Ion cyclotron emission properties in NBI-heated TUMAN-3M plasma

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Ion cyclotron emission (ICE) in routinely registered in many tokamaks. It was recently observed in the TUMAN-3M tokamak [1, 2] in ohmically and neutral beam injection (NBI)-heated regimes in D and H plasma. This paper describes some characteristic features of NBI-induced ICE observed in TUMAN-3M, with emphasis on spectral structure of the emission.

Experiments presented hereafter were performed on compact tokamak TUMAN-3M [3] (R₀/a = 0.55 m / 0.25 m, toroidal field B₉ < 1.1 T, plasma current Iₚ < 180 kA, central line average density nₑ < 6×10¹⁹ m⁻³) in NBI-heated scenario (60%-40% D-H mix, beam energy Eₜ < 20keV, beam power Pₜ < 400kW). Neutral beam was injected in toroidal co-plasma current, counter-toroidal field direction, with tangential radius R₉ = 0.42 m. Details of experimental set-up and diagnostic used may be found in [3]. Typical plasma parameters evolution in a shot with NBI heating and LH-transition is shown in Fig.1a. Characteristic example of ICE spectrum registered in a typical NBI shot in deuterium target plasma is shown in Fig. 1b. The ICE with frequency around 12.8 MHz appears ~2ms after NBI power was turned on, and disappears in ~5 ms, well before the end of the NBI pulse.

The ICE frequency observed in this experiment corresponds roughly, but not exactly, to the central ion cyclotron (IC) resonance frequency for hydrogen, which may be considered as a minority in the deuterium target plasma. When the same mix beam was injected in hydrogen plasma, the observed ICE frequency corresponded to deuterium minority central IC resonance. In some shots, main ion ICE was observed as well, though. ICE frequency was
found to follow toroidal field evolution, but only weakly dependent on plasma density, if any. This has led to conclusion [4] that physical mechanism behind ICE generation may be not related to CAE or MCI, which seems now not necessary to be true, as will be seen below.

Spectrum of hydrogen ICE is shown in Fig. 2a. It typically consists of up to three narrow, unevenly spaced discrete lines with amplitudes changing in time, but constant gaps between the lines. In this paper, an attempt is made to connect this ICE fine line structure with mass-energy spectrum of injected beam. In addition to main components of D$^+$ and H$^+$ ions with energy $E_0$, there are several well-identified lines corresponding to fractions of $E_0$; $E_0/2$, $E_0/3$ for hydrogen, and $E_0/2$, $E_0/3$, $2E_0/3$ for deuterium, see Fig. 2b, (here $E_0 = -eU$, were $U$ is accelerating voltage. These energy fractions are produced due to the acceleration of H$_2^+$, D$_2^+$, H$_3^+$, D$_3^+$, HD$^+$ molecular ions in the same tract, which are then decomposed into the H$^+$ and D$^+$ ions. In addition, there is a broader and lower peak corresponding to $\sim E_0/18$ for hydrogen and $E_0/10$ for deuterium due to inevitable presence and acceleration of water molecular ions.

A fast ion with longitudinal velocity $v_b$ will interact with a wave propagating in plasma through the Doppler shifted cyclotron resonance [5]

$$\omega = l\omega_{ci} + v_b k_\parallel + v_D k_\perp$$  \hspace{1cm} (1)

Here $\omega$ and $\omega_{ci}$ are wave frequency and fast ion cyclotron frequency, respectively, integer $l$ is cyclotron harmonic number, $k_\parallel$ and $k_\perp$ are wave vector components along and perpendicular to the magnetic field, and $v_D$ is ion drift velocity. Depending of fast ion trajectory in tokamak magnetic field, different terms in right hand side of eq. (1) may be important. Typical examples of fast ion trajectories in TUMAN-3M are shown in Fig.3. Trajectories presented in Fig.a and b are these of passing particles, with $v_b \gg v_D$, while trapped trajectories shown in Fig.3c and d have parts where $v_b \ll v_D$ – turning points of the banana in Fig 3d, or vertical part of the potato in Fig3.c.

It looks, however, that trajectories presented in Figs 3a and d could not be responsible for ICE excitation in the experiments presented here, as ions moving along these trajectories
spend only a small fraction of time in close proximity to $R=R_0$. Contrary, potato-like particles, moving along vertical part of the potato, remains at constant $R=52.5\text{cm}$ (for given initial conditions) for $\sim90\%$ of the bounce time. Passing particles circulating along the torus (referred hereafter as “stagnation” particles [6]) with approximately constant $R$, Fig.3b, are another possible candidate for central ICE excitation.

Figure 3 – Trajectories (in poloidal projection) of tangentially injected hydrogen ions in TUMAN-3M shot ($B_T=1\text{T}, I_p=134\text{kA},\text{ beam energy } E_0=17\text{keV}, \text{ tangency radius } R_b=0.42\text{m}$). Trajectories are different because of different location of birth point: (a) $x=0.2$, (b) $x=0.6$, (c) $x=0.775$, (d) $x=0.88$, where $x$ is relative distance from dippiest possible point inside vacuum vessel of TUMAN-3M along the tangential trajectory of the atomic beam.

For both potato and “stagnation” types of particles, the major radius of a region where they reside for a long time was obtained for realistic plasma and NBI parameter set and for different energy fraction of the beam. Only minority ions were considered, i.e. hydrogen in case of deuterium target plasma, and vice versa. For both type of trajectories, it was found that ion cyclotron frequency $f_{ci} = \omega_{ci}/2\pi$ is noticeably (~2 MHz for potato, ~1.5 MHz for “stagnation” particles) higher than experimentally observed ICE frequency $f_{ice}$. For potato particles, having $v_b=0$ on the vertical part of their drift orbit, it means that $k_{\perp}v_D<0$. Having in mind that $v_D>0$ (directed upward), one finds that $k_{\perp}<0$, i.e. the wave is propagating downward, and could expect a pronounced up-down asymmetry in registered ICE – which is not the case in the experiments: detected ICE amplitude is approximately the same in upper and lower halves of the torus. So, only the “stagnation” particles will be considered as a candidate source of free energy for ICE excitation. For the stagnation particles produced as a result of ionization of different components of atomic beam, ICE spectrum was calculated and shown in Fig.4. Again, ion cyclotron frequency for the “stagnation” particles is higher than experimentally measured one. Using eq. (1), and neglecting $k_{\perp}v_D$ term, one may conclude that $k_{\parallel}<0$, i.e. the wave is propagating counter-current direction. From the frequency difference

Figure 4 – Experimental ICE spectrum and one calculated from trajectories of the “stagnation” particles (see text) with different energies.

23.05.2018 #09 t = 62.05-62.15ms probe HF_p19_213 measured --- calculated

$\omega_{ci}^{1/2}$ $\omega_{ci}$ $\omega_{ci}^{1/4}$

$12.6$ $12.8$ $13.0$ $13.2$ $13.4$ $13.6$ $13.8$ $14.0$ $14.2$ $14.4$ $14.6$ $\text{MHz}$
$\Delta f = f_{ci} - f_{ice} \approx 1.6$ MHz for hydrogen ICE and fast ion energy 17keV one can find toroidal mode number $n \sim 4$. Moreover, even fine structure of the observed line is reproduced, at least qualitatively. In the frames of the model proposed, it is possible to calculate parametric dependencies of ICE frequency and to compare them with experimentally observed ones. For instance, Fig.5 illustrates dependence of the deuterium IE frequency on the beam energy. It is seen that there is a good agreement, if one attribute the systematic shift between experimental and calculated data to the $k_//v_b \sim 0.5$ MHz term.

![Figure 5 - Comparison of experimental (red) and calculated (black) deuterium ICE frequency as a function of beam energy. Systematic shift ~0.5MHz is attributed to $k_//v_b$ term (see text)](image-url)

It is interesting to note that if one assume that the instability responsible for ICE generation is of CAE (Compressional Alfven Eigemode) nature, and use as a dispersion relation $\omega = kV_A$, where $V_A$ is Alfven velocity, than eq. (1) for the “stagnation” particles becomes

$$\omega = l\omega_{ci} + \omega(v_b/V_A)(k_///k)$$

(2)

Note that in eq.(2) second term on RHS depends on plasma density through the Alfven velocity factor. However, this term is $\sim 10$ times smaller than the others; this may explain the absence of noticeable ICE frequency dependence on density in the experiments [1, 2, 4] when density was changed no more than by a factor of two. On the other hand, eq.(2) means that if $l=2, 3, \ldots$ one should expect the exact harmonics of the fundamental ICE frequency. It is consistent with the recent experiments on the TUMAN-3M tokamak where the exact second and third harmonics of fundamental ICE frequency were observed.

Acknowledgments

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