Observations of Ion Cyclotron Emission on NSTX-U

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This paper presents observations of ion cyclotron emission (ICE) in the spherical tokamak NSTX-U. The ICE studied in the conventional tokamaks JET [1], TFTR [2] and JT-60U [3] was attributed to resonant excitation of the magneto-acoustic or compressional Alfvén eigenmode (CAE) by super-thermal ions. Measurements of ICE may provide information on confined fast ions. While fluctuations similar to ICE were seen in early beam-heated NSTX plasmas, more commonly a broad range of CAE were seen at frequencies ranging from about half the edge Deuterium ion-cyclotron frequency, f_{ci}, up to greater than f_{ci} in the core in both MAST and NSTX [4]. These CAE are co-propagating and have toroidal mode numbers as high as n=15 and show the typical Alfvénic frequency dependence on density. In contrast, the ICE seen on NSTX-U is counter-propagating with toroidal mode numbers of n = -1 or 0, has frequency higher than the edge deuterium cyclotron frequency, has no frequency dependence on density, and harmonics as high as the 7^{th} have been seen.

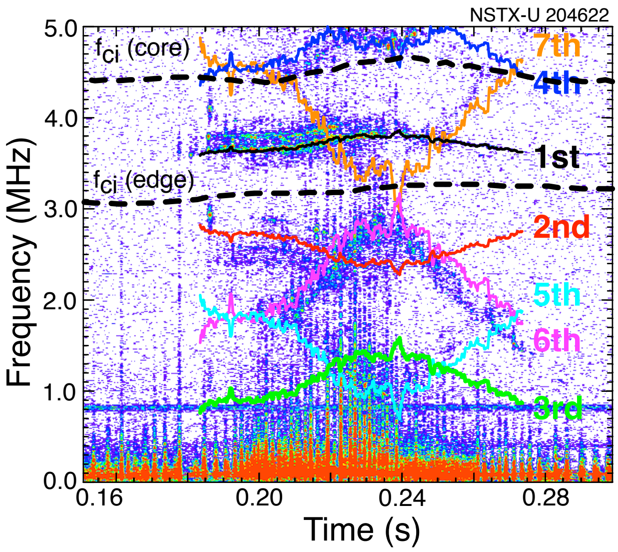

Fig. 1 Spectrogram of magnetic fluctuations showing fundamental ICE (labeled "1"), and aliased harmonics up to the the seventh, as labeled. The edge and core deuterium cyclotron frequencies are also shown.

In Fig. 1 is shown a spectrogram of data from a magnetic sensor on NSTX-U acquired at a digitization rate of 10 MHz. The fundamental deuterium ICE, labeled "1st", is seen at a frequency of about 3.8 MHz. Higher harmonics are also present (as labeled), but are aliased. For this figure the fundamental frequency evolution was tracked and used to estimate the frequencies of the harmonics. The colored lines indicate the approximate aliased frequencies of the higher harmonic modes. As can be seen, significant emission is seen at the 2^{nd}, 4^{th}, 5^{th}, 6^{th} and 7^{th} harmonics in this example. The 3^{rd} harmonic maps into the noisy, lower frequency part of the spectrogram and may be masked. The magnetic sensor response falls off approximately as the inverse of the frequency above ≈ 3 MHz, so the amplitudes can be considered as representative of the relative fluctuation level in Gauss.

The ICE frequency is significantly higher than the edge deuterium cyclotron frequency, indicated by the black dashed line in Fig. 1 at 3.2 MHz. The ICE is assumed to originate from the deuterium beam ions, as it is not consistent with the cyclotron frequencies of the D-D fusion products (He^3, T, and H), shown in Table I. If the ICE were assumed to originate from the second harmonic tritium, that would mean that the odd harmonics of tritium cyclotron emission would then be missing, which seems unlikely.

	freq. MHz
Hydrogen	6.40
He^3, 2^{nd} T	4.27
ICE	3.8
Deuterium	3.20
Tritium	2.13

Table 1. Approximate edge ion cyclotron frequencies energetic ions in NSTX-U.

The frequency of the ICE implies that it originates deeper in the plasma. In Fig. 2a are shown contours of the electron density profile (black contours), overlaid with the ion cyclotron emission spectrum mapped to major radius. At each point in time, the frequencies in the magnetic fluctuation spectrum are mapped to the radius of the corresponding deuterium ion cyclotron frequency. The local ICE frequency peak (red contours) roughly follows the contours of a strong local gradient in density, that is, an apparent internal density transport barrier. The correlation with the strong density gradient is more clear in the time slice of the density profile and magnetic fluctuation spectrum shown for 0.231s in Fig. 2b. The ICE emission appears to originate from approximately the half minor radius, far from the plasma last-closed flux surface. In this example, the ICE frequency variation is correlated with a radial shift of the plasma position, as indicated by the blue line in Fig. 2a, which shows the location of the magnetic axis. Whether or not causality plays a role, the

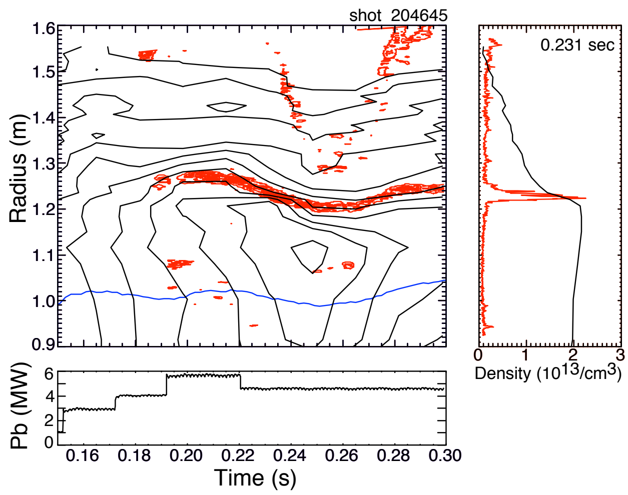

Fig. 2. a) Contours of electron density (black) with magnetic spectrogram overlaid (red), where spectrogram frequency has been mapped to major radius of ion-cyclotron frequency, b) density profile (black) and fluctuation spectra (red) at 0.231s showing bursting character of ICE, c) total beam power.

correlation with the density transport barrier is strong.

A leading theoretical model for the previous observations of ICE is that it is the excitation of a CAE excited through a Doppler-shifted cyclotron resonance with super-thermal ions. The co-propagating CAE can have frequencies approaching the ion-cyclotron frequency on NSTX. On MAST CAE were seen up to, and above the core ion-cyclotron frequency. The co-propagating, high frequency CAE were mostly absent in NSTX-U plasmas. An exception is shown in Fig. 3, which also has counter-propagating ICE. This example shows that the beam-driven co-CAE can co-exist with the ctr-propagating ICE. The ICE has a toroidal mode number of n = -1, indicating the mode is ctr-propagating. The CAE have toroidal mode numbers from n = 11 up to n = 15 and are co-propagating. In this case, the CAE frequency actually exceeds the edge ion-cyclotron frequency and the n=15 mode exceeds f_{ci} at the core.

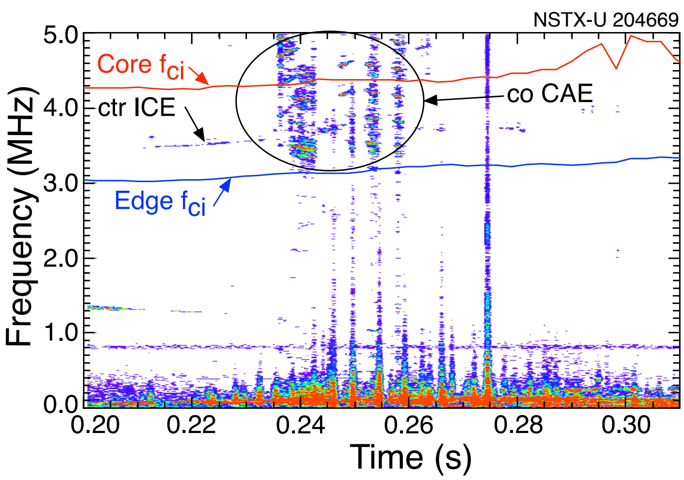

Fig. 3. Spectrogram of magnetic fluctuations showing fundamental ICE. In the region circled are co-propagating CAE with n = 11 to n = 15.

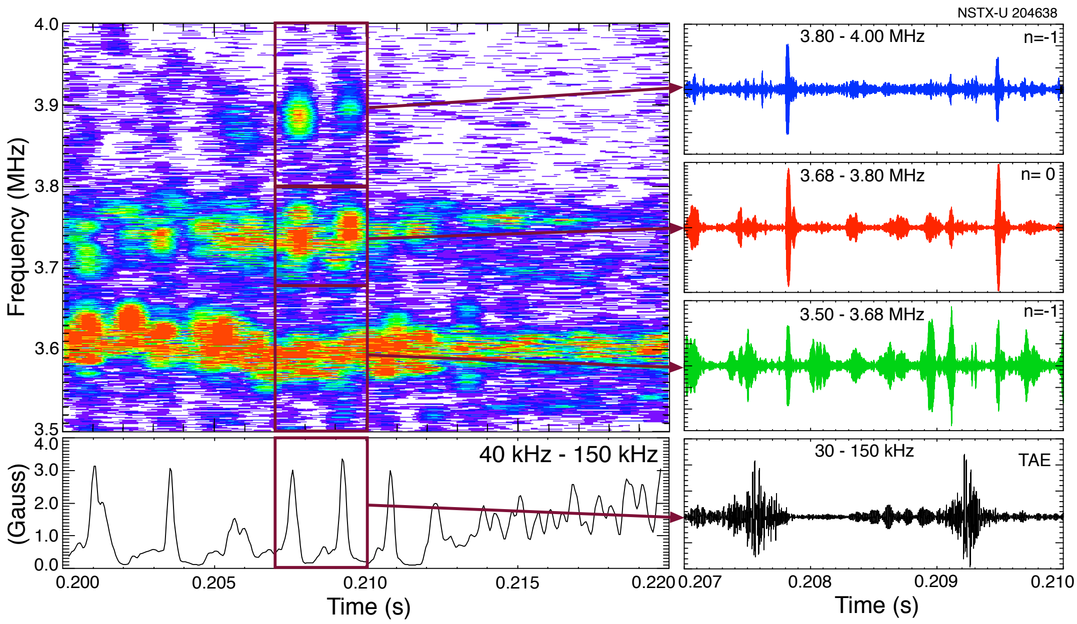

Fig. 4. a) spectragram of magnetic fluctuations showing ICE, b) filtered signal for the 3.9 MHz ICE frequency band, c) filtered signal for the 3.78 MHz ICE frequency band, d) filtered signal for the 3.6 MHz frequency band, d) filtered signal for the TAE frequency band and e) rms fluctuation level for the TAE frequency range.

The ICE on NSTX-U sometimes exhibits fine structure. That can be seen in Fig. 1 most clearly between 0.19s and 0.23s for the fundamental frequency. Similar splitting has previously been reported on JET and JT-60U and is explained by the trapped fast ion drift splitting the resonance [5]. The ICE on NSTX-U often, but not always, shows fine-structure splitting into two or three modes, with frequency splitting of between 100 kHz and 200 kHz. An example is shown in Fig. 4. Direct measurements of the spatial coherence of the emission show that the emission is from a spatially coherent mode with toroidal mode numbers of n=-1 for the lowest frequency, n=0 for the middle frequency and n=-1 again for the highest frequency burst,

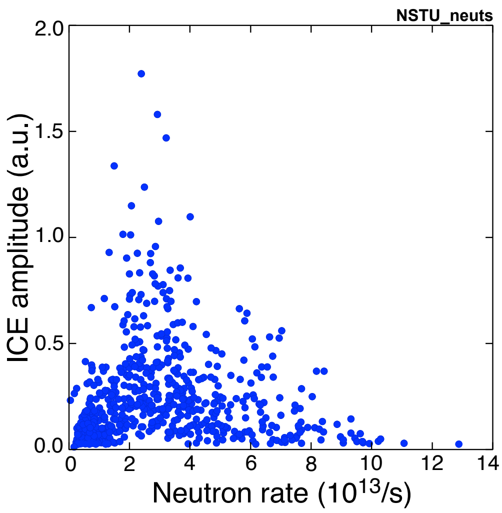

Fig. 5. Peak amplitude of ICE bursts, averaged over 0.8 ms, vs the neutron rate.

A database of ICE observations on NSTX-U was constructed which included the amplitude of the fundamental ICE and parameters of the plasma. Previous observations of ICE, originating from fusion products, had found, in some cases, a strong correlation of the ICE amplitude with the neutron rate. For the NSTX-U data there seems to be relatively little correlation as seen in Fig. 5. In this database, the plasma parameters are averaged over 16 ms intervals, corresponding to the time resolution for density and temperature measurements. The ICE amplitude shown here is the peak amplitude of the ICE, as averaged over an ≈ 0.8 ms window, in each of the 16ms intervals when ICE is present. The lack of a strong correlation with neutron rate probably reflects that this ICE is not originating from fusion products, and is probably originating from deeper in the plasma. The ICE is also weaker at the higher plasma densities where the strongest neutron emission is found.

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