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Observation of modes in the sub-cyclotronic range of frequencies in JET

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Abstract

The excitation of modes in the JET tokamak in the sub-cyclotronic range of frequencies (frequencies comprised between the Alfvén frequency and the cyclotron frequency) is for the first time reported. It is also the first time modes in this range of frequencies were observed to be destabilized by ICRH. The modes were identified as Compressional Alfvén Eigenmodes (CAE) and have characteristics similar to those of the sub-cyclotronic modes observed in other tokamaks, in particular those first reported in the NSTX tokamak. On the other hand, the modes observed in JET present some unique features.

The understanding of the interactions between energetic ions, as those produced by auxiliary heating or nuclear fusion reactions, and plasma waves is of crucial importance for a successful operation of future fusion reactors. These interactions are usually assumed to have a detrimental effect on the course of a discharge, as they may lead to undesired redistribution of energetic ions, moving them away from the plasma core where, in future machines, their energy will be needed to keep the plasma burning. On the other hand, from these interactions may also result beneficial effects like the "channeling" of energy from the energetic ion population directly to the thermal ion population instead of to the thermal electrons. It is then desirable to fully understand the wave-particle interactions so the deleterious effects can be minimized while at the same time taking advantage of the beneficial effects.

Modes with frequencies around the cyclotron frequency or harmonics of the cyclotron frequency of the energetic ions, $\omega \cong l\omega_{cf}$, where l is an integer and ω_{cf} is the cyclotron angular frequency of the fast ions, are often observed tokamaks. These modes have been identified as Ion Cyclotron Emission (ICE) [1, 2] and they are associated with the excitation of magnetosonic waves. On the other hand, modes propagating in the range of frequencies comprised between the Alfvén frequency and the cyclotron frequency (sub-cyclotronic range of frequencies) are not normally observed in currently operating tokamaks. Typically, these modes require the existence of populations of ions with parallel velocities above the Alfvén velocity to be destabilized [3, 4] but such populations are rare in today's tokamaks. The exceptions are the spherical tokamaks NSTX [3, 5] and MAST [6, 7], where sub-cyclotronic modes are routinely observed. Both NSTX and MAST are equipped with super-Alfvénic beams providing the populations of super-Alfvénic ions necessary to the excitation of the modes. Modes in the sub-cyclotronic range of frequencies have also been observed in beam-heated discharges in the conventional tokamak DIII-D but only when operating with low magnetic field B [4], so that the beam ions birth velocity is above or at least close to the Alfvén velocity ($v_{b0}>v_A$). Most of the instabilites observed at the sub-cyclotronic range of frequencies were identified as Compressional Alfvén Eigenmodes (CAE) [8-10] with some of the modes observed in NSTX and MAST being identified as Global Alfvén Eigenmodes (GAE) [11, 12]. As ICE, the CAE are also associated with the excitation of the magnetosonic wave. While ICE are destabilized when the parallel phase velocity of the wave is much larger than the thermal electron velocity, $\omega/k_{=} >> v_e$, CAE are excited in opposite conditions. For example, in DIIID, the required condition for destabilization was found to be roughly $\omega/k_{=} < 3v_e$ [4]. Here, $k_{=}$ is the wave vector parallel to the magnetic field. If the drive provided by the energetic ion population is large enough to overcome the overall damping, the magnetosonic wave is then excited through the resonance, $\omega \cong l\omega_{cf} + k_{=}v_{=} + k_{\perp}v_{drift}$. Here, $k_{\perp}$ is the perpendicular wave vector and $v_{=}$ and v_{drift} are the parallel and drift velocities of the energetic ions respectively. In the small $k_{=}$ limit, the terms proportional to the parallel and perpendicular wave vectors are negligible and the ICE frequency is given simply by the cyclotron frequency or one of its integer multiples. In the opposite limit, the excitation of CAE requires large values of the parallel wave vector $k_{=}$, implying that the term proportional to $k_{=}$ can no longer be neglected. This term induces a Doppler shift on the wave frequency, shifting it away from the cyclotron frequency. If the Doppler shift term $k_{=}v_{=}$ is large enough, the frequency of the waves verifying the l=1 Doppler resonance ($\omega \cong \omega_{cf} + k_{=}v_{=}$) may deviate significantly from the cyclotron frequency, explaining the observation of CAE at frequencies substantially lower than the cyclotron frequency.

The excitation of the magnetosonic wave is predicted to occur in ITER. The large electron temperatures characterizing ITER plasmas and consequent large electron velocities will favour the excitation of the wave in the limit of smaller ω and large $k_{=}$, this is, the limit corresponding to the excitation of CAE. The presence of sub-cyclotron instabilities in ITER is of importance as they may play significant roles like enhancing electron thermal diffusivity [13, 14], "alpha channeling" [15, 16] or stochastic heating of thermal ions [17, 18].

This letter reports on the first observation of modes in the sub-cyclotronic range of frequencies in the JET tokamak. This is, to the best of our knowledge, also the first time modes in this range of frequencies were observed to be destabilized by Ion Cyclotron Resonance Heating (ICRH) accelerated ions. One reason why these modes may not have been observed to be driven by ICRH accelerated ions before is that ICRH accelerates only the perpendicular velocity of the energetic ions $v_{\perp}$, so the condition $v_{=}>v_A$ is not easily fulfilled by ICRH accelerated ions. The experiments in which the sub-cyclotronic modes were observed in JET were carried out in the monotonic scenario with the safety factor on axis q_0 calculated by EFIT [19] being typically around $q_0 \cong 0.8$ to 0.9. The plasma was a low density (electronic density below $2.5 \times 10^{19} m^{-3}$) deuterium plasma with a moderate to high power (5-7 MW) ICRH of hydrogen minority being applied near the magnetic axis. No NBI was used. In this scenario, there is a threshold in density below which "grassy" sawteeth characterized by frequent and small amplitude crashes are observed [20, 21]. The discharges were carried out with densities just above this threshold so that sawteeth were stabilized and long quiescent periods (around one second) were observed between large amplitude crashes. Throughout the quiescent periods, the combination of high ICRH power and low plasma density allows a large population of highly energetic ions to build up in the plasma destabilizing a variety of instabilities [22-24].

This set of experiments was originally designed to analyse the effect of TAE and fishbones on the redistribution and loss of energetic ions, so, most of the diagnostics were set to an acquisition rate of 1 MHz. A few Mirnov coils were acquiring at a frequency of 2 MHz, allowing the observation of modes up to the Nyquist frequency of 1 MHz. Signals of frequencies above 1 MHz are expected to be eliminated, or at least significantly damped, by JET anti-aliasing filters.

Figure 1 (left) shows the frequency spectrum obtained from a Mirnov coil acquiring at 2 MHz during a period in which sub-cyclotronic modes are observed. Groups of modes are observed at two distinct ranges of frequencies, being each group composed by several modes.

The lower frequency group is observed at frequencies from around 650 kHz to 800 kHz while the higher frequency group is observed at frequencies from around 950 kHz up 1000 kHz, which is the maximum frequency detected by this coil. Since the Alfvén frequency in the plasma centre is around 450 kHz, the frequencies of the observed modes are well above the Alfvén frequency. Figure 1 (right) shows a zoom of the lower frequency group visible in the period from around t=8.45 s to t=8.7 seconds.

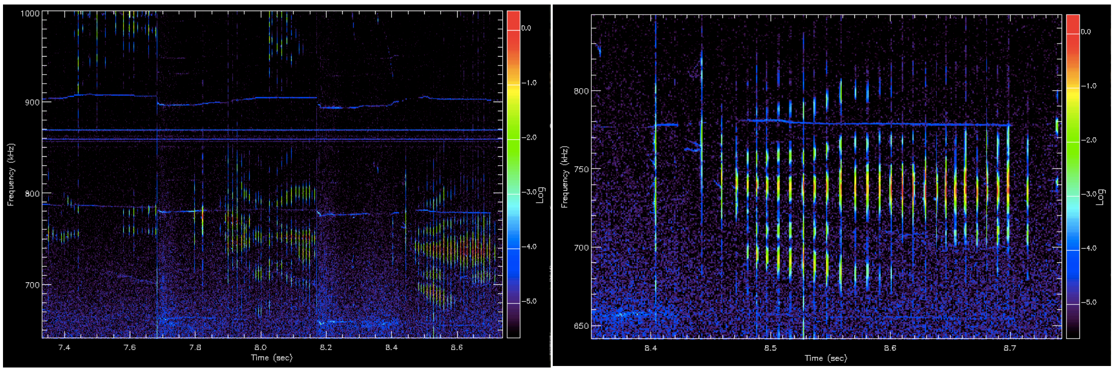

Figure 1: Left- Frequency spectrum (Mirnov coils) of modes $\omega > \omega_A$ in pulse #66318. Right- Zoom showing in detail one of the groups of modes.

The frequency spectrum of these modes looks like vertical stripes connecting several bunches of unstable mode signal peaks with all the unstable modes being excited and damped simultaneously. This description corresponds exactly to the description given in ref. [3], when the observation of sub-cyclotonic modes was first reported in NSTX. Besides, the modes belonging to different groups also become excited and damped at the same time. In figure 2 it is possible to see the existence of a symmetry in relation to the centre of the group. Often, a high amplitude mode appears in the centre of the group. Other characteristics associated with these modes are the existence of a higher number of unstable modes as well as modes with higher amplitudes in pulses carried out with higher ICRH power, the temporary suppression of the modes by large sawtooth crashes, the change of the modes' behaviour when core-localized TAE inside the q=1 surface (tornado modes) are excited and the inexistence of measured losses related to the modes.

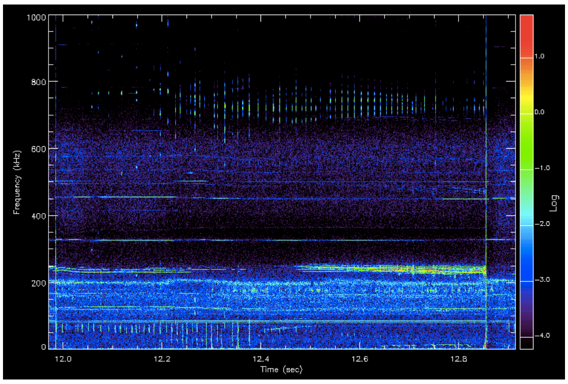

Figure 2: Frequency spectrums (Mirnov coils) of modes $\omega > \omega_A$ in pulse #66319, acquisition rate 2 MHz.

In the tokamaks where sub-cyclotronic modes have been previously observed, the modes appear in a hierarchy of groups at different frequency scales. The sub-cyclotronic modes appear grouped in "groups", with individual modes being separated by frequencies of a few dozens of kHz (fine splitting). The observed differences in frequencies between modes were 20 kHz in DIIID, 10-25 kHz in NSTX, 10-40 kHz in MAST and now 10-20 kHz in JET. Most commonly, several groups of modes are observed, being the groups separated by up to few hundreds kHz, 110 kHz in DIIID, 100-150 kHz in NSTX, 100-250 kHz in MAST and now 150-250 kHz in JET. Note that in JET, only two groups of modes could be observed at a given time. Finally, the groups of modes have been observed to be themselves grouped in "bands" with frequency gaps between them that can range up to 1 MHz. The limitation in the detected frequencies in JET did not allow observing if different bands existed. Values presented here are from references [3-7, 25, 26].

In order to complete the characterization of the sub-cyclotronic modes observed in JET, it is of interest to identify the range of frequencies at which the modes are observed as well as the toroidal and poloidal mode numbers. The frequency range of the sub-cyclotronic modes is from around 650 kHz to an unknown upper limit, as modes above 1 MHz could not be detected. In terms of normalized frequencies, this corresponds to a lower limit of around ω/ω_{cf} =1/60. The toroidal mode number as been computed using a series of signals acquired with a frequency of 1 MHz, which means the toroidal mode numbers of modes with frequencies up to 500 kHz are correctly calculated but for modes with frequencies comprised between 500 kHz and 1MHz the calculated toroidal mode numbers are the symmetrical of the actual ones. Figure 3 shows the toroidal mode numbers of a group of sub-cyclotronic modes obtained in pulse #66378. The signals in this figure are aliases of the real modes with the frequencies in this figure being related to the actual frequencies by f= (1000 – f_{alias}) kHz, which means the modes appear mirrored.

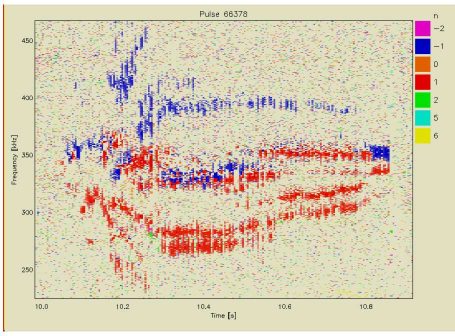

Figure 3: Toroidal mode numbers of a group of sub-cyclotronic modes.

All modes shown in figure 3 have follow |n|=1, propagating both in the direction and in the opposite direction relatively to the plasma current. Aside from the |n|=1, some |n|=2 modes were also observed. An attempt to calculate the poloidal mode numbers of the sub-cyclotronic modes has been made using signals from poloidal coils 1 to 5 on octant 8B. Though an accurate calculation of the poloidal mode numbers was not possible, the calculations allowed to conclude that the poloidal mode numbers of these sub-cyclotronic modes are low, typically $|m| \leq 4$. In other tokamaks, the observed frequencies and toroidal mode numbers of sub-cyclotronic modes cover a vast range of values depending on the scenarios. Some of the observed normalized frequencies are, $\omega/\omega_{cf} \approx 0.3$ to 0.6 in START, $\omega/\omega_{cf} \approx 0.5$ to 1.0; 0.18 to 0.37; 0.096 (low B) in MAST, $\omega/\omega_{cf} \approx 0.3$ to 1.1 in DIIID and $\omega/\omega_{cf} \approx 0.17$ to 0.33; 0.4 to 1.1 in NSTX. Corresponding toroidal mode numbers are |n|≈ 4 to 10; n=1 to 15 in MAST, -16<n<5 inferred in DIIID and |n|<8 in NSTX [3-7, 25, 26].

The most noticeable difference between the sub-cyclotronic modes observed in JET and those observed in other tokamaks is the low normalized frequencies (ω/ω_{cf}) the modes reach in JET. Besides, the toroidal mode numbers of the sub-cyclotronic modes observed in JET are mostly |n|=1 while in the other tokamaks they are usually higher, though in JET modes with higher toroidal mode numbers may also have existed not being detected. The case closest to JET is MAST low B experiments, were n=1 modes have been observed at frequencies f≈ 250 kHz ($\omega/\omega_{cf} \approx 0.096$) [7].

The sub-cyclotronic modes observed in JET present some unique peculiarities; It is the only case where sub-cyclotronic modes were destabilized by ICRH accelerated ions and not by super-Alfvénic beams and the groups of sub-cyclotronic modes contained modes with both positive and negative toroidal mode numbers, while in other tokamaks each group of modes contains modes with either positive or negative mode numbers.

There are two types of modes known to exist in the sub-cyclotronic range of frequencies, the Compressional Alfvén Eigenmodes (CAE) and the Global Alfvén Eigenmodes (GAE). The existence of striking similarities between the sub-cyclotronic modes observed in JET and those observed in other tokamaks is a strong indication that the modes should be of the same nature. The sub-cyclotronic modes first observed in NSTX, whose description nearly coincides with the description of the modes observed in JET, were identified as Compressional Alfvén Eigenmodes. It was later found that some of the modes observed in NSTX and MAST were actually GAE and not CAE. However, in conventional tokamaks, GAE are expected to be stable as they are subject to strong continuum damping. In DIIID it is thought that only CAE were observed. The way to unambiguously distinguish between CAE and GAE is by measuring the perturbed parallel magnetic field. However, such measurements were not available in the JET experiments described here. Though in magnetic spectrograms it is usually difficult to distinguish between CAE and GAE, there is a difference in the signals produced by these modes. While the frequency lines corresponding to different GAE may cross as time evolve, the frequency lines corresponding to CAE are not allowed to cross [27]. In this set of JET experiments, the frequency lines corresponding to the different observed modes don't seem to cross, though sometimes it is difficult to distinguish between them. This suggests that the observed modes must be CAE and not GAE, as expected for conventional tokamaks. Another difference between CAE and GAE concerns to their radial location. While GAE are core localized and peak in the plasma centre, CAE exist in a "potential well" where compressional Alfvén waves can propagate [5, 27, 28]. For a given toroidal mode number *n*, the potential well is delimited by the region where $(\omega/v_A)^2 > (n/R)^2$. In the JET experiments described here, over the midplane, the *n*=1 CAE is allowed to propagate on the low field side of the torus with frequencies above around 400 kHz throughout the whole range of minor radius, except near the edge where the plasma density drops. The *n*=2 CAE can also propagate from the core to close to the edge with frequencies above 800 kHz. Both CAE and GAE rely on the existence of super-Alfvénic populations in order to be excited, but as it will be shown, energetic ions with parallel velocities above the Alfvén velocity are only present in the outer regions of the plasma, suggesting the observed modes must extend to outer regions of the plasma, which do not happen for GAE. Taking into account all the considerations above, one may conclude that the sub-cyclotronic modes observed in JET are very likely to be Compressional Alfvén Eigenmodes (CAE).

Two issues particular to JET sub-cyclotronic modes require an explanation different than presented for other tokamaks: the drive and their low frequencies. The excitation of CAE typically required the beam ions birth velocity to exceed the Alfvén velocity ($v_{b0}>v_A$). The presence in the plasma of populations of energetic ions with large parallel velocities has two implications: first, the super-Alfvénic ions can resonate with and provide drive to the modes and second, the large parallel velocities induce a large Doppler shift of the order $k_{=}v_{=}\approx\omega_{cf}/2$ on the wave frequency, explaining this way the observation of modes with frequencies of the order $\omega \approx \omega_{cf}/2$. In JET experiments where sub-cyclotronic modes have been observed, the energetic ions are minority ions accelerated by ICRH, which accelerates the perpendicular velocity. At first sight, this seems to deprive the modes of both the drive and the Doppler shift. However, while in NSTX, MAST and DIIID the beam ions are injected into the plasma with energies of the order of dozens of keV, the energetic ions accelerated by ICRH in these JET experiments are in the MeV range of energies. On-axis ICRH produces tipically populations of energetic ions moving in banana orbits with tips around the vertical layer crossing the magnetic axis. The perpendicular velocity of the ions is $v_{\perp} = \sqrt{2E/m}$ at the tip of the orbits where $v_{=}=0$. As the ion moves into regions of lower magnetic field, the perpendicular velocity of the ion decreases in order to conserve the magnetic moment while the parallel velocity increases in order to conserve the energy. The maximum parallel velocity is reached at the point of minimum magnetic field along the orbit and it depends on the energy of the ion. For trapped ions in the MeV range of energies, it may exceed the Alfvén velocity in the outer half of the torus. In JET, sub-cyclotronic modes have only been observed in experiments with multi-MeV ICRH accelerated ions, which seems to indicate only ions in this range of energies can drive these modes.

Regarding a possible explanation for the low mode frequencies observed in JET, we start with the local resonance condition, $\omega \cong l\omega_{cf} + k_{=}v_{=} + k_{\perp}v_{drift}$. The observation of sub-cyclotronic modes at frequencies around $\omega \approx \omega_{cf}/2$ in other tokamaks was explained by assuming the wave is excited through the Doppler resonance l=1, implying a Doppler shift of the order $k_{=}v_{=} \approx \omega_{cf}/2$. The term proportional to the drift velocity has been consistently neglected. However, this explanation doesn't seem to work for the case of JET, where modes with frequencies as low as $\omega \approx \omega_{cf}/60$ would require a Doppler shift of the order $k_{=}v_{=} \approx \omega_{cf}$. The drift velocity term appearing in the resonance equation, which has been neglected, has a term which depends on the square of the perpendicular velocity. $v_{\perp}$ is very small for beam injected ions but is large for trapped ions in the MeV range of energies. Calculations show that for sufficiently high energies, the term $k_{\perp}v_{drift}$ may be around the same order of $k_{=}v_{=}$. However, this doesn't seem to be the likely explanation as the drift provided by the two terms is smaller than ω_{cf}. The most likely explanation for the low frequencies observed in JET is that the sub-cyclotronic modes were destabilized through the Cherenkov resonance l=0 and not through the Doppler resonance l=1. The possibility of sub-cyclotronic modes being destabilized through the Cherenkov resonance was first suggested in ref. [29] and is supported by recent numerical calculations [30]. For l=0, the resonance equation becomes $\omega \cong k_{=}v_{=} + k_{\perp}v_{drift}$. With the term proportional to the cyclotron frequency disappearing from the equation, low mode frequencies of the order $f \approx 1\ MHz$, can be easily achieved. However, the existence of negative toroidal mode numbers requires a reversed energy gradient of the distribution function, reason why the Cherenkov resonance has been originally excluded as part of a possible explanation [3]. The possible existence of bump-on-tail distributions in JET experiments with multi-MeV ICRH ions is being analysed and will be reported in a separate publication [31].

In summary, the existence of sub-cyclotronic modes in JET is for the first time reported. It is also the first time modes in this range of frequencies are observed to be excited by ICRH and not by NBI. The sub-cyclotronic modes are very likely to be Compressional Alfvén Eigenmodes and are very similar to sub-cyclotronic modes observed in other tokamaks, in particular with the modes first observed in NSTX, though presenting some unique features. The low frequencies of the modes seems to imply the modes should be destabilized through the Cherenkov resonance l=0.

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