ION CYCLOTRON EMISSION FROM NBI HEATED PLASMA IN THE TUMAN-3M TOKAMAK

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Abstract

The paper discusses some characteristics of Ion Cyclotron Emission (ICE) from the plasma of the TUMAN-3M tokamak under the neutral beam injection (NBI) heating. The ICE is identified as a high-frequency (from 6MHz and above) oscillation of poloidal magnetic field detected with an in-vessel array of fast magnetic probes and having a reach spectrum comprising several components close to the ion cyclotron (IC) resonance frequency and its harmonics. The emission usually, but not always originates from the core plasma near the magnetic axis. This type of NBI ICE called hereafter core ICE is observed in both hydrogen plasma heated by hydrogen beam and deuterium plasma heated by deuterium beam. The typical spectrum of the core ICE in both scenarios consists of the fundamental IC resonance frequency and several harmonics, up to 5 – 6. However, the fine structure and temporal dynamics of the spectral lines are different for the two isotopes. Using toroidal and poloidal arrays of the magnetic probes, mode numbers \( n \) and \( m \) for each of the spectral lines were found, resulting in parallel wavenumber \( k_{||} \) as a function of the spectral line’s frequency, i.e. the dispersion relation. This dispersion is found to be close to the dispersion of the magneto-sound wave propagating nearly normally to the magnetic field. The peripheral NBI ICE caused by the deuterium NBI but originating from the peripheral region was also observed in deuterium plasma. Its frequency spectrum corresponds to the peripheral magnetic field on the low field side of the torus. This peripheral NBI ICE may be caused by the fast ion outflux from core to the edge, or be a result of plasma density and temperature profiles modification by the NBI heating.

1. INTRODUCTION

The emission in the ion cyclotron range of frequencies, ICE, is routinely observed in magnetic fusion devices for many decades. In contrast to the electron cyclotron emission (ECE), the ICE is produced not by the thermal movement of the individual particles, but by an instability developing in the plasma in the presence of fast ions. In a sense, the ICE may be thought of as a reciprocal process to ion cyclotron heating. The importance of ICE is its potential to be used as a diagnostic tool for the fast ion population dynamics in hot plasma heated by these fast ions – charged fusion particles or NBI-produced ions. Understanding the fast ion confinement, loss mechanisms, distribution function dynamics etc. is important for optimization of plasma heating in tokamak-reactor such as ITER, as they will constitute the main source of plasma heating in such an advanced device. This justifies the extensive experimental and theoretical studies of the ICE physics performed in magnetic fusion laboratories worldwide.

The two main groups of fast ions capable of producing the ICE are charged fusion products (alphas, protons, deuterons, tritons) and NBI-produced ions. The first group has much higher energy, several MeV and more. They may be confined, and play a role in ICE generation, only in a relatively large toroidal device with a strong magnetic field – such as TFTR, JET, or ITER. In this case, these fast ions are born in the core plasma but obtain the pitch angle suitable for effective interaction with a wave identified as ICE when they drift away to the plasma periphery. Another group of ions that can generate ICE, NBI-produced fast ions, have much smaller energy, typically less than 100keV, and pitch angle defined by the geometry of the injection (tangential or perpendicular) and a type of their confined trajectory (banana, passing, stagnation, etc.) The ICE generated by NBI-produced ions is observed in many tokamaks and stellarators having a wide variety of sizes and toroidal fields (see [2] and refs. therein). Most frequently, this ICE originates from the plasma edge, but core-located ICE is also observed.

Spectral characteristics of NBI ICE include multiple harmonics of fundamental IC resonance and the fine structure of these harmonics. Fundamental frequency lines and harmonics may have very different amplitudes, and evolve differently in time. As for the fine structure of spectral lines, it comprises up to 3 (or sometimes even more) unevenly space very thin sub-lines, with different temporal behavior during transitional events such as saw-teeth. Despite great efforts made to describe a physical picture of NBI ICE, no final theoretical description...
of spectral characteristics of NBI ICE exists, capable of a comprehensive explanation of all the phenomena observed in different experiments.

2. CORE NBI ICE IN TUMAN-3M TOKAMAK

The NBI ICEs in the TUMAN-3M tokamak [3] are routinely observed in NBI heated plasmas using in-vessel arrays of magnetic probes [4 – 7]. The array consists of 16 probes evenly spaced poloidally in one poloidal cross-section plus several probes located at different toroidal and poloidal cross-sections. The probes, electronic circuitry, and analog-to-digital converters allowed frequencies up to 125 MHz to be registered. Digital filtering, phase delay, and Fourier analysis are applied to deduce poloidal and toroidal mode numbers, m and n.

Experiments were performed in both hydrogen and deuterium plasma, with toroidally injected hydrogen, deuterium, or mixed beam in different combinations. The beam energy was up to 24 keV, injection power up to 250 kW, with equivalent beam current up to 20 A [4]. At toroidal magnetic field up to 1T, and plasma density up to $5 \times 10^{19} \text{ m}^{-3}$, it means that the beam was sub-Alfvénic, with beam ion velocity less than Alfvén velocity. Most parts of the experiments were performed with co-current injection, due to the more effective fast ion confinement in this geometry. When deuterium or mixed beam was injected into deuterium plasma, fusion neutrons are registered giving information on the presence and intensity of the fast ion population. From measured exponential decay of the neutron flux after NBI pulse termination, a fast ion confinement time was calculated to be in the range of 3 - 5 ms, indicating a classical collisional deceleration of the fast ions and the absence of anomalous losses. A typical example of the NBI ICE spectrum is shown in Fig. 1. Here, ICE was registered in deuterium plasma with deuterium NBI, although the beam had a tiny fraction (less than 5%) of hydrogen. The lowest observed frequency is close to the fundamental IC resonance condition for deuterium close to the plasma center [7], which in the toroidal field $B \approx 0.86 \text{ T}$ is 6.5 MHz. This spectral line appears at the latter half of the NBI pulse duration, whereas the second harmonic with frequency $\approx 13 \text{ MHz}$ develops much earlier and continues till the end of the NBI pulse. Alternatively, this 1MHz line may be interpreted as fundamental IC resonance for hydrogen. However, the negligible concentration of fast protons in this scenario allows ruling out this explanation.

Note that the deuterium fundamental line has no fine structure, whereas the second harmonics consists of two narrow (~50 kHz FWHH) lines ~200 kHz apart. Also, the third and the fourth harmonics, much weaker though, are seen in the spectrum. Interestingly, no spectral lines survive longer than 0.1 – 0.3 ms after the termination of the NBI pulse, although fast ion confinement time longer than 3 ms, as concluded above from neutral flux measurements. This may be a manifestation of the fact that there exists a threshold in beam intensity for ICE generation, which is just barely overcome when the ICE is observable. A delay between the NBI pulse front and the start of ICE also confirms this idea. What is not clearly understood yet is a much longer delay of the odd harmonics onset, than the even ones, as seen in Fig. 1. NBI ICE at fundamental IC frequency of the main ion (deuterium in this case) may be suppressed since dielectric tensor properties near the fundamental IC frequency for the main ion effectively rules out effective particle-wave interaction between the main ion gyromotion and a plasma wave polarized circularly in opposing direction. This effect may be thought of as a reciprocal one to the inefficiency of IC resonance heating on the fundamental IC frequency, implying the necessity of a minority or second harmonic scheme. In contrast, when a hydrogen heating beam with the same energy is injected into hydrogen plasma, both fundamental and second harmonic ICE appear with a similar delay of approx. 3ms after the front of NBI pulse and last till the end of the NBI pulse, see the comparison in Fig. 2. These isotope-dependent properties of NBI ICE are also not properly explained yet.
FIG. 1. Spectrogram of core ICE during deuterium NBI heating of deuterium plasma in TUMAN-3M

FIG. 2. Spectrograms of core ICE in hydrogen (above) and deuterium (below) plasmas with the same-species beams

The fine structure of the NBI ICE line, if present, is not constant in time, but is modulated with saw-tooth oscillations. An example of such evolution is shown in Fig. 3. Here, again, the ICE signal is measured in deuterium plasma with deuterium beam injection. As it is seen, the ICE spectrum consists of two well-resolved lines near about ~13 MHz, approx. 200 kHz apart. The two components behave differently during the saw-tooth cycle: the higher frequency component exists between the saw-tooth crashes, while the lower frequency one appears mainly at the moment of crashes.
Fig. 3. Fine structure of the core ICE intensity (above) modulated by the saw-tooth oscillations, indicated by central soft X-ray signal (below)

The reason for this modulation of the ICE spectrum may be plasma current profile redistribution inside mixing radius during the saw-tooth cycle, resulting in a change in resonance conditions for different mode numbers or/and redistribution of fast ion population due to the change in magnetic field topology. As it was found earlier [6, 7], the most probable candidate for the fast ion group responsible for the NBI ICE excitation in the TUMAN-3M tokamak are fast ions residing on stagnation trajectories – a kind of passing trajectories with very little deviation from a major radius location $R \sim R_0$ near the magnetic axis of the discharge. Thus, these fast ions are the most vulnerable to the magnetic field perturbation caused by the saw-tooth oscillations. Note that ICE intensity modulation by saw-tooths, as well as fine structure of its spectral lines, were also observed on DIII-D [8].

Another interesting feature of the discharge 19021109 shown in Fig. 3, as compared to the very similar shot 19021120 pictured in Fig. 2, is the absence of fundamental deuterium ICE frequency in the former and its presence in the latter. A little difference between the two shots is in the injection energy: it was $W_0 \sim 18$ keV in shot 19021120 instead of $W_0 \sim 16$ keV in shot 19021109. Hence, it is a manifestation of a hindered excitation of the fundamental frequency ICE, requiring higher beam energy and higher fast ion number density.

3. NBI ICE DISPERSION RELATION MEASUREMENT

As was mentioned above, the ICE generated during NBI heating is a result of an instability development in the presence of fast ion population, rather than thermal radiation as is in the case of ECE. It would be interesting to measure experimentally some properties of this underlying unstable wave, i.e. its dispersion relation in a form $k = f(\omega)$, where $k$ is the wavenumber (or some of its components), and $\omega$ the angular frequency of the wave. To this end, the discharges of TUMAN-3M were found in which the NBI ICE spectrum had as many harmonics, as possible.

From a theoretical point of view, a most probable candidate for the unstable wave responsible for the NBI ICE excitation is thought to be a magnetosonic instability caused by the interaction of fast ions with a fast magnetosonic, also called compressional Alfven wave (CAW), see, for example, [9, 10]. This wave has a dispersion relation of the form $\omega = kV_\Lambda$, $V_\Lambda$ being the Alfven velocity. CAW travels at an arbitrary nonzero angle $\alpha$ to the field line and has both phase and group velocities equal to Alfven's $V_\Lambda = B_\perp (\mu_0 n_i m_i)^{-0.5}$ (for the case of a single-spices plasma), where $B_\perp$ is the toroidal field, $n_i$ and $m_i$ are the concentration and mass of plasma ions, $\mu_0$ is the magnetic constant. In this work, by measuring phase delays between the signals from the magnetic probes spaced apart toroidally and poloidally, the components of the wave vector for each of the frequency components of the NBI ICE spectrum are obtained.
For each of the experimentally measured NBI ICE harmonics (digitally filtered), the poloidal and toroidal mode numbers \( m \) and \( n \) were measured using magnetic probes separated in toroidal and poloidal directions [6, 7]. For the determination of \( n \), a couple of toroidally separated probes were used. Poloidal mode number \( m \) was obtained as a result of 2D Fourier transformation of signals of a poloidal array of 16 probes. This procedure allows the determination of not only the absolute value of the poloidal mode number but its sign as well. Then, the parallel wavenumber \( k_\parallel = (1/R_0)(n + m/q) \) was calculated for each harmonic. Here \( R_0 \) is the major radius of the torus, and \( q \sim 1 \) is the safety factor at the magnetic surface where the perturbation resides. It should be remembered, of course, that this approach assumes that all the harmonics follow the same dispersion relation, what may not be necessarily so.

Alternatively, parallel wavenumber \( k_\parallel \) was calculated from Doppler-shifted IC resonance condition \( \omega = l\omega_c + k_\parallel V_b \), here fast ion velocity \( V_b \) and its cyclotron frequency \( \omega_c \) were found in modelling of the stagnation trajectories which are thought to be responsible for core ICE excitation in the TUMAN-3M tokamak [7]. In this approach, a combination of experimentally measured parameter \( (\omega) \) and modelled \( (\omega_c \) and \( V_b \)) parameters were used to obtain \( k_\parallel \).

Then, in both approaches, the angle \( \alpha \) between wave vector \( k \) and magnetic field line, \( k_\parallel = k \cos \alpha \), was chosen to obtain a best possible fit between linear dispersion for CAW \( \omega = k_\parallel \cos \alpha \, V_b \) and values obtained from magnetic probes or form modeling of the trajectories.

Experimental study of the dispersion relation of the NBI ICE was carried out in a series of discharges with deuterium NBI with an energy of 16-17.5 keV and a power of \( \sim 250 \) kW in deuterium plasma (trace hydrogen content of the beam was typically lower than 5%). Due to the same isotopic content of the heating beam and the plasma, it was no ambiguity in the interpretation of detected signals as harmonics of ion cyclotron resonance (ICR) of deuterium. Not all the harmonics were present in the duration of NBI pulse simultaneously; the time intervals were for spectral and phase delay analysis were chosen to contain as many well-resolved spectral lines as possible, up to 4. The spectrum indicated the fundamental frequency, the second harmonic split into two sub-lines, and the fourth harmonic as well. The third harmonic is less pronounced and sometimes is difficult to detect. For the discharge 19021120, the analysis of the spatial mode structure was carried out in the temporal window 64.74–64.84 ms, in which all the above-mentioned spectral components were reliably detectable the frequency range from 6.62 to 26.92 MHz.

The results of mode number measurements using magnetic probes are given in Table 1. To determine the poloidal mode number \( m \), the 2D (poloidal coordinate and in time) Fourier transform was used, which allows, in contrast to 1D (spatial) transform which gives the sign-resolved poloidal mode number. The time interval for 2D analysis was selected in such a way as to contain a fixed number of 110 oscillation periods for each frequency, which corresponds approximately to the 4 to 16 \( \mu \)s time window inside time interval from \( t = 64.7794 \) to 64.7954 ms. For measurement of toroidal mode number \( n \), the signals from two magnetic probes located 150° apart in the toroidal direction were used. Time widows for this analysis were chosen to contain ten periods of oscillation. It varied depending on the harmonic frequency NBI ICE. The phase difference of the probe signals was analyzed taking into account the conditions of toroidal symmetry. It should be noted, that the phase shifts between the signals of the two probes can be determined only with an accuracy of \( 2\pi N \), where \( N \) – any integer. To choose \( N \), that is, to unambiguously determine the phase shift, it is necessary to apply additional information. One of such considerations comes from a negative Doppler shift \( k_\parallel V_b \) of the observed ICE frequency \( \omega \) with respect to the IC frequency in the laboratory frame \( \omega_l \); \( \omega = l\omega_c + k_\parallel V_b \). Here, \( l \) is harmonic’s number, \( V_b \) is the longitudinal projection of the fast ion velocity. The IC frequency \( \omega_c \) was calculated from magnetic field strength at the location of the stagnation fast ions found in numerical modeling of the beam-produced ions’ trajectories. So, for instance, for the fundamental line, from the relation \( \omega < \omega_c \), it follows that the wave propagates towards the injected heating beam: \( k_\parallel V_b < 0 \) [7]. This condition (fulfilled in this discharge, although not universal) allows one to exclude toroidal mode numbers corresponding to wave propagation along the beam and shown in Table 1 in brackets.

**TABLE 1. THE CORE ICE MODE NUMBERS \( n \) AND \( m \), AND LONGITUDINAL WAVENUMBER \( k_\parallel \) IN THE SHOT 19021120**

<table>
<thead>
<tr>
<th>Spectral component</th>
<th>( f ), MHz</th>
<th>filtering interval, MHz</th>
<th>( n )</th>
<th>( M )</th>
<th>( k_\parallel ), m(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f_1 ), fundamental deuterium ICR frequency</td>
<td>6.62</td>
<td>6.5-6.7</td>
<td>(-4), 1, 3, 8</td>
<td>1</td>
<td>3.8, 7.5, 17</td>
</tr>
</tbody>
</table>
Fig. 4 shows longitudinal wavenumbers for different harmonics. The blue triangles represent magnetic probe data (not all the points are shown), the black squares are data from modeling of the stagnation trajectories. It can be seen that for both approaches the majority of the points are grouped near straight lines, corresponding propagating a CAW with a dispersion law $\omega = k_\parallel V_A = k_\parallel V_A/\cos\alpha$ at an angle $\alpha = 84^\circ$ (from modeling) and $74^\circ$ (from magnetics) to the magnetic field line. For some points from Table 1, not shown in Fig. 4, $\alpha = 45^\circ$. Based only on the experimental data available, one cannot make a reasonable choice between these two waves with $\alpha = 45^\circ$ and $\alpha = 84^\circ$. However, it is known that for the sub-Alfvénic velocities of injected ions theory predicts an almost normal propagation of the CAW responsible for the NBI ICE [11,12]; therefore, the wave propagating at the angle $\alpha = 74^\circ$ seems to be more probable, and this is also closer to the results obtained from the modeling.

### Table 1: Wavenumbers for different spectral components

<table>
<thead>
<tr>
<th>Harmonic</th>
<th>$k_\parallel$ ($\text{cm}^{-1}$)</th>
<th>Range</th>
<th>$n$, $Q$</th>
<th>$\alpha$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_2$ (second harmonic)</td>
<td>13.28</td>
<td>13.2-13.4</td>
<td>(-2), 3, 10</td>
<td>1</td>
</tr>
<tr>
<td>$f_3$ (third harmonic)</td>
<td>20.10</td>
<td>20.0-20.2</td>
<td>(-7, 0, 5), 12</td>
<td>6</td>
</tr>
<tr>
<td>$f_4$ (forth harmonic)</td>
<td>26.92</td>
<td>26.8-27.0</td>
<td>(-4, 1), 8, 13</td>
<td>6</td>
</tr>
</tbody>
</table>

Fig. 4. The wavenumbers $k_\parallel$ for the different spectral components in the core ICE spectrum

4. PERIPHERAL ICE IN NBI HEATED PLASMA

As discussed above, NBI ICE in the TUMAN-3M, in most cases, originates from the core region. This follows from the fact that the ICE frequency is close to the central IC resonance. However, in some NBI shots, the ICE frequency was found to follow peripheral magnetic field, at the very edge of LFS of the torus.

This peripheral ICE has a spectrum very similar to ohmic ICE – the ICE which is observed in the TUMAN-3M with ohmic heating alone (see paper CN-286/1181 by S.V. Lebedev, this conference). An example of peripheral NBI ICE is shown in Fig. 5. This spectrogram indicates a significant increase in the intensity of harmonics (8th and above) of peripheral ICE during the NBI pulse just after gas puffing termination. This phenomenon has a lot in common with pure ohmic ICE, which is also was found to be strongly influenced by the termination of gas puffing. In contrast to pure ohmic ICE, the frequency of peripheral NBI ICE registered by the probes located at different positions along major radius $R$ doesn’t follow $1/R$ dependence (modified by ripple) but is approximately constant in the range $R = 0.7 - 0.8$ m at the LFS. This is illustrated in the Fig.6, were the registered frequency is plotted against the probe location for a set of NBI and ohmic shots and compared with magnetic field distribution indicated by the dashed line. In the NBI shots, peripheral probes register the same frequency, unlike the pure ohmic shots. This is similar to NBI ICE which produces the signals with the same frequency on all the probes. At the moment, it is difficult to tell if the observed peripheral ICE a kind of fast ion-driven instability, or a modification of the ohmic ICE by NBI heating through its influence on density and temperature gradients. Also, this effect – peripheral NBI ICE – was not reproduced in hydrogen plasma. This observation also has no explanation yet.
5. SUMMARY

The paper presents recent results of an experimental study of the NBI ICE in TUMAN-3M tokamak. Observed phenomena include core-located ICE with a frequency close to the IC near the magnetic axis (and its harmonics), and peripheral ICE originated from the plasma periphery.

The core NBI ICE is produced by the stagnation ions residing near the center of the discharge, and has the frequency spectrum corresponding to the central magnetic field. The dispersion relation for the core ICE was experimentally analyzed based on mode structure measurements using an array of the in-vessel probes, or calculated from the modelling of the Doppler shifted resonance condition for the fast ions on the stagnation trajectories. In the both approaches, the dispersion relation was found to be of a compressional Alfvén wave type, corresponding to the magneto-acoustic wave propagating nearly perpendicularly (at the angle of $\alpha = 74 - 84^\circ$) to the direction of the magnetic field vector.

The peripheral NBI ICE was observed only in deuterium plasma with deuterium NBI, but not with hydrogen plasma and beam. The spectra of the signals from peripheral probes during the peripheral NBI ICE are nearly
identical, and don’t follow the $f \sim B(R)$ dependence typical for ohmic ICE. The onset of the peripheral NBI ICE coincides with gas puffing termination; this feature was also observed for pure ohmic ICE and means that these phenomena probably have a lot in common. Thus, the nature of peripheral NBI ICE is unclear yet. It may be caused by fast ion outflux to the peripheral region, or be a result of profiles modification be joint action of NBI heating and gas puffing termination.

ACKNOWLEDGEMENTS

The experiments on the TUMAN-3M tokamak were carried out with the support of the government order of the Ioffe Institute.

REFERENCES