAST.

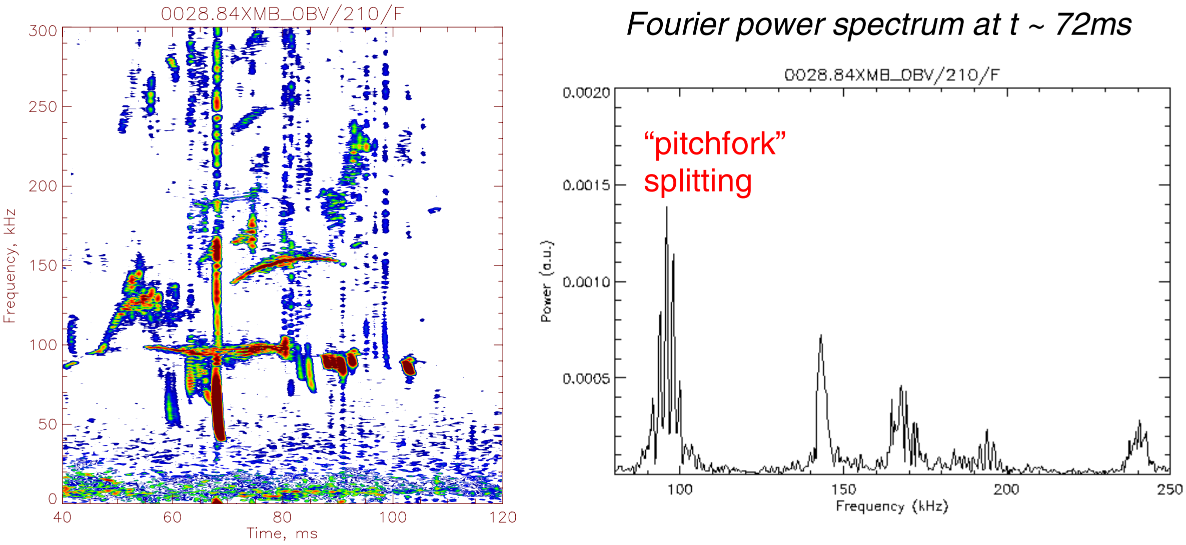

***Fig.2.*** *Long-lasting ($\tau$ > 20ms) modes with fine "pitchfork" splitting in TAE and EAE frequency ranges on MAST. Note that chirping modes at t ~ 80ms start from the TAE frequency (~ 100kHz). Shot #2884, $P_{NBI}$ ~ 0.77MW.*

Chirping modes have been observed on START and MAST in discharges with neutral beam injection. The mode usually appears before the sawtoothing phase of a discharge as a series of high-frequency "bursts" on the Mirnov coils and soft X-ray signals, and "whistles" down a factor of two in frequency in a single 0.2 - 0.3 ms burst (Fig.1, t = 23 – 42 ms). The starting mode frequency on START scales with the Alfvén speed $v_A$ [7]. On MAST, in some cases chirping modes were preceded by a TAE mode and started from the TAE frequency: see Fig.2, t = 80 ms.

Fishbones are usually observed during or just before the sawteething phase [4], (Fig.1, t = 63 – 75 ms) in NBH discharges. Although there is no evidence of a strong effect of fishbones or chirping modes on plasma heating and confinement, in high performance shots on START with $\beta_T \geq 30$ % these modes were weak or absent. The question of whether or not TAEs or EPMs would be expected to affect the NBI heating efficiency in STs will be addressed in conjunction with recent observations on NSTX of enhanced (anomalous) ion heating [8].

Anti-ballooning bursting modes lasting 0.5-2ms occurred at $f$ ~ 0.6 – 1 MHz in some NBI shots on START [5]. The instantaneous bandwidth was < 200kHz and the frequency generally exceeded the toroidal Alfvén eigenmode gap frequency (~150kHz), but was lower than the beam ion gyrofrequency $f_b$ ~ 2-3MHz) and did not scale with the Alfvén speed.

Equilibrium reconstructions of discharges with high frequency mode activity (obtained using the EFIT code) are used to compute continuous spectra of shear Alfvén waves. These spectra contain wide gaps (Fig.3) within which weakly-damped discrete modes could be driven unstable by energetic particles. For the case of beam-driven TAE-like activity, independent codes NOVA [10] & MISHKA [11] give consistent results for TAE mode frequencies & structure.

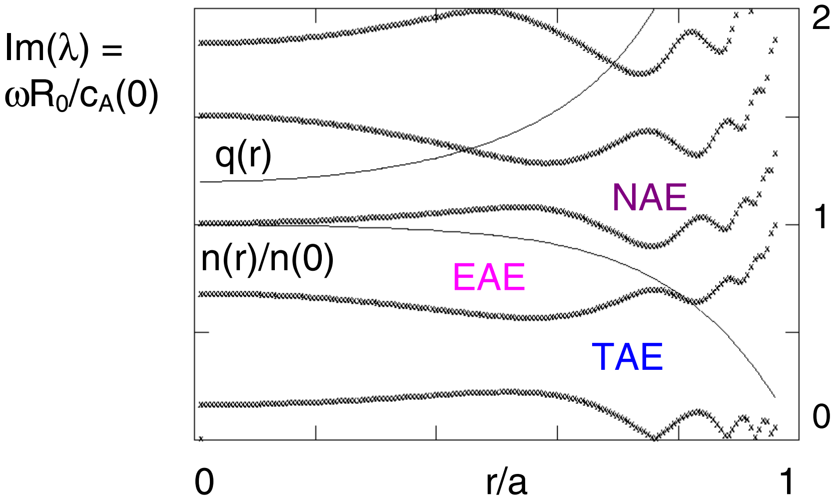

***Fig.3.*** *Structure of the ideal MHD continuum spectrum for n = 1 START shot #35305, t = 26.3ms from CSCAS. Im(λ) = 1 corresponds to f ~ 540kHz*

Fast particle distributions have been calculated for START discharges using the Monte-Carlo code LOCUST [12]. Analysis shows that the drive for AE is determined by the radial gradient of NBI pressure and the existence of a stationary bump-on-tail in the NBI energy distribution function. Several theoretical explanations of chirping modes have been proposed. Non-linear theory shows a symmetric up and down frequency chirping due to “hole-clump” generation in the distribution function [13]. Sometimes, these types of chirping modes have been indeed observed on MAST. However, chirping-down modes are more frequently seen. Also, the starting frequency often does not coincide with the TAE-frequency: an empirical scaling shows a $B_t\, n_e^{-0.5}\, \beta_t^{-0.75}$ dependence for the starting frequency [7]. This may be caused by a deficit of fast ions above the resonance velocity [14] in which case the modes may represent linear EPMs.

These results make it possible to investigate possible anomalous regimes of α-confinement in burning plasmas. JET, TFTR and DIII-D have already demonstrated that α-particle heating of electrons is consistent with the classical slowing down mechanism [2,15]. However, recent studies show [16], that the ion heating by α-particles in tokamaks may be not consistent with classical models and remains to be explained. Energetic particle-driven MHD Alfvén eigenmodes and chirping modes may affect plasma heating and confinement and cause problems in achieving the required Q-values. Plasmas in a burning ST device during current ramp-up and heating phases with low central shear and high edge pressure gradients may be affected by different new types of Energetic particle-driven MHD activity and longer resonant interaction between waves and energetic ions due to smaller shear. Small shear also affects the threshold for stochastic diffusion [17].

## Conclusions.

There is no experimental evidence to date that Energetic particle-driven MHD modes can significantly affect the performance of burning ST plasmas. No Energetic particle-driven MHD activity has been observed in high-β regimes on START and the energy losses in other regimes were low (unlike DIII-D). However, more activity has been seen on MAST and NSTX (long-lasting TAE modes and chirping modes during flat-top; new types of TAE-range modes in ohmic and NBH discharges). Further studies may change conclusions based on the START data. The main problem with Energetic particle-driven MHD modes during the burning phase may be connected with α-particle losses that could damage the first wall.

Good experimental data on EPD MHD modes in STs has already been obtained. More data is needed on:

- fast particle losses due to EPD MHD, IREs and sawteeth in the high-β burning plasma relevant regimes with low magnetic shear;
- energy losses due to EPD MHD activity in high-β high performance regimes;
- EPD MHD modes in collisionless high-bootstrap plasmas;
- quantitative analysis of mode amplitudes.

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