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Interpretation of core ion cyclotron emission driven by sub-Alfvénic beam-injected ions via magnetoacoustic cyclotron instability

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Abstract

Core ion cyclotron emission (ICE) signals have recently been observed in beam-heated plasmas on several tokamaks. In this Letter we present experimental evidence in support of core ICE being generated by the magnetoacoustic cyclotron instability (MCI), itself driven by the velocity-space inversion of sub-Alfvénic beam-injected ions. The observed core ICE dynamics in beam-heated plasmas is consistent with the MCI and is a result of competition between the beam ion fraction build-up (which increases the instability growth rate) and the slowing down of the dominant beam ion velocity component (which stabilizes the MCI).

Main Text

The velocity-space stability of fast ions (either wave-accelerated, beam-injected, or fusion-born) in D-T burning plasmas is crucial to the success of nuclear fusion as an energy source. If the fast ion distribution f becomes inverted in velocity space v (i.e. $\partial f / \partial v > 0$), free energy is available to drive homogeneous plasma instabilities [1, 2], which, in turn, may redistribute fast ions from their optimal configuration. One such instability-driven effect is thought to cause the ion cyclotron emission (ICE) and recent measurements show that it can exist in the plasma core near the magnetic center [3-5]. In this Letter we present experimental evidence supporting that core ICE is generated by the magnetoacoustic cyclotron instability (MCI) driven by the velocity-space inversion of sub-Alfvénic beam-injected ions. The MCI provides a viable explanation for the observed core ICE dynamics in beam-heated plasmas on ASDEX Upgrade: 1) the initial ICE amplitude growth follows the growth of the beam-injected fast ion fraction (which increases the MCI growth rate); and 2) when the beam power is switched off, we observe a rapid ICE amplitude reduction (on the timescale much faster than the beam ion thermalization time), which matches the MCI growth rate reduction due to the slowing down of the dominant beam ion velocity component (which stabilizes the MCI).

ICE signals in this study are generated via 21 deuterium NBI pulses (Fig. 1). Only one NBI source is used, with beam incidence angle that is intermediate between purely tangential and

purely radial to the magnetic axis (Fig. 1 (a)). Each NBI pulse is 15 ms in duration ($P_{\text{NBI}} = 2.5$ MW) and spaced apart by 300 ms (Fig. 1 (d)). The 300 ms duration is longer than the energy slowing down time τ_{SD} of the full-energy component of beam D^+ ions (birth energy $E_0 = 92.5$ keV, birth speed $v_0 = 3.0 \times 10^6 \text{ m s}^{-1}$). As a result, the fast deuterium ions do not accumulate/pile-up with each consecutive NBI pulse (Fig. 1 (g)). The fast deuterium ion contents for this discharge are obtained using TRANSP [6] and its fast ion NUBEAM module [7]. Note that each NBI pulse is preceded by a short (3 ms in duration), full power (2.5 MW) preconditioning pulse to decrease the rise time of the main NBI pulse. The ion cyclotron emission signals are quantified using a low-field side B-dot probe (Fig. 1 (a)). The signal from the B-dot probe is split into two halves via a 3dB splitter: one half of the signal is bandpassed (10-50 MHz) and rectified to extract the ICE amplitude; the second half is directly sampled at 125 MHz to obtain the ICE frequency spectra. The reader is referred to [3] for a full description of the ASDEX Upgrade ICE diagnostic used for this study. The plasma discharge is in L-mode to avoid edge localized modes and their influence on the probe measurements [8], is heated with ECRH power to prolong the discharge duration to 8 s (Fig. 1 (d)), and is in the upper single null configuration to prevent the H-mode transition. The on-axis magnetic field $B_T = -2.5$ T (Fig. 1 (b)) and the plasma current value has two plateaux ($I_P = 0.465$ MA and $I_P = 0.623$ MA) (Fig. 1 (c)). The first 9 NBI pulses occur during the lower I_P value, the last 11 NBI pulses take place during the higher I_P value, and NBI pulse #10 takes place during the I_P transition at $I_P = 0.55$ MA (Fig. 1 (c)). The overall combination of the magnetic field (Fig. 1 (b)) and the core plasma density (Fig. 1 (e)) results in the Alfvén speed $c_A = 8.9 \times 10^6 \text{ m s}^{-1}$, making the beam-injected ions sub-Alfvénic. 20 out of 21 NBI pulses generate ICE; no ICE signal is detected only during the 3rd NBI pulse (Fig. 2). Additionally, no detectable ICE signal is observed during any of the preconditioning pulses.

The observed ICE frequencies (37-38 MHz) match the ion cyclotron frequency of the fundamental hydrogen cyclotron harmonic Ω_{H^+} in the plasma center (Figs. 2 (a) and (c)), but also the 2nd harmonic deuterium $2 \times \Omega_{\text{D}^+}$. Both fast ion species are present in D-D plasmas heated with deuterium NBI: fast protons are generated via D-D nuclear fusion reactions and fast deuterons are injected by NBI. The fast ion birth speed favors the (super-Alfvénic) fusion proton over the (sub-Alfvénic) beam deuteron as the ICE driver [9]. However, the core ICE observation in hydrogen plasmas heated with hydrogen NBI (Fig. 3) strongly suggests the beam origin of this instability, as no other source of fast ions is present in these hydrogen discharges. The expected second harmonic hydrogen frequency is 76 MHz (core $B_T = -2.5$ T), which appears in our fast ICE diagnostic at its aliased frequency $49 \text{ MHz} = 125 \text{ MHz} - 76 \text{ MHz}$ (Fig. 3). No signal that would correspond to the fundamental hydrogen cyclotron harmonic in the core (~ 38 MHz) is observed, matching the deuterium results [3].

All 20 of the observed ICE bursts have a common feature: they all disappear within ~ 1 ms after the NBI turn-off time, much faster than the thermalization times of the beam ions (Fig. 2 (b)). The abrupt end to core ICE after the NBI turn-off time is not unique to ASDEX Upgrade plasmas: similar observations have been reported in the TUMAN-3M tokamak [5]. To quantify and follow the beam-injected deuteron population in the plasma on a short (~ 1 ms) timescale, we use TRANSP [6] and its NUBEAM module [7]. The time evolution of the beam-injected fast ion fraction during a single NBI pulse (#11) and the corresponding beam-injected ion velocity-space distribution are shown in Fig. 4. We use this data to estimate the instability growth rate in the following section.

ICE is normally attributed to fast Alfvén wave excitation via the MCI, first discussed by Belikov and Kolesnichenko for the case of wave propagation strictly perpendicular to the magnetic field

[10]. The analytical theory of the MCI was later extended by Dendy and co-workers to the case of oblique propagation [11]. An important feature of the obliquely-propagating MCI is that it can account for the excitation of ICE by sub-Alfvénic fast ions: this has been demonstrated analytically for ICE driven by charged fusion products in the Tokamak Fusion Test Reactor (TFTR) [12], and numerically for emission driven by beam ions in the Large Helical Device (LHD) [13]. As in most other conventional tokamaks, beam-injected fast ions in ASDEX Upgrade are born in the plasma at sub-Alfvénic velocities, and therefore it is worth exploring the possibility that the obliquely-propagating form of the MCI can account for the ICE discussed in the present paper.

Following [11] and [12], we assume that the beam ion distribution can be approximated as a shifted Gaussian in parallel velocity $v_{\parallel}$ and a delta function in perpendicular velocity $v_{\perp}$:

$$f = \frac{n_b}{2\pi^{3/2}u_{\perp}v_r} \exp\left(-\frac{(v_{\parallel} - u_{\parallel})^2}{v_r^2}\right) \delta(v_{\perp} - u_{\perp}). \quad (1)$$

Neglecting damping due to electrons and bulk ions, and assuming that the beam ion density n_b is much smaller than the bulk ion density n_i (consistent with our plasmas, see Fig. 4 (a)) it can then be shown [11] that the growth ($\gamma > 0$) or damping ($\gamma < 0$) rate of the obliquely-propagating MCI for the l -th beam ion cyclotron harmonic is given by

$$\gamma = \frac{n_b}{n_i} \frac{\Omega_i^4}{[\Omega_i + (\omega - \Omega_i)N_{\parallel}^2][\Omega_i - (\omega + \Omega_i)N_{\parallel}^2]} \left(\frac{l\Omega_i}{k_{\parallel}v_r} M_l - \frac{2u_{\perp}^2}{v_r^2} \eta_l N_l \right) \frac{\sqrt{\pi}}{2\omega} e^{-\eta_l^2}, \quad (2)$$

where Ω_i is the ion cyclotron frequency, ω is the mode frequency, $N_{\parallel}$ and $N_{\perp}$ are the parallel and perpendicular refractive indices of the wave defined with respect to the Alfvén speed, i.e. $N_{\parallel} = k_{\parallel}c_A/\omega$, $N_{\perp} = k_{\perp}c_A/\omega$ where $k_{\parallel}$ and $k_{\perp}$ are the parallel and perpendicular wavenumbers, $\eta_l = (\omega - k_{\parallel}u_{\parallel} - l\Omega_i)/k_{\parallel}v_r$ and the quantities $\mathcal{M}_l$ and $\mathcal{N}_l$ are defined by the expressions

$$M_l = 2l \frac{\omega}{\Omega_i} \left(J_l'^2 + \frac{1}{z_b^2} (l^2 - z_b^2) J_l^2 \right) - 2 \frac{\omega^2 - \Omega_i^2}{\Omega_i^2} \frac{J_l J_l'}{z_b} [l^2 N_{\perp}^2 - (z_b^2 - 2l^2) N_{\parallel}^2] + \frac{2J_l J_l'}{z_b} (z_b^2 - 2l^2), \quad (3)$$

$$N_l = -2l \frac{\omega}{\Omega_i} \frac{J_l J_l'}{z_b} + \frac{\omega^2 - \Omega_i^2}{\Omega_i^2} \left[N_{\perp}^2 \frac{l^2 J_l^2}{z_b^2} + N_{\parallel}^2 \left(\frac{l^2 J_l^2}{z_b^2} + J_l'^2 \right) \right] + \frac{l^2 J_l^2}{z_b^2} + J_l'^2. \quad (4)$$

Here, J_l denotes the Bessel function of order l with argument $z_b = k_{\perp}u_{\perp}/\Omega_i$. As discussed in [12], $\mathcal{M}_l$ is generally negative in the sub-Alfvénic regime $u_{\perp} < c_A$ (applicable to beam ions in ASDEX Upgrade), while $\mathcal{N}_l$ is generally positive. It follows from this that the $\mathcal{M}_l$ term Eq. (2) is stabilising while the $\mathcal{N}_l$ term is destabilising if $\eta_l < 0$, which means that the Doppler-shifted mode frequency $\omega' \equiv \omega - k_{\parallel}u_{\parallel}$ lies below the cyclotron harmonic $l\Omega_i$ (the above expressions are applicable only for $k_{\parallel} > 0$ and must be modified for negative parallel wavenumbers [11]).

Specialising to the experimentally-relevant case of $l = 2$, we follow the time evolution of the beam-injected distribution (Fig. 5 (a)) calculated with TRANSP/NUBEAM and the corresponding instability growth rate (Fig. 5 (b)). In our calculations of the growth rate (Eq. (2)), we use the beam velocity spread $v_r/u_{\perp} = 0.08$ (consistent with Fig. 5 (a)) and the pitch=0.5 (Fig. 4 (c)). Note that the $k_{\parallel}$ value is not measured in this experiment: to illustrate the trend

expected from oblique propagation we choose a nearly perpendicular propagation angle $\theta=80^\circ$ (which provides us with $k_{||}\approx(\omega/c_A)*\cos\theta$). The fast ion fraction n_b/n_i is given in Fig. 4 (a). The maximum growth rate first experiences an almost linear increase in value (Fig. 6), as the fast ion fraction in the core builds up during the NBI-on phase (Fig. 4 (a)). After the NBI source switches off, we observe a rapid drop of the maximum growth rate, which tracks the drop of the ICE signal (Fig. 6). Such behavior is in agreement with an observed correlation between edge ICE intensity and linear MCI growth rate for the case of sub-Alfvénic fusion-born ^3He in TFTR plasmas (see. Fig. 6 in [12]). A correlation of this type has also been seen in fully nonlinear (particle-in-cell) simulations of fusion product-driven ICE in JET [14]. In our specific case, this rapid growth rate reduction and stabilisation is attributed to the drop in the dominant beam speed value (and, hence, $u_\perp$), see Fig. 5 (a) for $t=4.669$ s. In fact stabilisation could occur even when the linear growth rate is positive, due to electron and bulk ion damping. The high sensitivity of γ/Ω_α to $u_\perp$ provides a possible explanation of the rapid disappearance of ICE following the end of the beam heating phase, since the presence of collisional friction in the absence of a beam source means that $u_\perp$ starts to drop immediately. Finally, we would like to mention that the MCI growth rate remains at zero for the fundamental $l = 1$ harmonic, which is consistent with our experimental measurements: no ICE signal has yet been observed on ASDEX Upgrade that would match the frequency of the fundamental beam ion harmonic in the plasma core.

To summarize, we present experimental evidence in support of core ICE being generated by the obliquely propagating MCI driven by the velocity-space inversion of (sub-Alfvénic) beam-injected fast ions. The observed core ICE dynamics is a result of competition between the fast ion fraction build-up (which increases the MCI growth rate) and the slowing down of the dominant beam ion velocity component (which stabilizes the MCI). The lack of the fundamental beam ion harmonic in the measured ICE signal is also consistent with the MCI as the growth rate of the $l = 1$ harmonic is 0.

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Figures

FIG 1. (a) The top cross-sectional view of ASDEX Upgrade. The magnetic axis (Mag.), the separatrix (Sep.), the ion cyclotron emission (ICE) probe, and the neutral beam injection (NBI) geometry (Source #8) are shown. Key discharge parameters for discharge #34607 are shown: (b) the on-axis magnetic field B_{Field} , (c) the plasma current I_p , (d) the NBI and the electron cyclotron resonance (ECRH) heating powers, (e) the core plasma density $n_{e \text{ core}}$, (f) the core electron temperature $T_{e \text{ core}}$, and (g) the core fast D^+ content.

FIG. 2. (a) Ion cyclotron emission (ICE) spectra during all 21 deuterium NBI pulses; (b) an example of a detailed ICE amplitude time history during a single NBI pulse (#11); (c) a detailed time history of ICE spectra during NBI pulse #11. The red dotted line in (a) and (c) shows the on-axis value of the second harmonic deuterium cyclotron frequency, as estimated from magnetic equilibrium reconstruction.

FIG. 3. Observation of core ICE in hydrogen plasma heated by hydrogen NBI (Source #8) (Fig. 1 (a)). The signal appears at its aliased frequency 49 MHz = digitization frequency 125 MHz – actual 76 MHz.

FIG. 4. A detailed time evolution of (a) the NBI power P_{NBI} and the beam ion fraction n_b/n_i and (b) the ICE amplitude during NBI pulse #11. The vertical arrow in (a) indicates the time at which the fast ion distribution function (in pitch-energy space) is computed via TRANSP/NUBEAM, shown in (c). A dashed horizontal line in (c) corresponds to the dominant pitch value = 0.5. The three peaks in (c) correspond to the full, the $1/2$, and the $1/3$ energy components of the beam-injected ions.

FIG: 5. Time evolution of (a) TRANSP-calculated beam ion velocity distribution and (b) the MCI growth rate from Eq. (2) for an example NBI pulse (#11), $\omega' \equiv \omega - k_{||} u_{||}$. The vertical dashed lines in (a) show the dominant beam energy and the red circles in (b) show the maximum growth rate values. The NBI turn off time is indicated in (a).

FIG: 6. The time evolution of the ICE amplitude and the maximum instability growth rate γ/Ω_α , as computed via Eq. (2) for the case of $l = 2$. The maximum growth rate values are taken from Fig. 5 (b).