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Observation and Explanation of the JET $n = 0$ Chirping Mode

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Introduction

Presented here is an analysis of JET data [1,2] that contains persistent, chirping $n = 0$ modes, where n is the toroidal mode number. These chirping modes are only found to be experimentally established when there is high field side (HFS) ion cyclotron resonance frequency (ICRF) heating applied and where the power applied by neutral beam injection is not too large (typically <5 MW). The issues addressed are the identification and mechanism of excitation of the basic plasma mode being observed. It will be shown that the mode is related to the geodesic acoustic wave [3] and the source of instability must come from the inversion of the energetic ion population, where $\partial F(E, \mu, P_\phi)/\partial E > 0$ (E, μ and P_ϕ are the energy, magnetic moment and canonical angular momentum of particles in an equilibrium distribution.

Experimental Observations

Rapidly chirping axisymmetric ($n = 0$) oscillations have been observed to exist on JET for several seconds during a discharge (figure 1), beginning when HFS ICRF heating is applied and quenched by the application of >5 MW of NBI heating or the removal of the ICRF heating. These oscillations typically occur between 20 and 60 kHz. They simultaneously chirp upwards in frequency by up to 40% and downwards in frequency by up to 25% of the starting frequency. Most of these oscillations have been observed in discharges with a reversed shear q profile as evidenced by the existence of Alfvén cascades [4-6], but they have also been observed in discharges with steady frequency TAEs and no Alfvén cascades, suggesting a flat or monotonic q profile.

These modes are only observed on the Mirnov coils when the ICRF heating resonance is located on the high field side of the magnetic axis. This heating can produce energetic particles with a fast ion tail temperature ∼250 keV and this production is the suggested source of the free-energy that drives the oscillation. The $n = 0$ mode has not been observed when the ICRF heating resonance is on the low field side of the magnetic axis or from neutral beam injection heating alone. Additional evidence for this mode arises from examining the reflectometer signals, when the reflectometer is operated in an "interferometer" mode [7], and from the signals observed on the soft X-ray detectors installed in a horizontal port viewing a vertical plane 15.6 degrees off the major radius. These modes have been localized near the core by cross-correlation analysis between the signals from the X-ray detectors and the signal from a Mirnov coil. Signals from the diodes whose views had a tangent to a magnetic flux surface at $r/a \sim 0.15$ show the strongest correlation with the Mirnov coil signal at the same frequencies as the $n = 0$ mode.

The starting frequency of the $n = 0$ mode has been found to scale as $\sqrt{T_e(r/a = 0.15)}$, as measured by the ECE diagnostic, in cases with only ICRF heating (figure 1). When greater

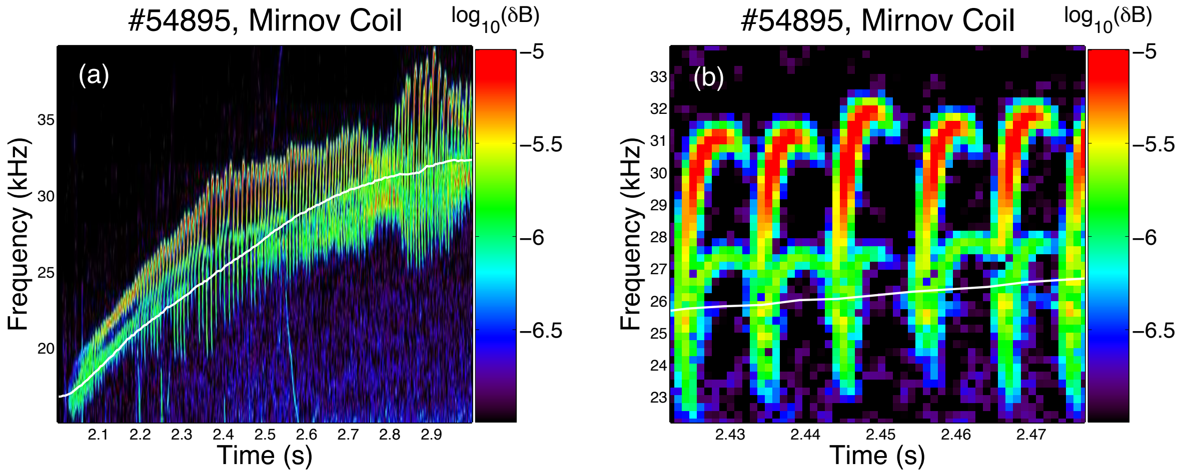

Figure 1: *Spectrograms of the signal from a Mirnov coil on JET. (a) The rapidly chirping n=0 mode. (b) A zoom of (a) showing the frequency chirping in more detail. In both plots the white line is proportional to* $\sqrt{T_e(r/a = 0.15)}$.

than 5 MW of neutral beam heating is applied after the mode has been excited, the starting frequency of the mode increases dramatically by up to a 60%.

Theoretical Considerations

Fast particle driven modes are usually driven by the radial gradient of the energetic particle population. However, as this drive is proportional to the toroidal n-number, it does not exist for these $n = 0$ modes. In this case the source of instability must come from $\partial F(E,\mu,P_\phi)/\partial E > 0$ at constant magnetic moment and constant angular momentum. The SELFO code [8] was used in a Monte-Carlo calculation for determining the distribution function for high field side ICRF heating in a tokamak JET-like geometry. It is found, from this code, that at a given magnetic moment and angular momentum, there is a region in the distribution function where $\partial F(E,\mu,P_\phi)/\partial E > 0$. This latter result was also found with low field side ICRF heating, but in this case the region of phase space with $\partial F(E,\mu,P_\phi)/\partial E > 0$ is substantially smaller and hence it would be more difficult to excite this instability with low field side ICRF heating.

It is expected that the observed $n = 0$ mode is a weak resonance instability where the experimental frequency at each instant is equal to an orbit resonance frequency which in this case is the bounce frequency of particles trapped in the tokamak's magnetic mirror fields. In order for the frequency sweeping to spontaneously appear, the resonance position in phase space has to be located at a point where the energy distribution has a positive slope. A calculation using HAGIS [9] shows the bounce frequency for particles with a fixed magnetic moment and angular momentum decreases with increasing particle energy. In the region where the distribution function has this positive slope the bounce frequency varies between 32 and 42 kHz, the same frequency range of the observed $n = 0$ mode.

The changing mode frequency can be interpreted as a synchronism between the mode frequency and the resonance frequency as explained in the model developed in references [10,11]. At the phase space region associated with a given mode frequency there are particles trapped in the fields of the wave. The distribution function of these trapped particles are in the form of a clump (hole) where the wave trapped particle distribution has a larger (smaller) value than the ambient distribution. Because background dissipation absorbs wave energy, the phase space structure cannot be stationary in time as the structure needs to compensate for the

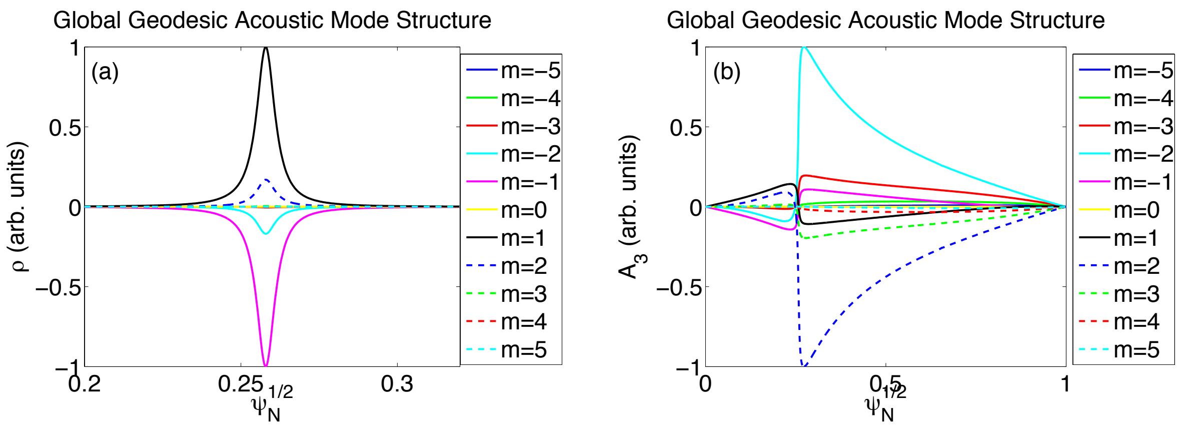

Figure 2: *Eigenmode structure of the global geodesic acoustic mode found slightly above the peak in the geodesic acoustic wave continuum, located at $\sqrt{\psi_N} = 0.26$, for a reversed shear, circular JET-like equilibrium. (a) The perturbed mass density and (b) the perturbed parallel vector potential.*

power being absorbed by dissipation. To extract energy from the distribution function the distribution function must have less kinetic energy in the later time state than in the earlier time state. Therefore a clump (hole) must head to lower (higher) energy, and thus the frequency must increase (decrease). Note that this direction of chirping of the holes and clumps is opposite to the direction in the chirping modes found in the bump-on-tail instability [10] or for the TAE [12].

The basic mode that the resonant particles excite is apparently a global geodesic acoustic mode (GGAM). This mode was found, using the resistive MHD normal mode analysis code CASTOR [13] with a circular, reversed shear, JET-like equilibrium. A global mode was found when the continuum geodesic acoustic wave [3] has a maximum frequency off axis. The GGAM mode structure is shown in figure 2 where in 2(a) the localized electrostatic mode structure (primarily $|m| = 1$) is shown and in 2(b) the mode component proportional to δB_r is shown where the primary $|m|$ component is 2. Note, that though the perturbed electrostatic component is internally localized, the magnetic component, which is small where the electrostatic excitation is localized, is global elsewhere, reaching out to the Mirnov coils. The geodesic acoustic continuum is given by the dispersion relation

$$\omega^2 = \frac{\gamma p}{\rho R^2}\left(2 + \frac{1}{q^2}\right) \tag{1}$$

where γ is the adiabatic constant, p is the plasma pressure, ρ is the mass density, R is the major radius of the tokamak and q is the safety factor and if this frequency has a maximum it satisfies the condition,

$$s = \left(q^2 + \frac{1}{2}\right)\frac{r}{L_T}, \tag{2}$$

where $s = r/q(dq/dr)$, r is the minor radius and $L_T = [1/T(dT/dr)]^{-1}$. The GGAM is found to exist at a frequency just above the peak frequency defined by equations 1 and 2. In the more typical cases were the plasma temperature peaks on axis the q profile must be reversed for the GGAM to exist, while in a monotonic q profile discharge the temperature must be peaked off axis. In all cases analyzed the electron temperature was peaked on axis, but in cases without Alfvén cascades detailed measurements of the q-profile are not available and therefore a rigorous test of the condition in equation 2 has not been done. The frequency of the GGAM is closely associated with the peak in the continuum, and therefore has a $\sqrt{T_e}$

dependence when the ion temperature is significantly smaller than the electron temperature. The increase in the frequency when greater than 5 MW of NBI heating is applied is likely due to the increased ion temperature that arises from beam heating. We also expect that T_i/T_e should be larger during the earlier time of figure 1 before HFS ICRH reaches its maximum value, so that if finite T_i/T_e could be accounted for, the theoretical comparison (the white curve) would be shifted towards the experimental data. The results from CASTOR (see figure 2) show a localization of the density oscillations associated with this mode around the peak in the continuum spectrum, consistent with the localization of the mode by the cross-correlation technique used on the soft X-ray diagnostic.

Conclusions

A chirping $n = 0$ mode is observed on JET only when high field side ICRF heating is applied. The initiation frequency of this mode is found to scale as $\sqrt{T_e}$ when ICRH is the dominate heating mechanism. The mode behavior is consistent with a global geodesic acoustic mode excited by energetic particles whose distribution function has $\partial F(E, \mu, P_\phi)/\partial E > 0$ at the phase space region associated with the mode resonance . The observed chirping behavior is consistent with it being a weak resonance instability where the experimental frequency at each instant is equal to an orbit resonance frequency, in this case the bounce frequency of the energetic particles, as described in references [10,11]. One may also note that the nonlinear particle dynamics of this mode is robustly one dimensional since the particles magnetic moment and canonical angular momentum are conserved at low frequency (with respect to the cyclotron frequency) for an $n = 0$ mode. This effective reduction of dimension greatly simplifies the understanding of particle dynamics in an intrinsically higher dimensional tokamak experiment.

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