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Unambiguous observation of toroidal Alfven eigenmode driven by alpha particles in Joint European Torus deuterium-tritium experiments

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A toroidal Alfven eigenmode (TAE) has been observed to be driven by fusion generated alpha particles in the Joint European Torus (JET). The observation was made in dedicated deuterium-tritium experiments where radio-frequency (RF) heating was absent, in the so-called "afterglow" period when neutral beam heating was removed. Agreement with reduced and perturbative models is comparable to previous results in reference deuterium discharges where TAEs were readily excited with RF. These results obtained for elevated safety factor and monotonic magnetic shear support similar findings on the Tokamak Fusion Test Reactor (TFTR) where Alfven cascades and their possible transition to TAEs was observed.

As tokamaks approach conditions relevant for net energy production, the confined alpha particles produced in the deuterium-tritium (DT) reaction are anticipated to play a larger role in the dynamics of the plasma. One fifth of the energy liberated in the fusion reaction is carried by the alpha particles which heat the plasma, and in future proposed "burning plasma" tokamak experiments such as ITER [1], this will exceed the externally applied heating. Of particular concern is the potential of the more abundant alpha particles to excite collective instabilities such as the toroidal Alfven eigenmode (TAE) [2] due to a resonant wave-particle interaction with the energetic particles [3]. Alfven eigenmodes with finite wavelength in the toroidal direction break the toroidal symmetry of a tokamak, potentially leading to the radial transport of fast ions.

Comparatively few experiments have been conducted in tokamaks with DT, so most of the opportunities to study energetic particle drive of TAEs occur during predominantly deuterium experiments (DD) with fast ions introduced via radio-frequency (RF) heating or energetic neutral beam injection (NBI). However, the velocities produced through these mechanisms are not distributed evenly in all directions, which is very different from the isotropic production of fusion products, resulting in appreciable predicted differences in TAE drive. Unambiguous experimental verification of genuine alpha particle drive of TAEs is important to establish and an important resource for later detailed validation. Previous observations of alpha driven instabilities on the Tokamak Fusion Test Reactor (TFTR) during DT [4], originally attributed to TAEs, were later interpreted to be a closely related Alfvenic phenomenon known as Alfven cascades [5] associated with safety factor q having a vanishing or reversing radial gradient. Later experiments on the Joint European Torus (JET) during the first DT campaign [6] produced very clear TAEs when both RF heating and alpha particles were present, obscuring the conclusion that the modes were genuinely driven by the alpha particles alone. More recent experiments on JET in deuterium-helium 3 (D-He3) [7] demonstrated elliptical Alfven eigenmodes (EAEs) in the presence of a three-ion RF scheme [8] with highly directional RF generated ions. The toroidal propagation direction of some of the observed EAEs was computed to be unfavourable to wave-particle power transfer from the RF generated ions, and the conclusion reached was that D-He3 fusion products with an unusual bump-on-tail energy distribution was responsible for driving the EAE modes. Dedicated experiments were designed for the second JET DT campaign, which omitted RF heating so that the only fast particle population capable of driving TAEs was the alpha particle population. The radial gradients in NBI distributions on JET are not typically sufficient to destabilize TAEs, so JET DD shots without RF heating do not exhibit TAEs.

This letter reports on unambiguous evidence for a TAE driven by alpha particles on JET.

The observation of a TAE occurred in JET shot #99946 in an internal transport barrier (ITB) scenario with monotonic magnetic shear and elevated safety factor at the magnetic axis $q(0) = 1.6$, vacuum toroidal field at geometric axis $B_0 = 3.45T$ and plasma current $I_p = 2.5MA$ with approximately 50:50 DT concentration, with small amounts of hydrogen and other impurities. This is the so-called ITB afterglow scenario where the NBI power is removed during peak fusion performance, resulting in a fall in NBI fast ion density and plasma temperature, but with a remaining population of confined alpha particles that have a longer characteristic slowing down time than beam ions. The details of the design of the plasma scenario are given in [9]. Figure 1 shows the variation in DT fusion neutron rate with time in response to the applied NBI heating, as well as the Fourier spectrograms obtained from fast far-infrared interferometry [10] and soft x-ray cameras [11]. Prominent and coherent modes are seen in both spectra extending for several hundred milliseconds. At low frequencies, these are visible on Mirnov coils, and once Doppler shift from plasma rotation is accounted for, imply oscillations in the plasma frame at approximately 10kHz. Similar prominent signals at higher frequencies on the density measurements appear to be nonlinear harmonics of these lower frequency modes seen on magnetics and are unlikely to belong to the linear spectrum of the plasma response; these prominent features will not be discussed in this letter any further.

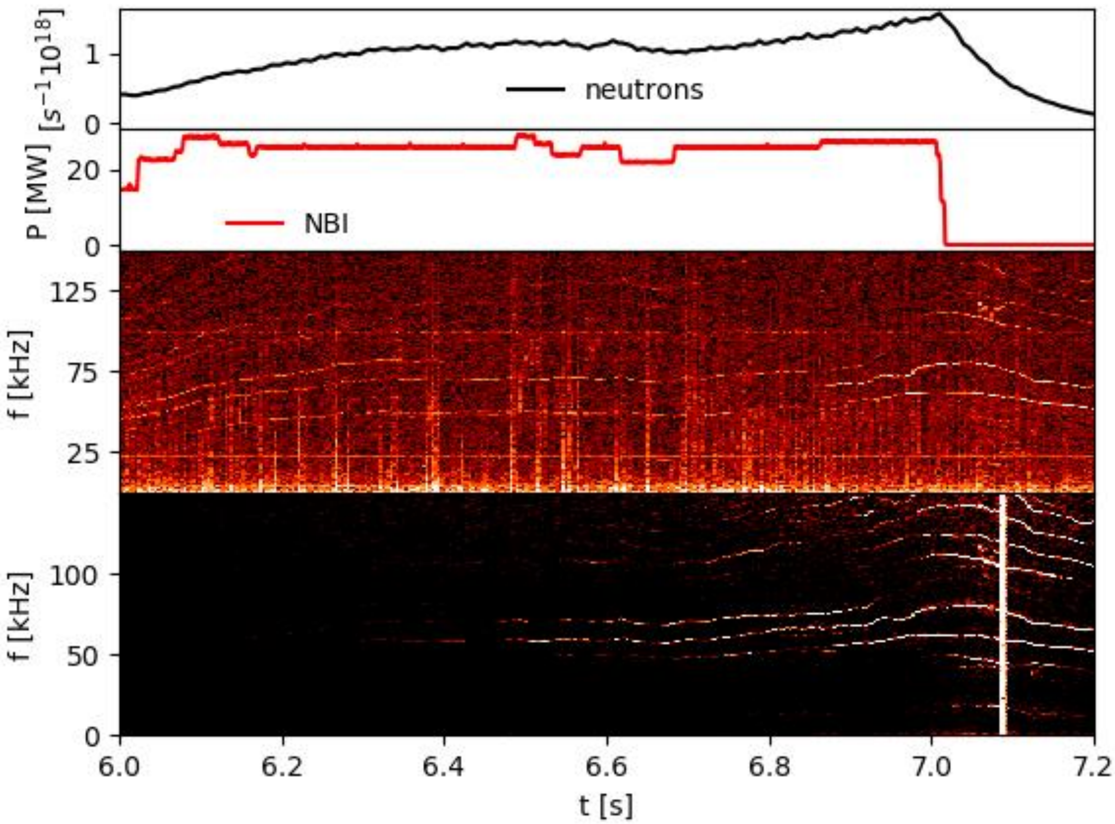

Figure 1: Time traces from JET shot 99946, showing measured neutrons and input power, and associated Fourier spectra of plasma fluctuations measured during the afterglow from t=7.0s onwards. The middle figure is obtained from interferometry, and the bottom from soft X-ray emission.

A less prominent, but nevertheless clear, discrete 115 kHz oscillation is observed at 7.05s. This oscillation can be identified in both spectra in Figure 1, with the likely interpretation of a density fluctuation. The spectrum obtained from a single Mirnov coil is presented in Figure 2. The oscillation is faint but discernible among a broad spectrum of other activity. Cross-correlation of phase between magnetics and soft-x-ray spectra was used to produce a much cleaner confirmation of the mode signal on magnetics (Figure 2). This implies a fluctuation in both magnetic field and density consistent with an electromagnetic mode in the plasma.

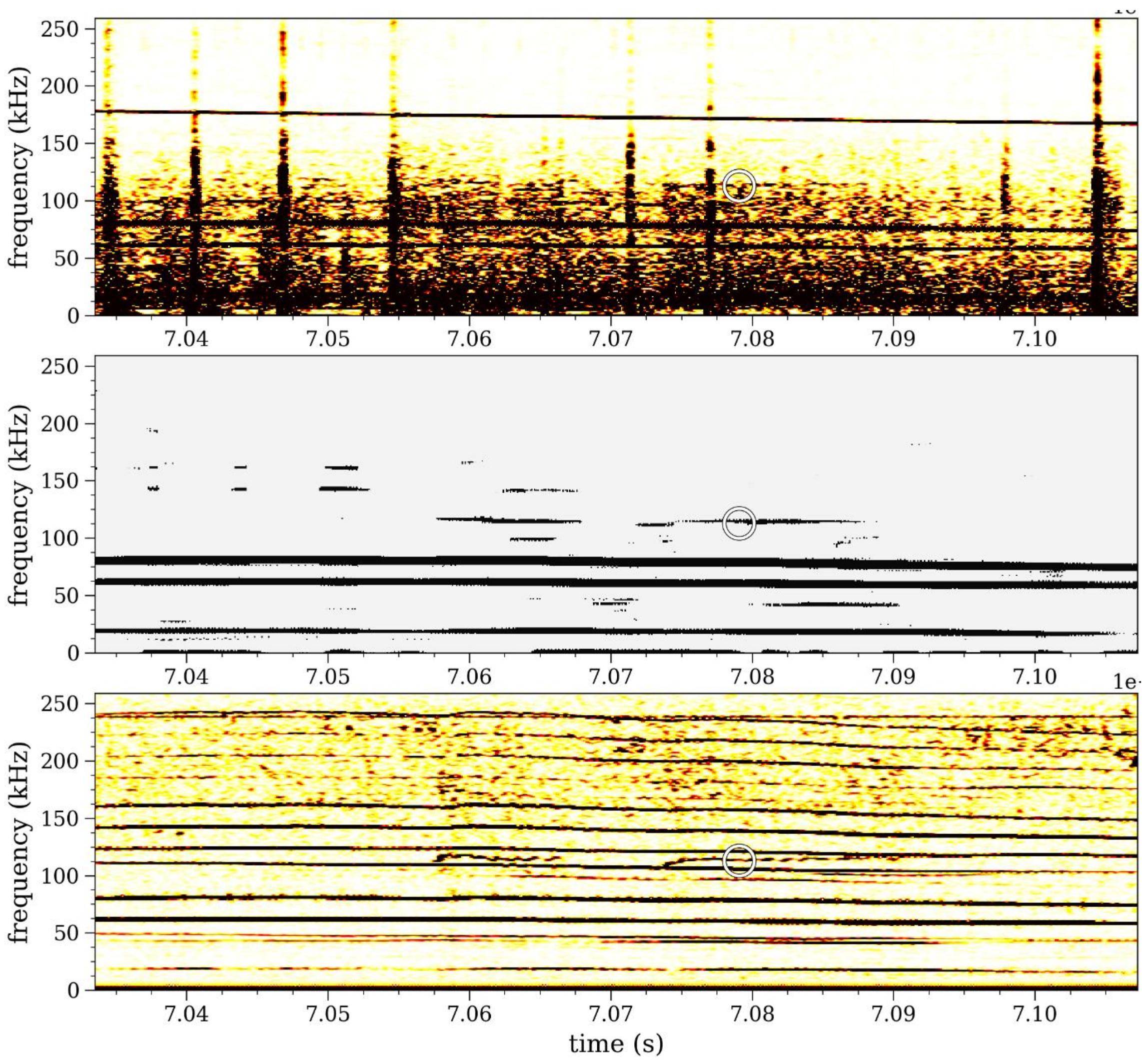

Figure 2 Phase correlation (middle) between magnetics (top) and soft-x-rays (bottom) in JET shot 99946 shows that the density perturbation is associated with an electromagnetic perturbation. The oscillation is highlighted with a circle.

Previous analysis of the afterglow ITB scenario in JET has demonstrated that TAEs can be modelled as incompressible ideal MHD eigenmodes in the bulk plasma, with nonideal effects included perturbatively [12]. Following a similar procedure, equilibrium reconstruction was performed using magnetics and pressure, with an additional constraint on the safety factor q being provided by electron cyclotron emission (ECE) measurements of q rational surfaces. Linear ideal eigenmodes were generated with the MISHKA [13] code for toroidal mode numbers $n = 4,5,6$ as observed in previous deuterium experiments excited by hydrogen minority RF heating, but also for $n = 2,3$ to allow for effects coming from the larger orbit-width of alpha particles compared to fast protons. The predicted eigenmode frequencies in the plasma frame were Doppler shifted to the laboratory frame using the rotation value obtained at the average radial position of the mode. The rotation assumed was the measured rotation profile obtained from charge exchange recombination spectroscopy (CXRS), acquired ~50ms before the mode appearance. The correspondence between predicted and measured frequencies is presented in Figure 3.

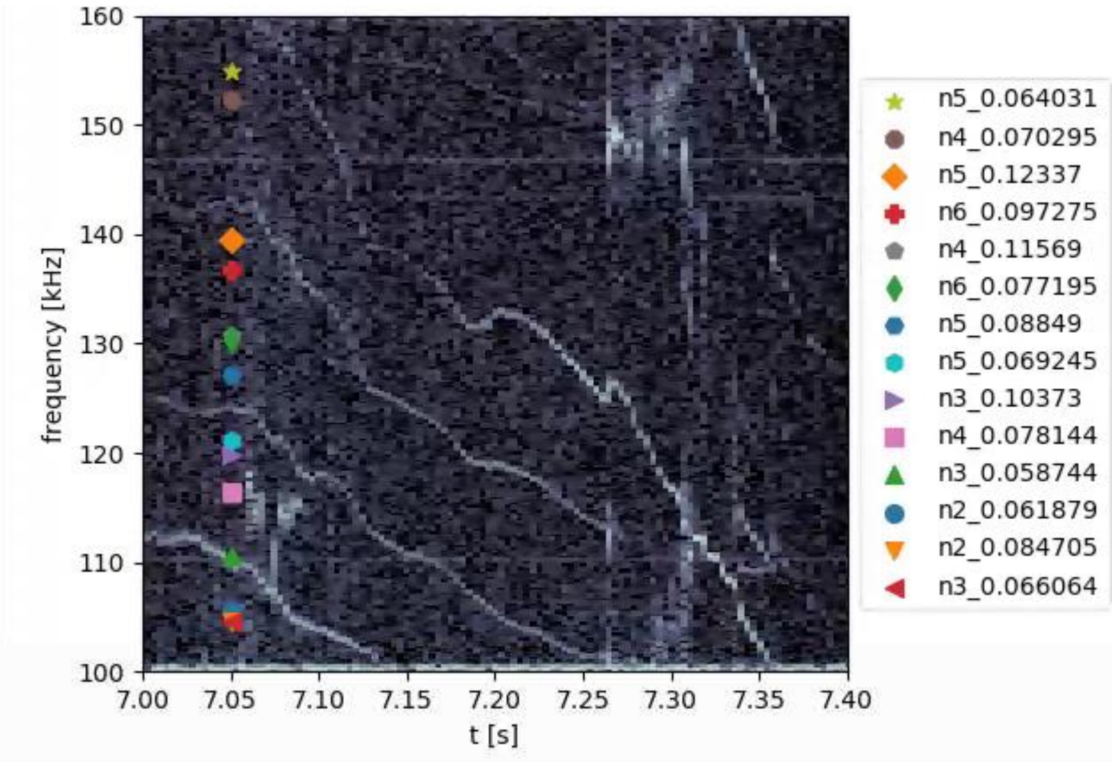

Figure 3 All possible n=2-6 ideal incompressible MHD eigenvalues for TAEs obtained from the MISHKA code superimposed on the spectrum measured by inteferometry in JET shot 99946. Eigenmodes are uniquely labeled using a combination of normalized eigenvalue and toroidal mode number.

The oscillation lies in the range of frequencies predicted for a TAE. The closest matches are found for toroidal mode numbers $n = 3{,}4$. The difficulty in observing this mode on multiple Mirnov probes meant that phase difference information and thus toroidal mode number could not be obtained.

Having established that the oscillation is consistent with a range of possible linear TAE eigenmodes, calculations were performed to determine if these modes could be driven by alpha particles. The alpha particle pressure profile was computed with the TRANSP code [14] and modelled as a slowing down distribution function [15]. Kinetic treatment of the resonant wave-particle drive was carried out using the HALO code [16] which solves the Vlasov-Maxwell problem perturbatively for the alpha particle distribution, assuming the eigenmodes resulting from the computations with MISHKA. The resulting linear growth rates are presented in Figure 4. Two of the three most driven modes have frequencies within 5% of the measured signal. This correspondence between the strongest predicted driven modes and the modes that actually appear is a repeat of what occurred previously in DD when more prominent and obvious TAEs driven by RF accelerated minority protons were observed [12].

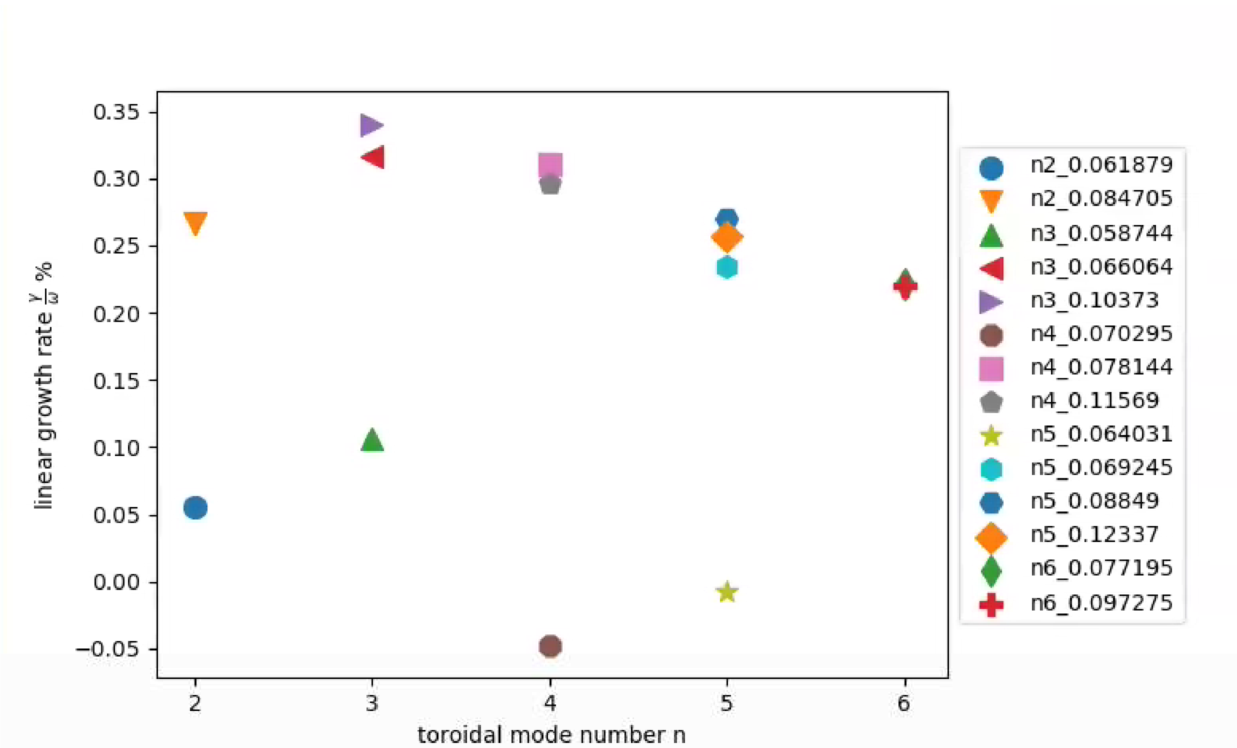

Figure 4 Linear alpha particle drive computed with the HALO code for all the MISHKA eigenmodes identified.

In the previous work, it was found that non-ideal effects from the bulk plasma provide damping which is in competition with the alpha particle drive. In particular radiative damping, where the TAE mode loses energy to the kinetic Alfven wave, was previously found to be dominant in suppressing the TAEs. Inclusion of this effect requires contributions from finite Larmor radius and finite parallel electric field in the eigenvalue problem, as found in kinetic treatments. Non-ideal effects can also be captured in resistive MHD by adopting a resistivity value with real and imaginary components [17]. The complex resistivity η is proportional to the nonideal parameter $\xi = \frac{3}{4} + \frac{T_e}{T_i}(1 - i\delta)$ and the square of the ion Larmor radius, both of which are obtained from experimental values. The δ term represents the conventional resistive wave dissipation from collisions, which can be scanned to identify the kinetic contributions.

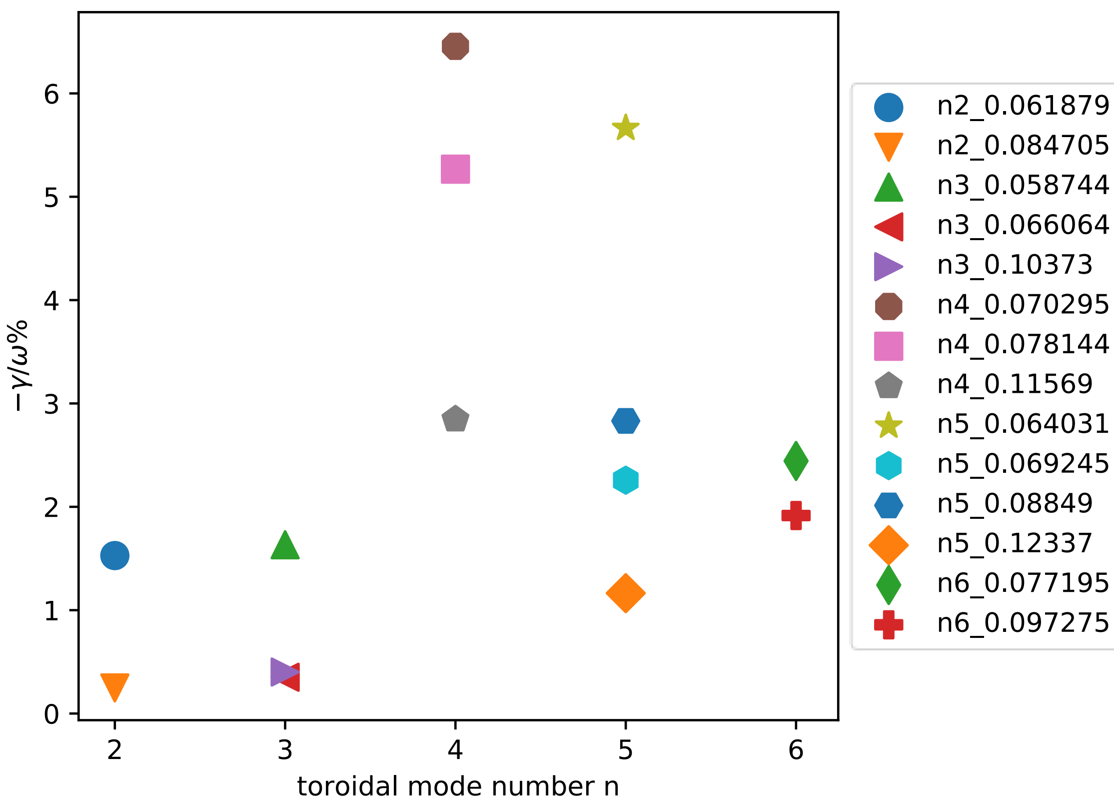

Figure 5 Radiative damping values computed with the CASTOR code

The CASTOR resistive linear MHD code [18] was used to compute the radiative damping, with results presented in Figure 5. Very strong variation is observed depending on mode position and frequency. Given that the alpha particle drive is computed to be well below $\frac{\gamma_L}{\omega} \sim 1\%$, many of the computed MISHKA eigenmodes can be completely ruled out, including the n=4 TAE mode which was among the strongest driven. However, the n=3 mode which happened to be the most driven also happens to have a low value of radiative damping. The radiative damping is computed to be $\frac{\gamma_d}{\omega} = 0.4$ which is within 10% of the computed alpha particle drive, albeit exceeding it. Technical limitations of the version of CASTOR used meant that a single resistivity value was specified for the entire plasma, computed at the average TAE position in each example. There is likely some room for improvement in both the representation of the alpha particle distribution and the bulk non-ideal effects beyond these first calculations. On these numbers however, we can say that the TAE should be marginally stable and that if it is observed, it should be faint.

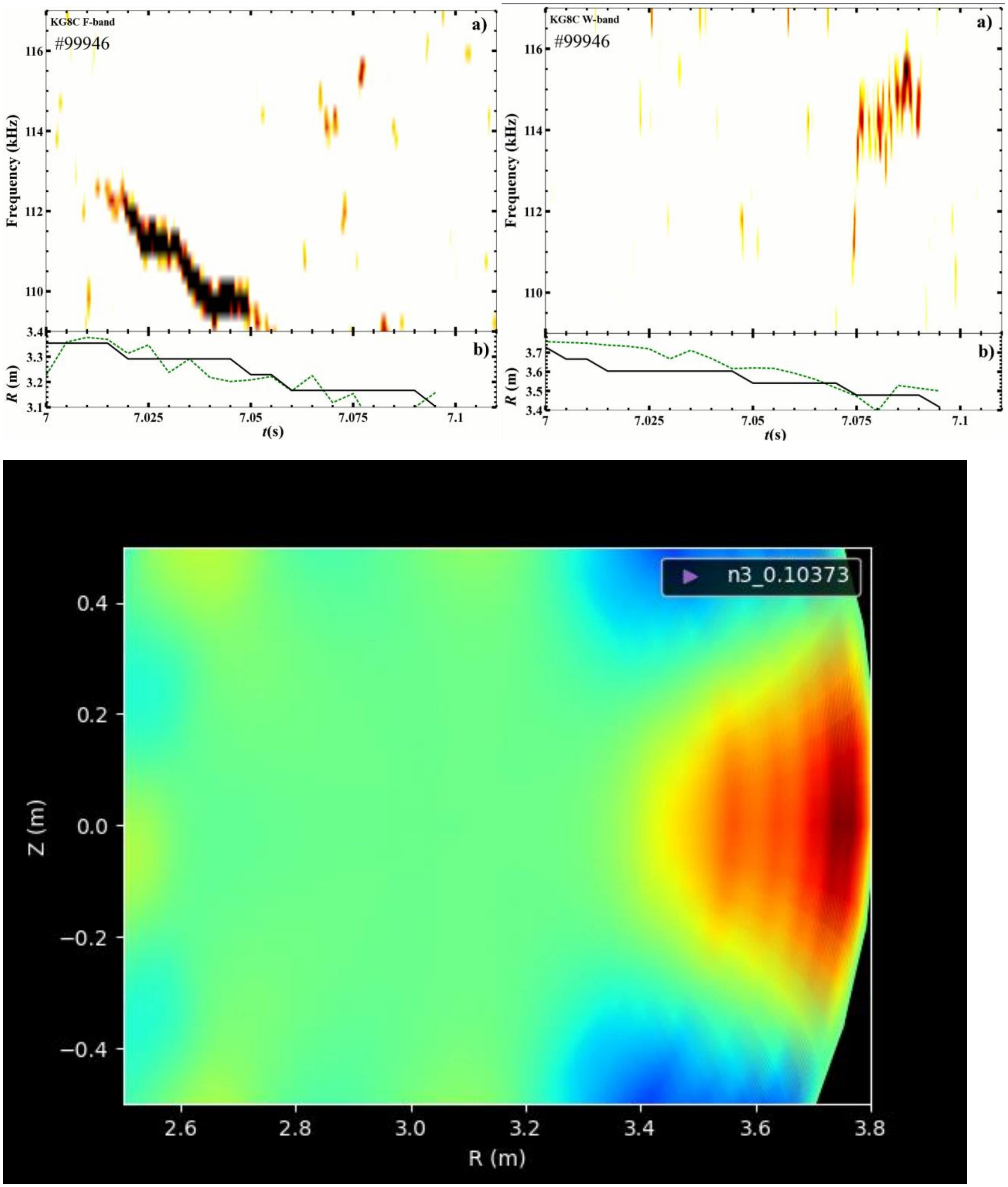

Figure 6 Reflectometry measurements of localized density perturbation in the core (above left) and the edge (above right) in JET shot 99946. Below is the MISHKA prediction of density perturbation due to the marginally stable TAE. Two different computations of radial position are given in each reflectometry plot, based on two different line-integrated density measurements.

The localisation of the density perturbation due to the mode was also detected on reflectometry [19], with spectra presented in Figure 6. At the time of interest 7.05s, the F-band (i.e.: 90-140 GHz) was probing the core ~3.1$\pm$0.1m, and the W-band (75-110 GHz) was probing the edge ~3.6$\pm$0.1m. MISHKA predictions of the density perturbation $V^1\frac{dn}{ds}$, also shown in Figure 6, indicates a global TAE in the high magnetic shear region near the edge of the plasma. The measurement of density perturbation is clearly showing that the mode exists near the edge, although not quite extending all the way to 3.7m as MISHKA predicts. The mode at 115kHz is absent from the core and has a leading edge at 3.4m as predicted. This level of agreement in mode position is comparable to previous DD TAE results [12]. Although thermal ion landau damping and neutral beam damping has not yet been calculated, neither are likely to be appreciable for a mode outside the core.

In conclusion, a marginally unstable TAE in a monotonic magnetic shear plasma has been observed in the edge of JET where the only fast particle species capable of providing drive is the alpha particles. Agreement for mode frequency and position from MHD calculations is comparable to that found previously in DD, and alpha drive and radiative damping calculations predict the observed frequency to within 5%. In future work, this provides an important and rare opportunity to validate tools used in the prediction of burning plasma stability before burning plasmas are realised in future tokamaks.

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