Identification of NBI ICE in the TUMAN-3M

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The ion cyclotron emission (ICE) has become in recent years a potentialy promising method for fast ion (FI) population studies in magnetic fusion devices. FI confinement and transport physics are important as they play a key role in fusion plasma heating. There are two main kinds of FI: one is produced by fusion itself. These FI, namely alphas and protons, have energies in MeV energy range, and are confined only in large devices with a strong enough magnetic field. Another type of FI is generated by a radiofrequency ion cyclotron resonance (ICR) heating, or by neutral beam injection (NBI). The FIs of both origins are eventually responsible for the bulk plasma heating. In addition, they may play a role in the excitation of instabilities dangerous to plasma and FI's confinement. The necessity for FI diagnostics justifies the interest in ICE measurement and investigation on many magnetic fusion installations [1 and Refs. therein]. One may think about ICE generation as a process reciprocal to ICR heating. It is known that ICR heating is ineffective in a single-species plasma because of unfavorable polarization of wave's electric field rotating in opposite direction with respect to the ion's in the point of IC resonance. To ensure energy transfer from the wave to the ions, different approaches may be used, such as minority heating, second harmonic heating, or ion-ion hybrid and three ion schemes. Having in mind the reciprocity principle, one may conclude that the same scenarios are to be found when the ICE is generated.

This paper reports on the ICE study performed on the small tokamak TUMAN-3M in NBI heated hydrogen, deuterium, and helium plasmas. The toroidally (co-current) injected atomic beam consisted of deuterium (with 5-7% inevitable admixture of hydrogen) or nearly pure hydrogen with energies of up to 24 keV. The injection power was up to 250 kW, with an equivalent beam current up to 20 A. The ICE in the TUMAN-3M is routinely observed [2] both in ohmic and injection heated scenarios using in-vessel arrays of the magnetic probes. The probes measured the poloidal component of the oscillating magnetic field. The probes, electronic circuitry, and ADCs used in the experiments allowed for the registration of the oscillating magnetic field with the frequency up to the 125 MHz, which roughly corresponds to the 8th to 10th harmonic of ICR for hydrogen in the center of the TUMAN-3M plasma with the typical toroidal magnetic field up to 1T. In contrast to numerous experiments, in the TUMAN-3M, the ICE frequency is close to the central (i.e., not peripheral) ICR condition. The central ICEs were also observed on some tokamaks [3], though relatively rare, and treated theoretically [4]. For TUMAN-3M experimental conditions, the FI group responsible for NBI ICE generation is so-called stagnation ions, localized in a narrow radial region near the toroidal magnetic axis [5]. Among characteristic features of NBI ICE in the TUMAN 3M are their very narrow spectral lines ($\Delta f/f \leq 5\cdot 10^{--3}$) and a fine structure consisting of up to 4 thin sub-lines.

Figure 1 illustrates the typical behavior of the ICE spectrum measured in deuterium plasma under the injection deuterium beam (D) with low (<5%) hydrogen (H) admixture. At least four spectral lines are clearly seen; two of them being odd (~6.2 MHz fundamental and ~18.6 MHz 3rd) harmonics of the deuterium ICR, while the other two (~12.5 MHz and ~25 MHz) may be equally the even deuterium harmonics (2nd and 4th), or fundamental and 2nd harmonic of hydrogen ICR.

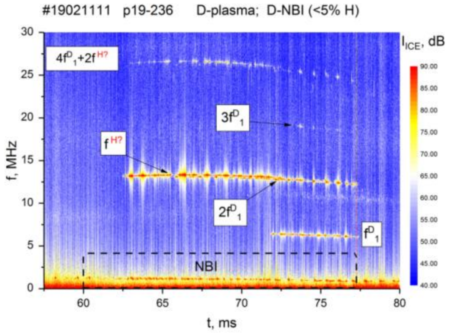

Figure 1 – Spectrogram of core ICE during deuterium NBI heating of deuterium plasma in TUMAN-3M

It is seen that the strongest emission is observed in the vicinity of 12.5 MHz. This spectral line appears first after the NBI pulse switching on, and lasts till the end of the heating pulse. As the fraction of hydrogen FI is expected to be very low in this experiment, at least in the initial part of the NBI pulse, one might interpret this spectral line as the one produced by second-harmonic deuterium ICE (in a process reciprocal to second-harmonic deuterium ICR, or hydrogen minority heating, as discussed above). Later on, approx. 12.5 ms after the beginning of the NBI pulse, a weaker spectral line with the frequency ~6.2 MHz appears, corresponding to the fundamental deuterium ICR. Apparently, this emission is made possible by the accumulation of the hydrogen in the center of the discharge, which creates a kind of ion-ion hybrid resonance layer residing between ICRs for the two isotopes. Fast deuterons with Doppler-shifted ICR frequency play a role of the resonant third ion in the three-ion mechanism here. This long delay (~ 12.5 ms) is required for hydrogen content to reach the level required for effective particle-wave interaction.

Another interesting example of NBI ICE generation was observed in the recent experiment with hydrogen atomic beam injection into the helium plasma, see Fig. 2a & b.

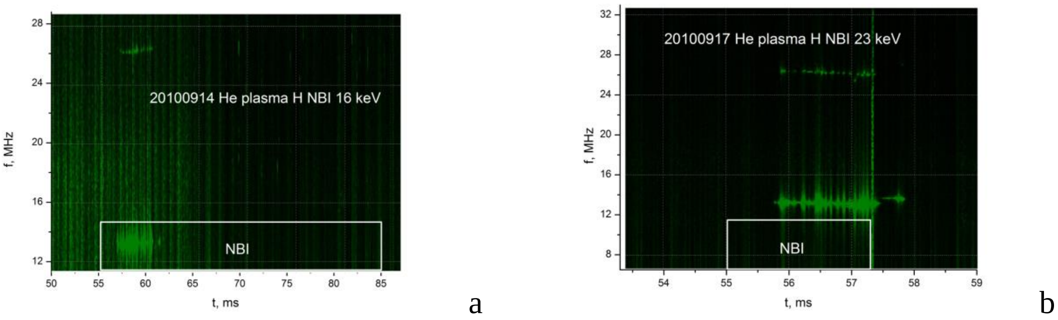

Figure 2 – Spectrograms of core ICE during hydrogen NBI into helium plasma in TUMAN-3M

As shown in Figure 2a, the ICE with a frequency of ~13MHz appears shortly after the start of NBI but lasts no longer than ~3ms. Here, the observed picture corresponds to the minority emission scheme (reciprocal to minority ICRH). As the beam is 100% hydrogen here, its concentration builds up rather quickly, so the phase of hydrogen FI minority is only a short and transient one. After the end of NBI, the energy of the FI hydrogen effectively dissipates faster than its concentration, and the ICE is not generated again. However, if the NBI pulse is very short, see Figure 2b, the ICE survives ~0.5 ms after the end of the NBI. The FI hydrogen concentration doesn't reach the critical level when it is minority no more, and after the end of the NBI, the emission continues while the energy and concentration of FI both gradually disappear.

Of course, the above interpretation of ICE spectrum and dynamics remains to be purely qualitative. A quantitative analysis will require both measurements of the concentrations of both thermal and FI fractions of the isotopes, and modeling of the particle-wave interactions relevant to the experimental conditions.

An important issue in the interpretation of the observed ICE spectra is the physical nature of the instability which develops in the presence of FI. Theory agrees that the most probable candidate is the unstable fast magneto-sound wave, also referred to as compressional Alfvén wave. It is important to check this notion experimentally through measurement and analysis of the dispersion relation of the observed emission. Earlier, the wave vector of the observed emission k was measured using poloidally and toroidally separated magnetic probes and found to be consistent with fast wave theory predictions [6]. In this paper, an attempt is made to interpret the observed spectra of NBI ICE in the TUMAN-3M basing on the Doppler-shifted ICR condition for FI: $\omega = l\omega_c + k_{||}V_b$. The fast ion velocity V_b and its cyclotron frequency ω_c were found in modeling of the stagnation trajectories which are located close to the toroidal magnetic axis and thought to be responsible for core ICE excitation in the TUMAN-3M tokamak [5]. Thus, the measured ICE frequency $f = \omega/2\pi$ and modeled FI IC frequency ω_c and velocity V_b were combined to obtain $k_{||}$ for different components of the ICE spectrum. Then, the angle α between wave vector k and magnetic field line, $k_{||} = k \cos \alpha$, was chosen to obtain the best possible fit between linear dispersion for fast wave $\omega = k_{||}/\cos \alpha \, V_A$ and values obtained from modeling of the trajectories. Here, V_A is the Alfvén velocity calculated for the given experimental conditions. Figure 3 presents the results of this analysis for 23 keV H NBI in He plasma.

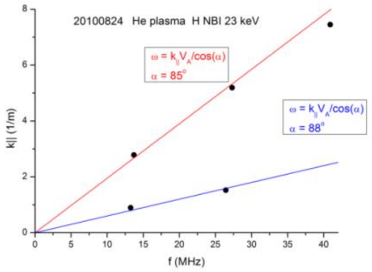

Figure 3 – Dispersion relation for H ICE during H NBI in He plasma. Dots are obtained from Doppler-shifted ICR condition, lines are linear fits to them

It is seen that the measured spectral components agree well with the linear dispersion relation for two fast waves propagating nearly perpendicularly to the magnetic field.

To summarize, this paper presents the results of the analysis of the observed NBI ICE spectra and their dynamics in the TUMAN-3M tokamak from the point of view of the reciprocity of IC emission and ICR heating. In particular, it is found, that in some cases the observed behavior may be understood as a minority IC emission, while in others the ion-ion hybrid scheme looks more relevant. The analysis of the dispersion relation for the observed ICE suggests that the unstable wave responsible for the IC emission is the fast magneto-sound wave destabilized by FIs.

Acknowledgments

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