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Excitation of Alfvén Eigenmodes with Sub-Alfvénic Neutral Beam Ions in JET and DIII-D Plasmas

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* See annex of M. L. Watkins et al, "Overview of JET Results",
(Proc. \square IAEA Fusion Energy Conference, Chengdu, China (2006)).

INTRODUCTION

The condition for the excitation of Alfvén eigenmodes is one of the most basic properties of fast ion driven instabilities that must be understood in order to predict the stability of modes in the burning plasma regime. Until recently the quantitative data available on the excitation condition for Alfvén eigenmodes was limited due to the lack of sensitive core fluctuation diagnostics on the one hand and the use of Ion Cyclotron Resonant Heating (ICRH) excitation on the other where the tail ion temperature is typically not known with high accuracy. However, new data obtained on the JET [1,2] and DIII-D [3,4] devices using sensitive core fluctuation diagnostics and precisely calibrated neutral beam injection velocities reveal for the first time (a) a much lower velocity threshold for the excitation of Alfvén eigenmodes than previously observed and (b) high sensitivity of mode excitation to the direction of neutral beam injection. The asymmetry in beam direction can be attributed to differences in the fast ion distribution owing to finite orbit width effects and to a possible intrinsic sensitivity of these modes to the direction of the particle. These observations are particularly relevant to advanced confinement regimes where core localized Alfvénic activity is readily excited in existing experiments.

DIAGNOSTIC SETUP

Fast ion driven Alfvén instabilities require an efficient energy exchange between the particles and the waves; i.e. a resonance condition. In most cases, such as with the Toroidicity induced Alfvén Eigenmodes (TAE), the main resonance occurs at $V_A = V_b$ and $V_A/3 = V_b$. However, in reversed shear scenarios, eigenmodes exist localised in the zero shear region and lead to Alfvén Cascades, also known as Reversed Shear Alfvén Eigenmodes (RSAE). Due to the time evolution of the safety factor (q) profile, Alfvén Cascades sweep in frequency from values $\omega_{AC} \ll \omega_{TAE} \sim \omega_A/2$ well below the TAE frequency. At these lower frequencies, Alfvén Cascades will resonate with ions well below the Alfvén velocity $V_b < V_A$ [5].

In addition, efficient energy exchange between the mode and the particles requires the radial mode width Δ_m to be larger than the radial orbit particle drift Δ_p . Since the radial mode width is inversely proportional to the toroidal mode number (n) and magnetic shear (s) $\Delta_m \propto 1/(ns)$, in conventional scenarios instability is limited to low mode numbers, $n < 10$. In reversed shear scenarios, the presence of a region of zero shear ($s=0$) allows larger mode numbers ($n > 10$) to be excited in the plasma core. Core localised waves with large n , invisible to external diagnostics such as magnetic sensors, require internal measurements for the detection and study of these instabilities.

The diagnostic setups in JET and DIII-D have recently been upgraded to allow core resolved measurements of fluctuations in the Alfvén frequency range. In JET, the data acquisition system of the far infrared DCN interferometer have been modified so that 3 vertical chords out of the 4 available channels measure line-integrated density fluctuations $\Delta n_e L$ where L is the path length in the plasma. New waveguides installed for the microwave reflectometer system allow for greatly improved radial localized density fluctuation measurements using O-mode and X-mode propagation, shown in figure 1. In JET, the far infrared DCN interferometer diagnostic is the most versatile diagnostic for providing

information on the instabilities throughout the discharge over a very wide range in density. This interferometer system is analogous to the CO₂ interferometer system on DIII-D [6] but operating at much longer wavelengths.

The O-mode microwave reflectometer system is used as an interferometer in the JET experiments reported here owing to the low operating density. This system provides the best signal to noise ratio for viewing the core localized modes, but relies on the density being close to, but not exceeding, the plasma frequency. Operating in the Xmode, the reflectometer is able to detect NBI driven Alfvén cascades and give valuable information on the radial location as shown in Figure 1. The magnetic probes are only sensitive to low toroidal mode number instabilities ($n=2,3,4$), due the radial extent of these modes. In DIII-D, a CO₂ interferometer with 4 chords (three vertical and one radial), allows line-integral DneL fluctuations measurements. In addition a recently upgraded Beam-Emission Spectroscopy (BES) system provides spatially localized measurements of Δn_e with increased sensitivity and Far-Infrared Scattering (FIR) allows line-integrated measurement of density fluctuations over a large range of wavenumbers.

EXPERIMENTAL SETUP

The JET experiments reported here focus on the study of the fast ion energy dependence on the excitation of Alfvén Cascades. Neutral Beam Injection (NBI) heating sources with different energies were used for this purpose at the maximum magnetic field in order to minimise V_b/V_A . Keeping the main plasma parameters constant; magnetic field, $B_T = 3.46\text{T}$, plasma current, $I_p = 2.1\text{ MA}$, density $n_e = 10^{19}\text{ m}^{-3}$, and using 2MW of Lower Hybrid Current Drive (LHCD) to create reversed magnetic shear, low power ($\sim 3\text{MW}$) NBI was injected at difference voltages (50keV, 80keV and 117keV). A similar scan was performed on DIII-D however due to the plasma parameters it was not possible to reduce the beam to Alfvén velocity ratio V_b/V_A much below 0.35. However a new capability on DIII-D is the rotated neutral beam line allowing the exploration of the directional sensitivity of Alfvén Cascade excitation.

In DIII-D the resulted reported in this paper are for the following plasma conditions: magnetic field $B_T = 2.1\text{T}$, plasma current, $I_p = 1.1\text{MA}$, density $n_e = 2 \times 10^{19}\text{ m}^{-3}$ —and using low power ($\sim 5\text{MW}$) NBI injected in the co and counter direction with beam voltage 80keV ($V_b/V_A = 0.4$).

EXPERIMENTAL RESULTS FROM JET AND DIII-D

With the highest beam ion energy on JET of 117 keV, Alfvén cascades with various toroidal mode numbers ($n > 2$) were observed in the frequency range between 30kHz and 140kHz. By decreasing the beam energy to 80keV, the Alfvén Cascades were still observed but with reduced signal strength on a range of diagnostics. At 50keV injection energy corresponding to $V_b = V_A/6$, Alfvén instabilities are still observed in the Alfvén frequency range between 40kHz to 60kHz (Figure 2). This confirms that Alfvén Cascades can be driven by fast ions with velocities well below the Alfvén velocity (V_A). In ITER, $V_b = V_A/6$ corresponds to alpha particles in the range of 100keV.

Experiments in DIII-D, showed that the number of Alfvén eigenmodes is much reduced in the case of dominant counter neutral beam injection (Figure 3). This asymmetry could be due to the difference in drive due to finite orbit width effects on the radial distribution of co/counter going ions and/or on an intrinsic sensitivity of the mode to ion direction [7]. This result suggests that Alfvén eigenmodes driven by passing ions, the dominant drive mechanism expected in ITER, may be sensitive to the direction of the ion motion.

EVOLUTION OF MINIMUM OF Q SURFACE

It has been shown that the observation of Alfvén cascades can be used to accurately track the evolution of the minimum of q surface in reversed shear scenarios [8]. The excitation of Alfvén cascades using NBI and the improved capability of measuring these instabilities in the plasma core with high n, significantly expands this capability. In JET and DIII-D, it was possible to identify the Alfvén instabilities patterns corresponding to qmin crossing 3 integer surfaces. At JET, these results are consistent with the measurements using the Motional Stark Effect (MSE) diagnostic shown in Figure 4. Therefore, information from the Alfvén waves can be used to reconstruct the q-profile evolution more accurately and validate the MSE measurements in these discharges.

CONCLUSIONS

These results demonstrate that Alfvén instabilities, in particular Alfvén Cascades, can be excited by passing sub-Alfvénic ions in the velocity range $0.1 < V_b/V_A < 0.3$. This suggests that a significant interaction can take place for nearly thermalized alpha particles in a reactor, particularly in advanced confinement regimes where there is a significant region of extended weak magnetic shear in the plasma core. In addition, the asymmetry in beam direction suggests that the interaction of these modes with the energetic particles may induce preferential redistribution of passing ions with one sign of the parallel velocity. Such an interaction may be used to tailor the current drive in advanced tokamak regimes [9].

ACKNOWLEDGEMENTS

This work was carried out under the European Development Agreement, supported in part by DOE contracts DE-AC02-76CH03073, DE-FC02-04ER54698, DE-FG03-01ER54615, SC-G903402 and supported by the European Communities and “Instituto Superior Técnico”, has been carried out within the Contract of Association between EURATOM and IST. Financial support was also received from “Fundação para a Ciência e Tecnologia” in the frame of the Contract of Associated Laboratory. The views and opinions expressed herein do not necessarily reflect those of the European Commission, IST or FCT.

REFERENCES

- [1]. S. Sharapov et al., Phys. Rev. Lett. **93**, 165001 (2004)
- [2]. H.L. Berk et al., Phys. Rev. Lett. **87**, 185002 (2001)
- [3]. R. Nazikian et al., Phys. Rev. Lett. **96**, 105006 (2006)
- [4]. M. Van Zeeland et al., Phys. Rev. Lett. **97**, 135001 (2006)
- [5]. S.E.Sharapov et al., Nuclear Fusion **46** (2006) S868
- [6]. M. VanZeeland et al., Plasma Phys. Control. Fusion **47** L31-L40 (2005)
- [7]. B.N.Breizman et al., Physics of Plasmas **10** (2003) 3649.
- [8]. E. Joffrin et al., Plasma Phys. Control. Fusion **44** (2002) 1739–1752
- [9]. K.L. Wong et al., Phys. Rev. Lett. **93**, 085002 (2004)

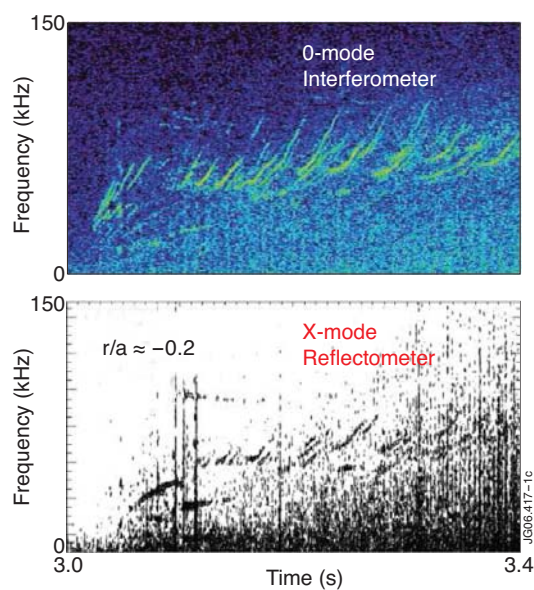


Figure 1: Alfvén Cascades measured using O-mode and X-mode Reflectometry near $r/a = -0.2$ (Pulse No: 67732).

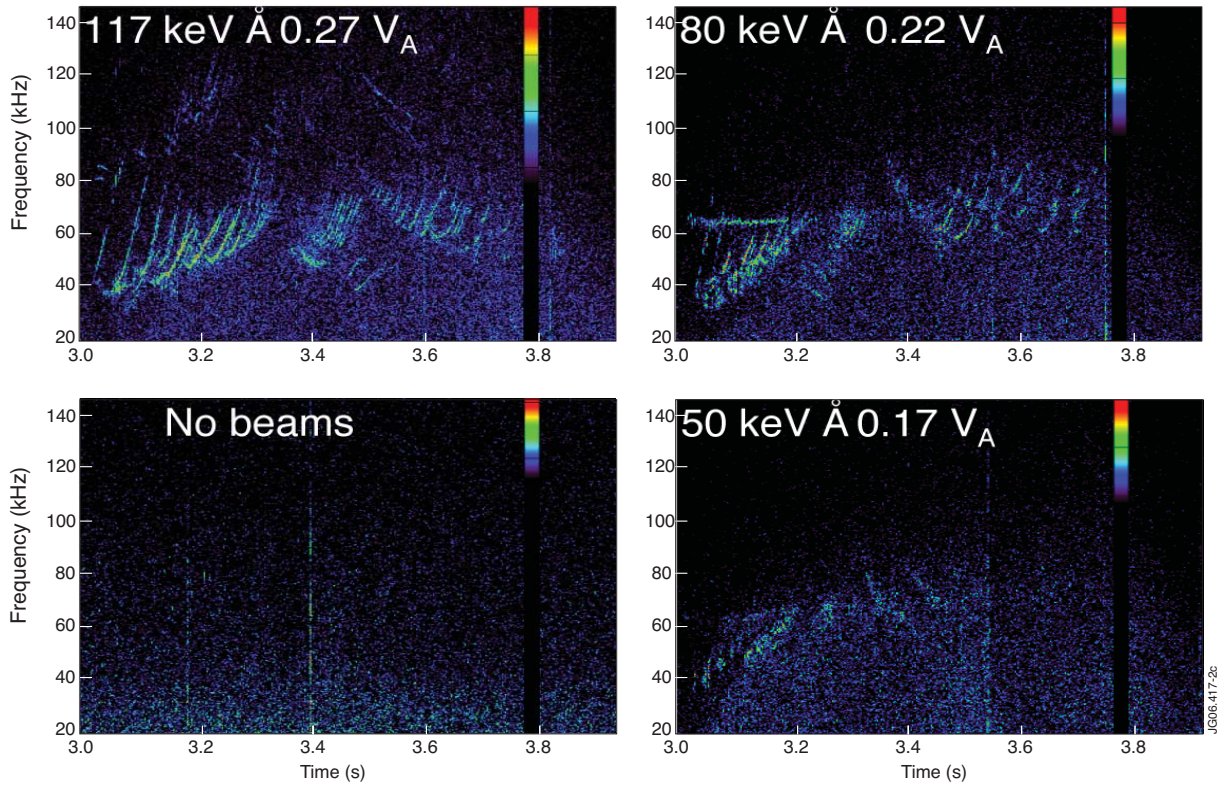


Figure 2: Microwave interferometer measurements of Alfvén eigenmodes in 3.46 Tesla JET discharges with 2-3MW of injected deuterium beams and for a range of beam ion energies corresponding to 1/3 to 1/6 the Alfvén velocity (V_A) (Pulse No's: 66959, 66962 and 66963). A discharge with no beams is shown for comparison (Pulse No: 66964).

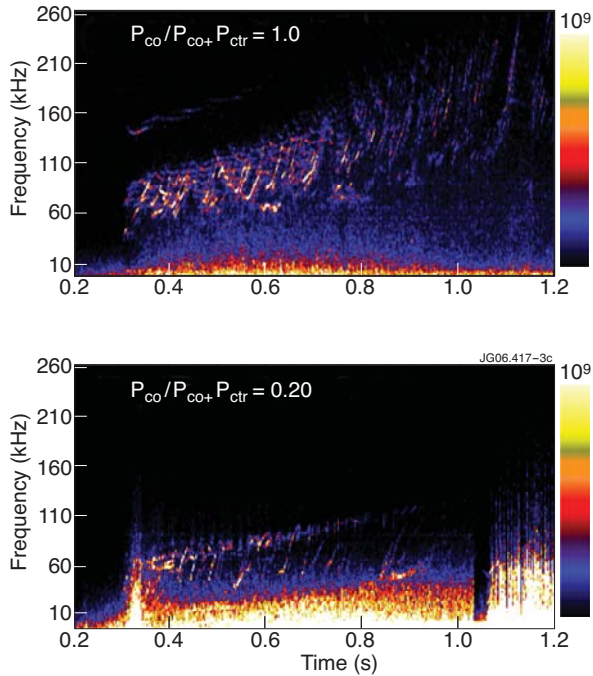


Figure 3: CO_2 interferometer measurements of Alfvén eigenmodes in 2.1 Tesla DIII-D discharges with 5MW of injected deuterium beams and for all co-injection (top Pulse No: 126581) and 20% co-injection (bottom Pulse No: 126597).

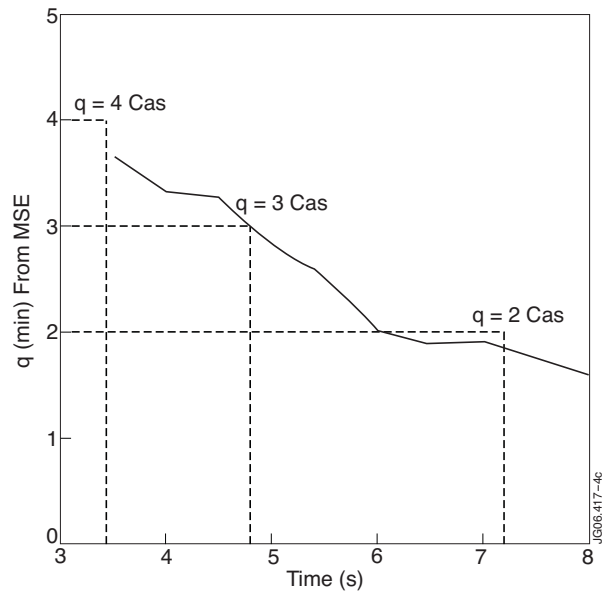


Figure 4: Measurement of the evolution of q_{min} using Motion Stark Effect (MSE) as a function of time compared with the time of the appearance of the Alfvén instabilities patterns corresponding to q_{min} crossing 3 integer surfaces (Pulse No: 67674).