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

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ABSTRACT

- The Ion Cyclotron Emission (ICE) is identified as high-frequency (from 6MHz and above) oscillations of the 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. It depends on plasma and beam species, beam energy, etc. Some lines have a fine structure – several well-resolved sub-lines
- 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.
- In some deuterium discharges with deuterium NBI a peripheral ICE was observed as well, with the spectrum and the spatial distribution different from these of core NBI.

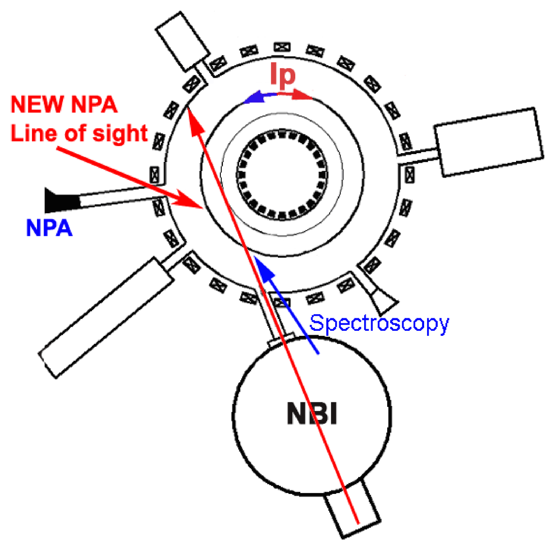
INTRODUCTION

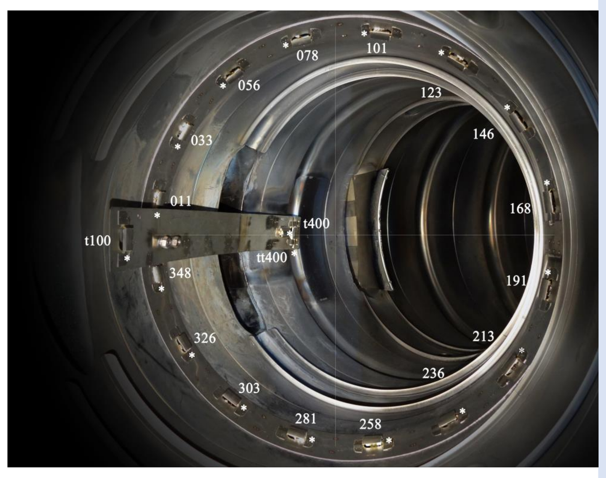
- The emission in the ion cyclotron range of frequencies, ICE, is routinely observed in magnetic fusion devices for many decades.
- In contrast to the electron cyclotron emission (ECE), the ICE is produced not by the thermal movement of the individual particles, but by an instability developing in the 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 products 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.

EXPERIMENTAL SETUP AND METHODS

TUMAN-3M PARAMETERS

- circular limiter configuration
- $R_0 = 0.53$ m $a_l = 0.22$ m
- $B_T < 1.0$ T $I_p < 190$ kA
- $n_e < 6\cdot 10^{19}$ m^{-3}
- $T_e(0) < 0.8$ keV $T_i(0) < 0.4$ keV



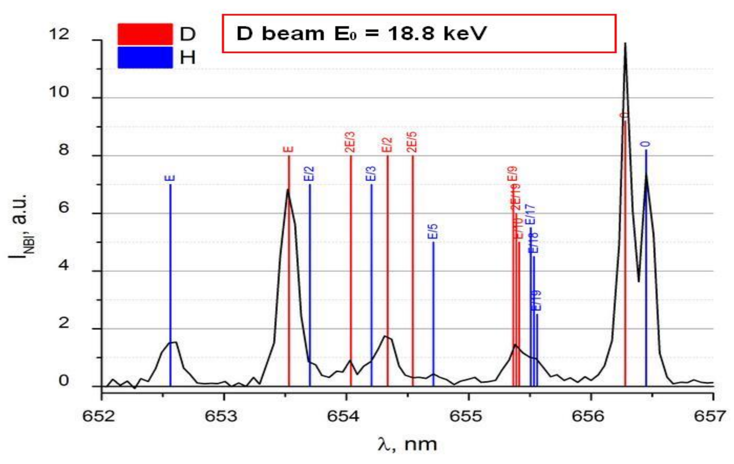


NBI PARAMETERS

- Species: $D^0/H^0 \rightarrow D^+/H^+$
- $P_{NBI} < 0.3$ MW $\tau_{NBI} = 60$ ms
- $E_{NB} = 25$ keV
- Setup: Co, tangential,
- Tangency radius $R_{tan} = 0.42$ м

MASS AND ENERGY SPECTRUM OF THE BEAM

- May have both D and H components with energies E_0, $E_0/2$, $E_0/3$…



IN-VESSEL PROBE ARRAY

- 16 probes poloidal array
- several individual probes throughout the torus
- 250MS/s ADCs with broad-band amplifiers

EXPERIMENTAL DETERMINATION OF THE DISPERSION RELATION

- Test candidate – compressional Alfvén wave (CAW) with dispersion low $\omega = k V_A$
- To obtain a dispersion relation for the wave responsible for the ICE generation in a form $\omega = f(k)$, wave numbers $k_{||}$ are obtained for each of the individual components in ICE spectrum
- Poloidal mode number m is found sign-resolved as a result of 2D Fourier transformation of poloidal array probes' signals
- Toroidal mode number n calculated from phase delays between toroidally separated probes
- Then, $k_{||} = (n + m/q)/R_0$ is calculated assuming q ~1 (ICE location near the magnetic axis!)
  1. Then, the angle α between wave vector k and magnetic field line, $k_{||} = k \cos\alpha$, is chosen to obtain a best possible fit between linear dispersion for CAW $\omega = k_{||}/\cos\alpha\, V_A$
  2. Alternatively, $k_{||}$ was found from Doppler-shifted ICR condition $\omega = l\omega_{Bi} + k_{\|} v_b$

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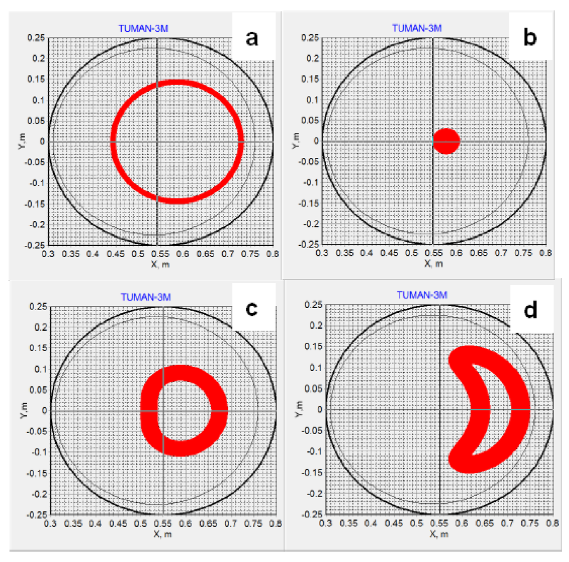
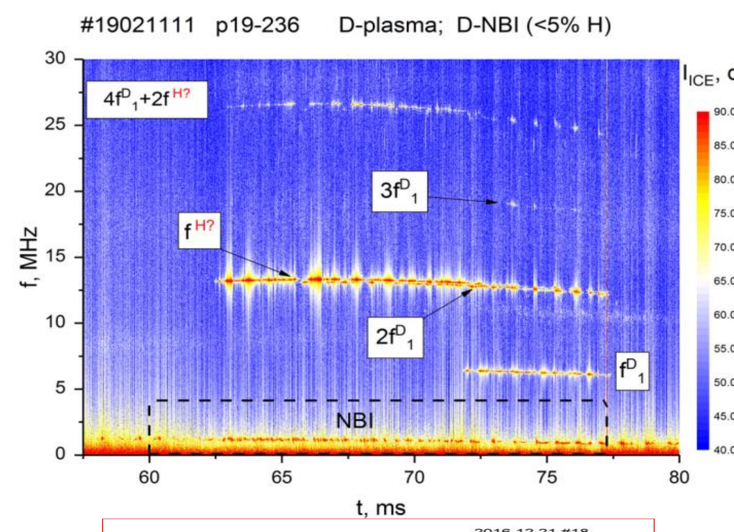
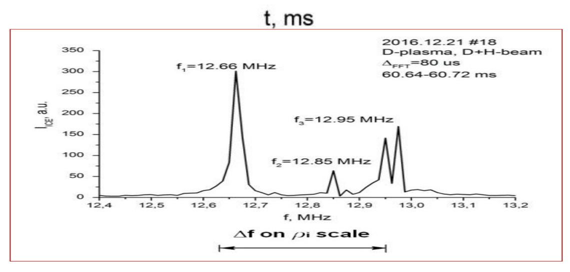
NBI ICE PROPERTIES IN THE TUMAN-3M TOKAMAK

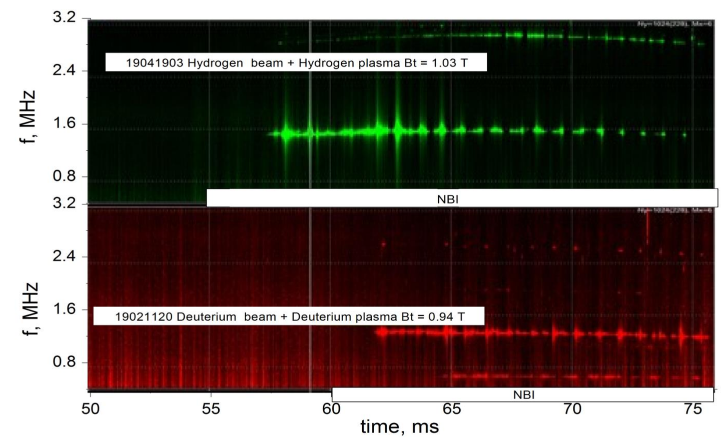
GENERAL PICTURE

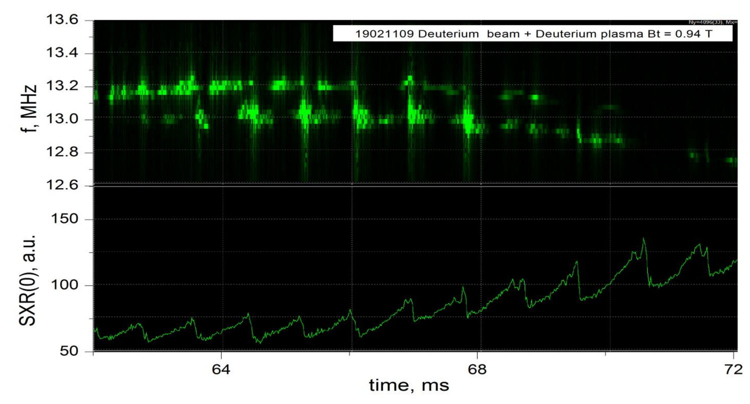
- Typical spectrum of NBI ICE in D plasma with D beam (H <5%) consists of fundamental deuterium ICR line plus several (up to 4) harmonics
- Fundamental frequency corresponds to the central IC resonance
- Some lines are split into several (2 - 3) narrow sublines
- Temporal dynamics of fundamental and harmonics is different in (H plasma+H NBI) and in (D plasma + D NBI)
- ICE intensity and spectrum are modulated by saw-teeth
- Fast ions on stagnation trajectories may be source of free energy for core ICE (see picture "b")
- Doppler-shifted IC resonance condition governs the NBI ICE frequency
  $\omega = l\omega_{Bi} + k_{\|} v_b \;(\ldots + k_{\perp} v_D)$





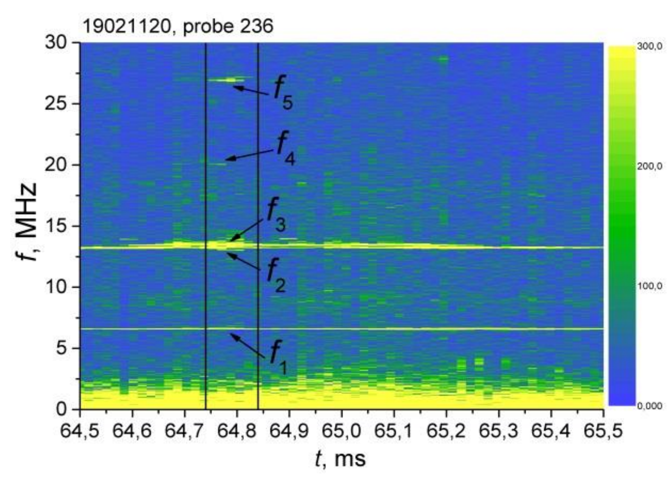






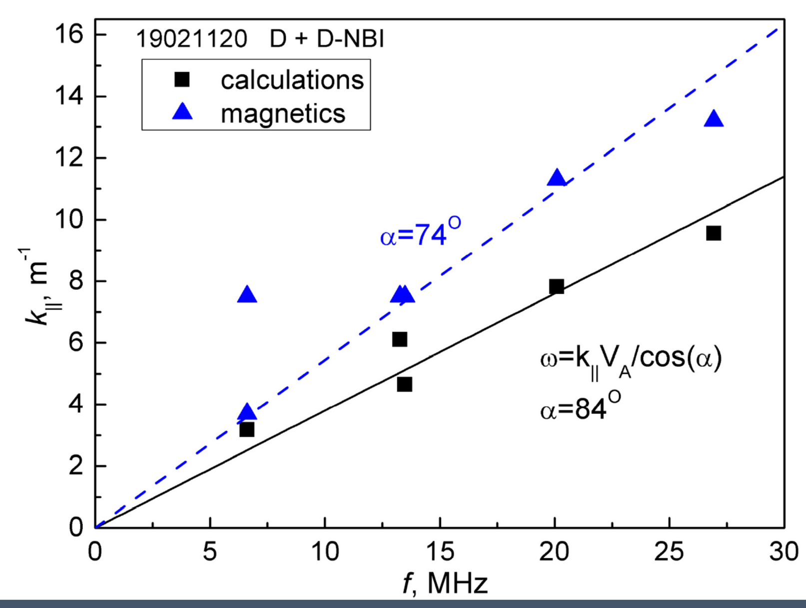
DETAILS MAY BE DIFFERENT THOUGH

- Minority ICE observed as well (H ICE in D plasma and vice versa)
- In some shots peripheral ICE originated from low field side edge is observed during NBI ICE pulse (see below) - caused by passing ions "a" ?



MEASUREMENT OF DISPERSION RELATION OF CORE NBI ICE

- Time window for dispersion analysis containing as many harmonics as possible was taken
- Each spectral line is digitally filtered and then mode numbers n and m and $k_{||} = (n + m/q)/R_0$ were calculated
- Some values were ruled out because of Doppler shift condition $k_{||}V_b < 0$
  - Alternatively, $k_{||}$ was found from Doppler-shifted ICR condition $\omega = l\omega_{Bi} + k_{\|} v_b$
  - Here, ω – experimentally measured ICE frequency, ω_{Bi} *and* v_b reslut from the stagnation trajectory modeling
  - Both methods agree well with CAW (magneto-sound) dispersion for nearly perpendicular propagation $\omega = kV_A = k_{||}V_A/\cos\alpha$ with $\alpha = 74^o$ from magnetic probes and $\alpha = 84^o$ from modelling of the trajectories



PERIPHERAL NBI ICE IN TUMAN-3M

- Observed in deuterium shots only
- Peripheral ICE spectrum follow peripheral Bt – not the center Bt!
- The spectrum is very similar to ohmic ICE (see poster CN-286/1181 by S.V. Lebedev, this conference).
- Increase in the intensity of harmonics (8th and above) during the NBI pulse and just after gas puffing termination.
- The frequency of peripheral NBI ICE registered by the probes located at different positions along major radius R approx. constant in the range R = 0.7 – 0.8 m at the LFS.
- 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.