Characteristics of Ion Cyclotron Emission on ASDEX Upgrade

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Ion Cyclotron Emission (ICE) has been observed on different tokamaks: JET [4], DIII-D [1], TFTR [2] and JT-60U [7] and was the object of several theoretical investigations [6] [5] [9] as a promising diagnostic for fast ions studies. We present here the first observations of this instability on ASDEX Upgrade and analyze the consistency of its features with the results of other machines.

Experimental Setup

Measurements were carried out on ASDEX Upgrade from 2009 to 2011 with two cross-dipole antennas located in the vacuum vessel (see Figure 1). They pick up both electromagnetic and electrostatic parts of received waves. An additional voltage probe is located inside an ICRH antenna behind the Faraday Shield (with around 30dB attenuation). The probes are connected to an Acqiris digitizer with 100MHz bandwidth, 250MS/s sampling rate and 12bits resolution. Each channel has a limited memory of 2MB, limiting the record to 8ms. To get the temporal evolution of the instability during longer timescales of several seconds, the signals are sampled for $6\mu s$ every 15ms. Before being digitized, signals are filtered to remove the main ICRF frequency and amplified with a 30dB low noise amplifier (Mini-Circuits ZFL-500LN) to get a better Signal to Noise Ratio.

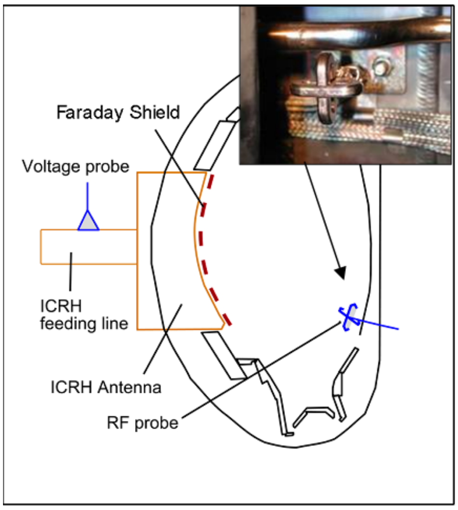

Figure 1: *Configuration of voltage and RF probes on ASDEX Upgrade.*

Measurements

The measurements can be classified into three families presented on Figure 2. The first type occurs between 50 and 120ms at the beginning of tangential NBI injection and has a level of 40dB above the noise floor on the RF probe and is not visible on the voltage probe. Its average frequency corresponds to the first harmonic of Deuterium cyclotron frequency in the center and follows the same time evolution when the central magnetic field is varied. The second or the third harmonics can also be excited. This central emission has rarely been observed on other machines, except on JFT-2M [10] and DIII-D [1].

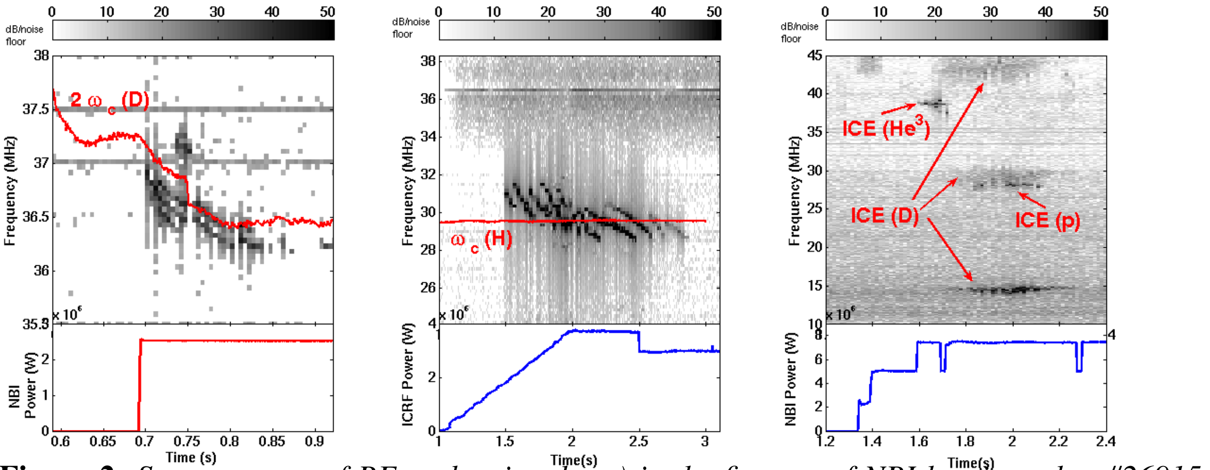

Figure 2: *Spectrograms of RF probe signals: a) in the first ms of NBI heating -shot #26915, shot b) during ICRH H minority heating -shot #25546 c) during NBI heating -shot #26980.*

The second type of signal is measured with ICRF H minority heating in conditions shown on Figure 3 and is likely to be minority ICE [3]. The average frequency corresponds to the principal Hydrogen cyclotron frequency at the edge ($\rho_t = 0.95$) . The sampling process makes it possible to highlight a fine structure of several frequencies and its time evolution.

The last type of signal is recorded during NBI heating with power above 5MW. The behavior observed is very similar to what was observed on TFTR and JT-60U: a first burst of instabilities of several milliseconds with a unique frequency matching the first harmonic of Helium-3 cyclotron frequency at the edge, succeeded by a longer phase with multiple wide and diffuse frequencies corresponding to Deuterium cyclotron frequency and its harmonics. At power above 10MW and correlated with a high neutron rate, a narrow frequency peak is visible just under the 2nd harmonic $2\omega_c$ of Deuterium and was identified on JT-60U [8] as a signature of proton.

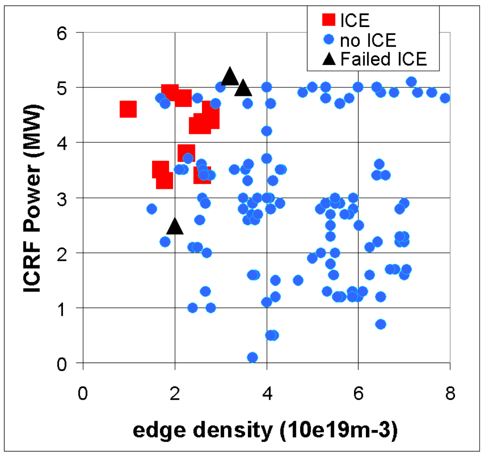

Figure 3: *Discharges parameters to trigger ICE with ICRH*

Interpretation

There are four types of ICE instabilities observed: ICE produced by fusion products (FP-ICE), by ICRH accelerated minority species (mICE), beam supported ICE -all three occuring at the edge- and central ICE. In all cases, the source of free energy for the instability is provided by fast ions which build an inversion of the ion distribution function at high energies.

The origin of these fast ions depends on the type of ICE: they can be fusion products (He^3, proton...) or minority species like Hydrogen accelerated by ICRH with a large orbit extension grazing the edge or particles from the neutral beams directly ionized at the edge or in the center. These fast ions transfer their free energy to the waves by resonant cyclotron coupling.

The type of wave excited depends on the ion velocities (super-alfvenic for FP-ICE and mICE, supra-alfvenic for beam-ICE): they can be fast waves or electrostatic waves (ion cyclotron or Bernstein wave). The nature of the interaction is also unknown: either local (the emission growth rate γ higher than the drift periods of fast ions) or global (several passes from fast ions necessary to excite the instability). In the latter case, the energy builds up if global modes from the plasma, the so-called Compressional Alfven Eigenmodes (CAE) are excited. We check that the characteristics of the emissions measured on ASDEX Upgrade are consistent with these main features of ICE. For central ICE, a TRANSP simulation was carried out to get the distribution function of fast deuterons in the center ($\rho_t < 0.05$) presented on Figure 4: two tails of fast ions at 60keV and 30keV indeed build up during ICE when a first beam is injected. However a second beam adds a bump at 90keV which does not prevent the extinction of the emission: not only the slope of the distribution function but also the concentration of fast ions should be taken into account for the excitation threshold.

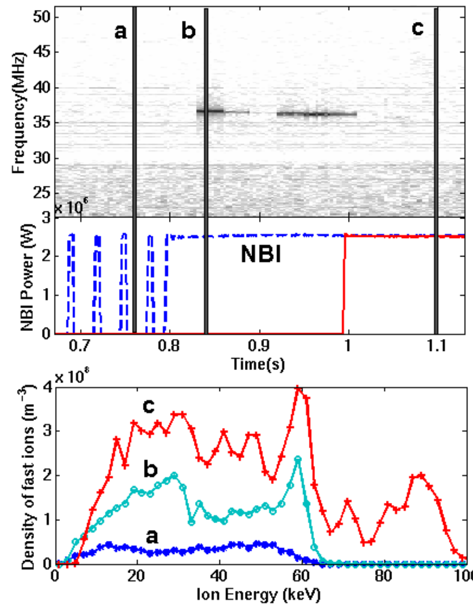

Figure 4: *Shot #25533 - Distribution functions of fast ions with $v_\parallel/v = 0.6$ in the center before (a), during (b) and after (c) ICE. First beam with $E = 60keV$, second beam with $E = 95keV$.*

At the edge, with NBI, observations with the Fast Ion Loss Detector (FILD) did not reveal any loss of fast ions during the emission: either they remain confined in the plasma (although near the edge), or they have escape trajectories outside the observation window of the detector. However, a clue is given by the correlation on Figure 5 between the ICE signal and the increase of the neutron rate, especially when the frequency corresponding to $\omega_c(proton)$ is present. An interesting fact on this figure, already pointed out on JT-60U, is the unexplained correlation of the peak of ICE with the high beta poloidal phase.

During ICRF heating, ICE is observed when the heating efficiency is sufficient to produce an increase of the population tail visible on the neutral particle analyzer. The evolution of the frequencies can be correlated with the Alfven velocity (see Figure 6), confirming the role of Alfven Eigenmodes in the emission.

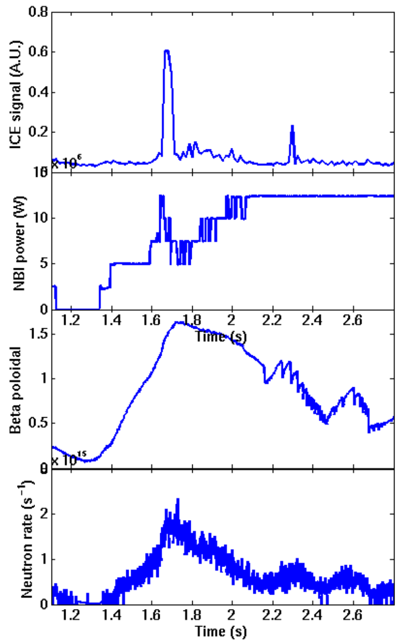

Figure 5: *Shot #26424 - Correlation between edge ICE signal, neutron rate and Beta poloidal during high power NBI heating.*

Conclusion

The measurements of ICE on ASDEX Upgrade are consistent with the results of other tokamaks, especially TFTR and JT-60U. The fast digitizers make it possible to distinguish the fine structure during central ICE and mICE, opening a new way to get information on the distribution of fast ions. To demonstrate the validity of the existing theories and to use the emission as a diagnostic, we need an independent way to measure the distribution function, like the coherent thomson scattering diagnostic that we plan to request in the next experiments.

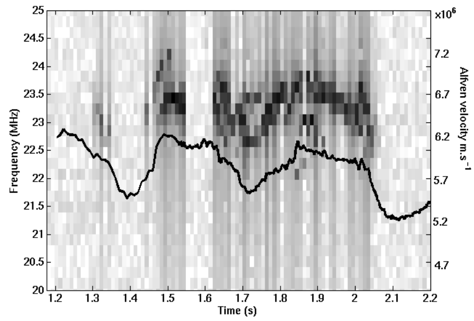

Figure 6: *Shot #25503 - Comparison of temporal evolution from the mICE frequency and Alfven velocity at the edge during ICRF.*

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