Ion Cyclotron Emission in the Presence of Beam Ion Losses*

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Recent DIII-D experiments obtained full spectrum measurements of ion cyclotron emission (ICE) that correlate with neutral beam prompt losses (i.e., injected neutrals ionizing such that their first poloidal ion orbit intersects with the plasma facing surfaces) and further, show a unique spectral signature depending on beam injection geometry. ICE has previously been used to probe the energetic ion distribution in tokamaks [1] and renewed interest in spectral measurements is aimed at developing a passive diagnostic in ITER [2]. These new observations suggest that neutral beam prompt losses represent regions of energetic ion velocity space contributing to the excitation of particular ICE, which will greatly improve codes and allow new models of ICE spectra to serve as synthetic diagnostics that identify energetic ion losses in future reactors.

The DIII-D ICE diagnostic discussed here is an instrumented antenna strap previously used for high power ion cyclotron resonance heating [3]. Initial indications of possible correlation between ICE measurements and beam ion losses were obtained during plasmas in which different neutral beams injected individually. As shown in Fig. 1, DIII-D features eight neutral beams that are labeled according to their toroidal location and whether they are the left or right beam in the main housing, e.g., 30L and 30R. These beams can be parallel (co-current or co-Ip) or anti-parallel (counter-current or ctr-Ip) to the plasma current, and more perpendicular or more tangential to the toroidal field.

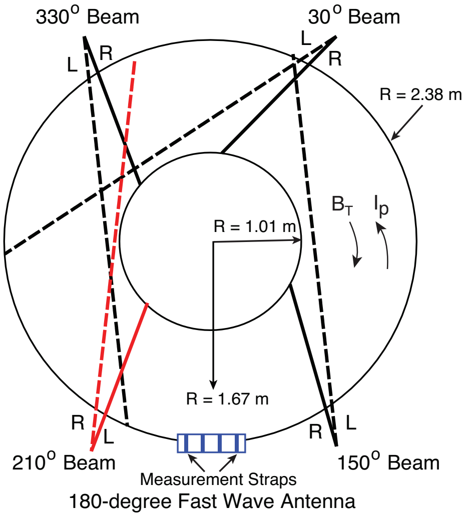

Figure 1: *Top view of the DIII-D mid-plane indicating the geometry of the eight neutral beams and the fast wave antenna used to collect ICE data.*

Figure 2 shows unique spectra observed according to the injecting neutral beam in shot 164186 ($B = 2.1$ T and $I_p = 1.20$ MA). In Fig. 2(a), the raw trace of magnetic fluctuations indicates that the amplitude of ICE is considerably larger during tangential co-Ip and tangential ctr-Ip beam injection. The co-current tangential beam produces strong emission corresponding to the 2nd harmonic of deuterium near the plasma center (≈ 30 MHz), while the perpendicular co-current beam produces only scattered weaker lines. An emission line possibly representing the 4th harmonic of deuterium near the plasma edge (≈ 47 MHz) is produced during injection of the tangential counter-current beam, which also regularly produces more than ten times the prompt loss flux of a co-current beam. Since the ICE emission follows the beam injection it is likely that these lines are produced by beam ion prompt losses according to the particular geometry of each beam. It remains to be determined why the ICE amplitude during co-Ip perpendicular beam injection is effectively zero. The prompt loss amplitude is larger for perpendicular beams than tangential, and we would therefore expect the ICE power to be larger as well. One proposed explanation for this observation is that differences in the spatial extent of the beam deposition (in the plasma) and prompt loss strike pattern (along the wall) can account for the ICE measurement at the antenna. A reversed-Ip plasma discussed next provides additional support for this argument.

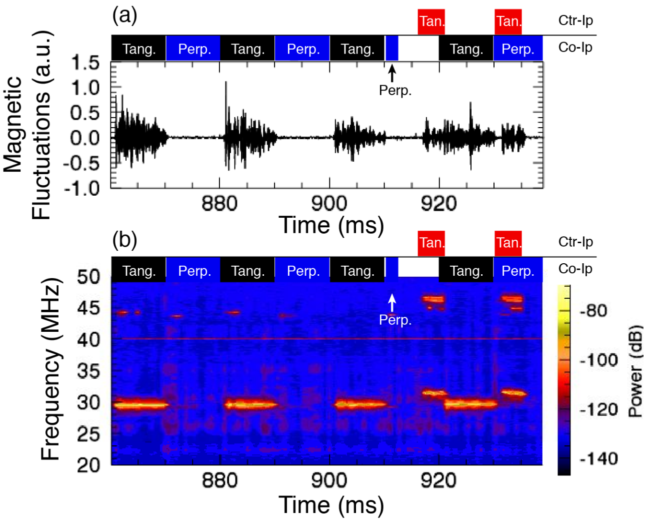

Figure 2: *Measured fluctuations of the toroidal magnetic field in DIII-D shot 164186 with annotations indicating neutral beam injection status. (a) Raw trace of the fluctuations, (b) spectrogram.*

Standard DIII-D operation sets magnetic helicity using a plasma current and toroidal magnetic field combination leading to six co-current and two counter-current beams. Experiments concerning quiescent H-mode [4], however, reverse the direction of the plasma current and the resulting six counter-current beams make for a large prompt loss fraction of beam power. This allows for the study of ICE as produced by three beams with the same injection geometry (three ctr-Ip tangential and three ctr-Ip perpendicular), but a toroidal displacement of their origin.

A summary of the time evolution of ICE in one such case is presented in Fig. 3 for shot 163486 ($B = 1.5$ T and $I_p = 0.75$ MA). During the time period between 1000 and 1400 ms, three ctr-Ip tangential beams are injected and a fairly consistent ICE spectrum with a peak in the 8 - 9 MHz frequency range is observed [Fig. 3(a)]. These beams are interleaved such that there are 10 ms periods with only 30L injecting followed by 10 ms of combined 150L/330L injection [Fig. 3(b)]. The average ICE power over the 8 - 9 MHz range slowly increases during this period, eventually matching the injected beam power trace before reducing to a nearly constant value [Fig. 3(b)]. The initial ICE power increase seems to follow the increase in beam prompt loss and far-edge ionization [Fig. 3(c)], which itself is a product of the increasing plasma density [Fig. 3(d)].

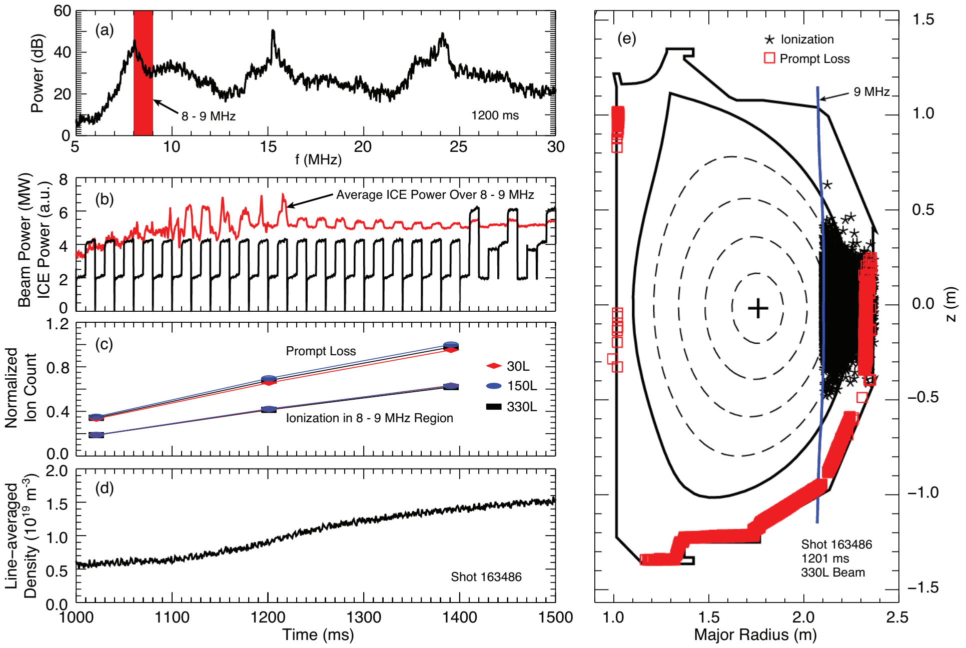

Figure 3: *Survey of ICE observations in shot 163486. (a) Fast magnetics spectrum at* $t = 1200$ *ms with the 8 - 9 MHz region highlighted by the red rectangle. Time evolution of (b) injected beam power (black) and average ICE power over the 8 - 9 MHz range (red), (c) numbers of prompt loss ions (upper traces) and ionizations within the spatial range corresponding to 8 - 9 MHz ion cyclotron frequencies for each of the counter-current neutral beams, and (d) line-averaged electron density. (e) Magnetic equilibrium at* $t = 1201$ *ms along with the 9 MHz ion cyclotron frequency line (blue) and the prompt loss (red) and ionization outside of the 9 MHz line (black) for the 330L beam.*

Prompt loss and ionization profiles are calculated using a Monte Carlo code that includes the scrape-off layer [5]. Results from this calculation for the 330L are shown in Fig. 3(e), where the prompt loss ion strike locations along the wall are indicated along with the injected neutral ionization locations that occur at radial positions corresponding to an ion cyclotron frequency below 9 MHz (the 8 MHz location is approximately the outer wall itself). While the apparent number density of ionizations and wall strikes is similar for the three beams, the resulting toroidal locations differ according to the toroidal displacement of each beam. Toroidally localized beam ion losses and scrape-off layer ionization have previously been found to play important roles in the experimental observation and interpretation of Alfvénic instabilities [6], and similar techniques are likely to be applicable in this investigation. Future work will necessarily focus on understanding the relationship between possible ICE sources and the resulting amplitude of the instability.

A final example of the utility of ICE measurements is given for the helium plasma of shot 166944 ($B = 1.9$ T and $I_p = 0.99$ MA) and depicted in Figure 4. This shot features both a helium plasma and helium-injecting neutral beams. The rarity of this scenario is such that beam deposition tools do not exist as they do for deuterium beams. The measured ICE power averaged over 41 - 45 MHz (consistent with the fourth harmonic in the core of the plasma) is plotted in Fig. 4(a). This mostly follows the behavior of the edge plasma electron density [Fig. 4(b)] while the beam power (and the specific beams) remain constant [Fig. 4(c)]. As in the other deuterium cases, the observations are consistent with ICE frequencies and powers indicating the level of beam ion loss through both the wall strike pattern and ionization profiles of beam prompt losses.

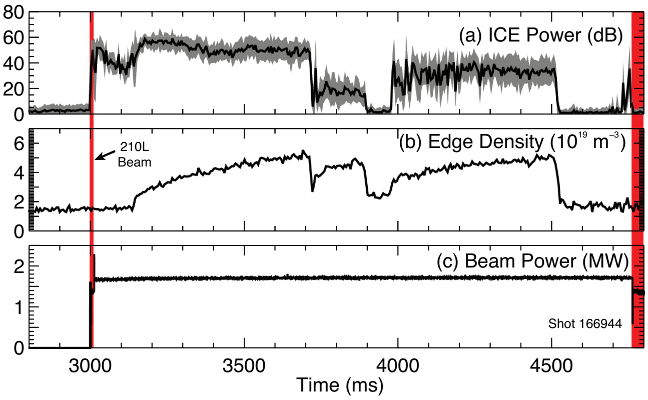

Figure 4: *ICE observations in shot 166944, with brief injections of the 210L beam indicated by red bars. (a) ICE power averaged over 41 - 45 MHz, (b) Edge electron density, (c) Total injected beam power.*

The helium result demonstrates that different ions can produce similar spectra due to the charge to mass ratio resulting in the same ICE frequency. This may limit the ability of ICE diagnostics to separate out the transport of fusion-produced alphas from beam injected deuterons in machines like ITER. Since ITER beams will not penetrate to the center of the plasma, however, and that is where the majority of fusion will take place, different frequency regions of ICE may be assumed to come from one species or the other. Continued development of this diagnostic for using ICE signals as a detector of energetic ion losses will prove useful in ITER and later reactors where traditional in-vessel probe detector designs fail.

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