Ion species mix, magnetic field, and distribution function dependence of instabilities in the ion cyclotron range of frequencies

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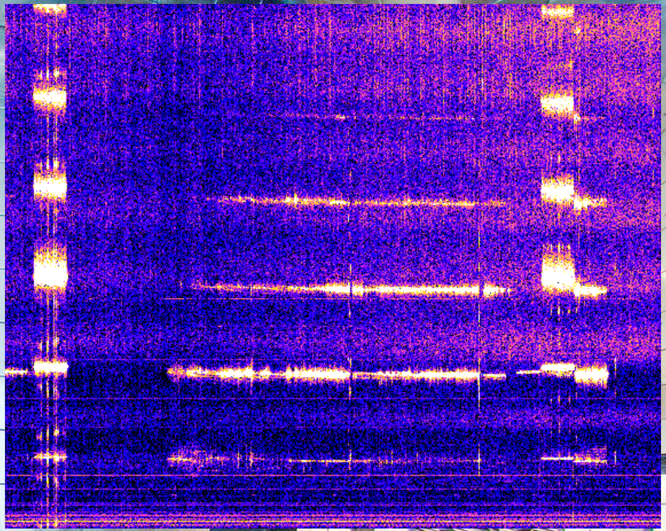

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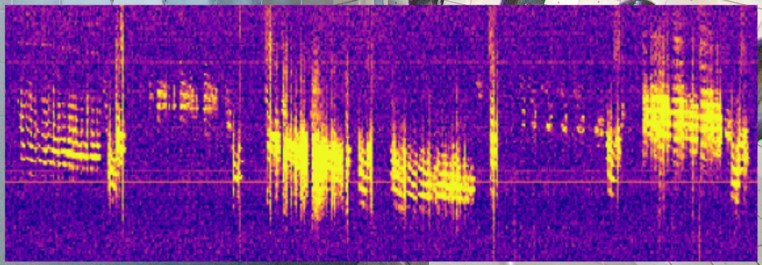

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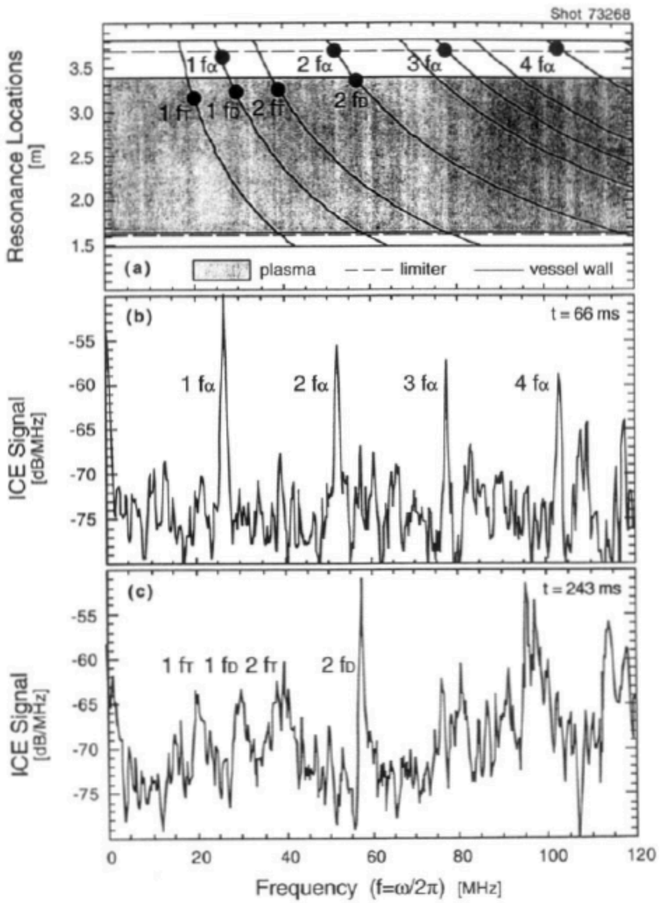
OUTLINE

- Ion cyclotron-range instabilities in mixed species plasmas are relevant in fusion and space physics
- Alfvén eigenmodes (AEs) near ~0.6f_{ci} depend on hydrogen concentration, prefer low B_T
- Ion cyclotron emission (ICE) dependent on magnetic field, dominant harmonics can change with hydrogen concentration

INTRODUCTION

Multispecies ICE could be exploited to diagnose fast ions in burning plasmas



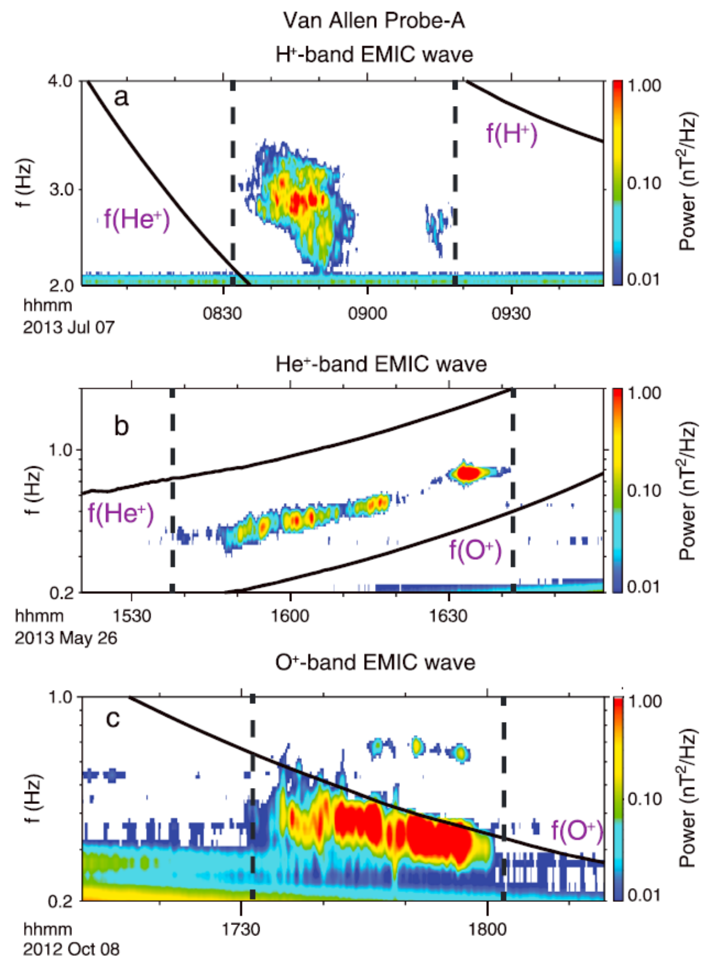
ICE data from TFTR supershot[2], depicting edge ICE from a mixed DT plasma.

- **ICE seen on many different devices, including during DT experiments on JET[1] and TFTR[2]**
  - Categorized as either core or edge ICE, depending on the emission radius
  - Core ICE is seen in L-mode plasmas while edge ICE is observed on H-mode
- **Future reactor-relevant devices will contain multiple species**
  - ICE diagnostic is passive and has potential to survive and thrive on devices like ITER
- **Compressional AEs (CAEs) possibly contribute to ICE in tokamaks[3,4] and may be sensitive to species mix**

[1] Cottrell G.A. et al 1993 Nucl. Fusion 33 1365
[2] Cauffman S., et al. 1995 Nucl. Fusion 35 1597
[3] Gorelenkov, N. 2016 New Journal of Phys.
[4] Gorelenkov, N. 1995 Nucl. Fusion 35 1743

L-mode multi-species tokamak plasmas excite instabilities similar to those in space

- **Space instabilities have possible tokamak counterparts**
  - Electromagnetic ion cyclotron (EMIC) wave frequency range corresponds to that of CAEs and global AEs (GAEs) in tokamaks
  - ICE is the tokamak counterpart to equatorial noise
- **Fast-ion populations can come from neutral beams (50-81 keV) rather than geomagnetic storms or plasma plumes**
  - Can control species mix and distribution
  - Measurement of global rather than localized distribution function possible
- **Radiation belts see ions with various values of A/Z: H^+, He^+, and O^+**
  - Achieved in hot tokamak by using H^+, D^+, and $3He^{2+}$



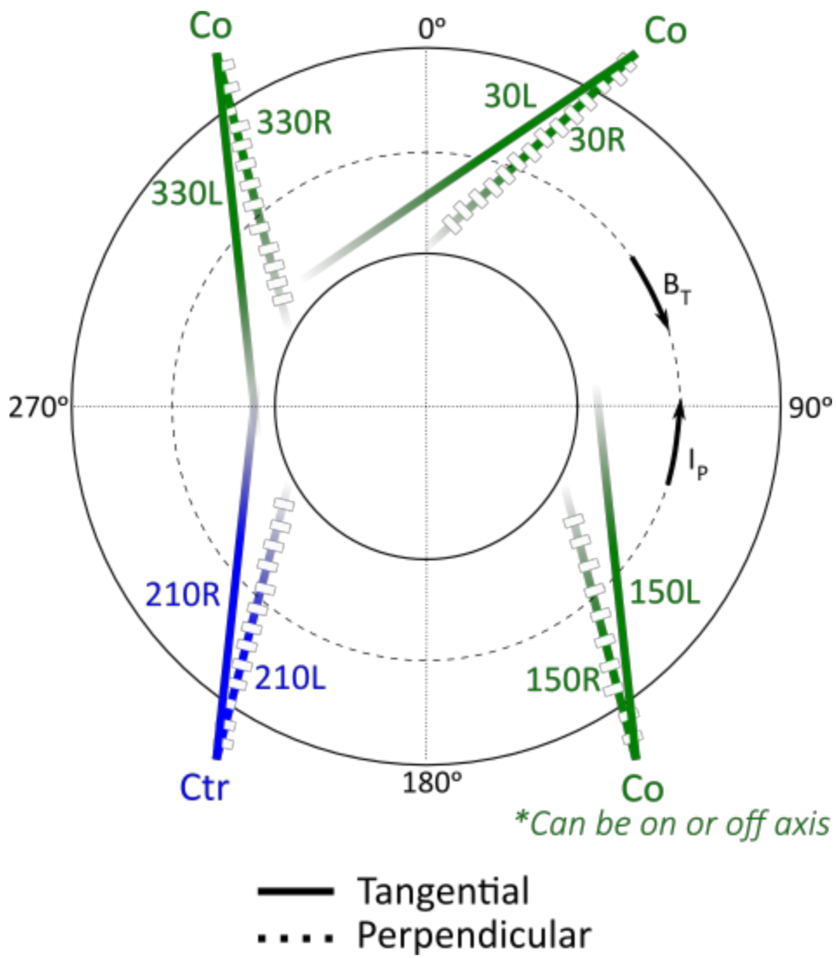
[1] Saikin, A. A. et al., J. Geophys. Res. Space Physics 10.1002/2015JA021358 (2015).
[2] Balikihin, M. A. et al., Nature Commun., DOI: 10.1038/ncomms8703 (2014).

SETUP AND PLASMA CONDITIONS

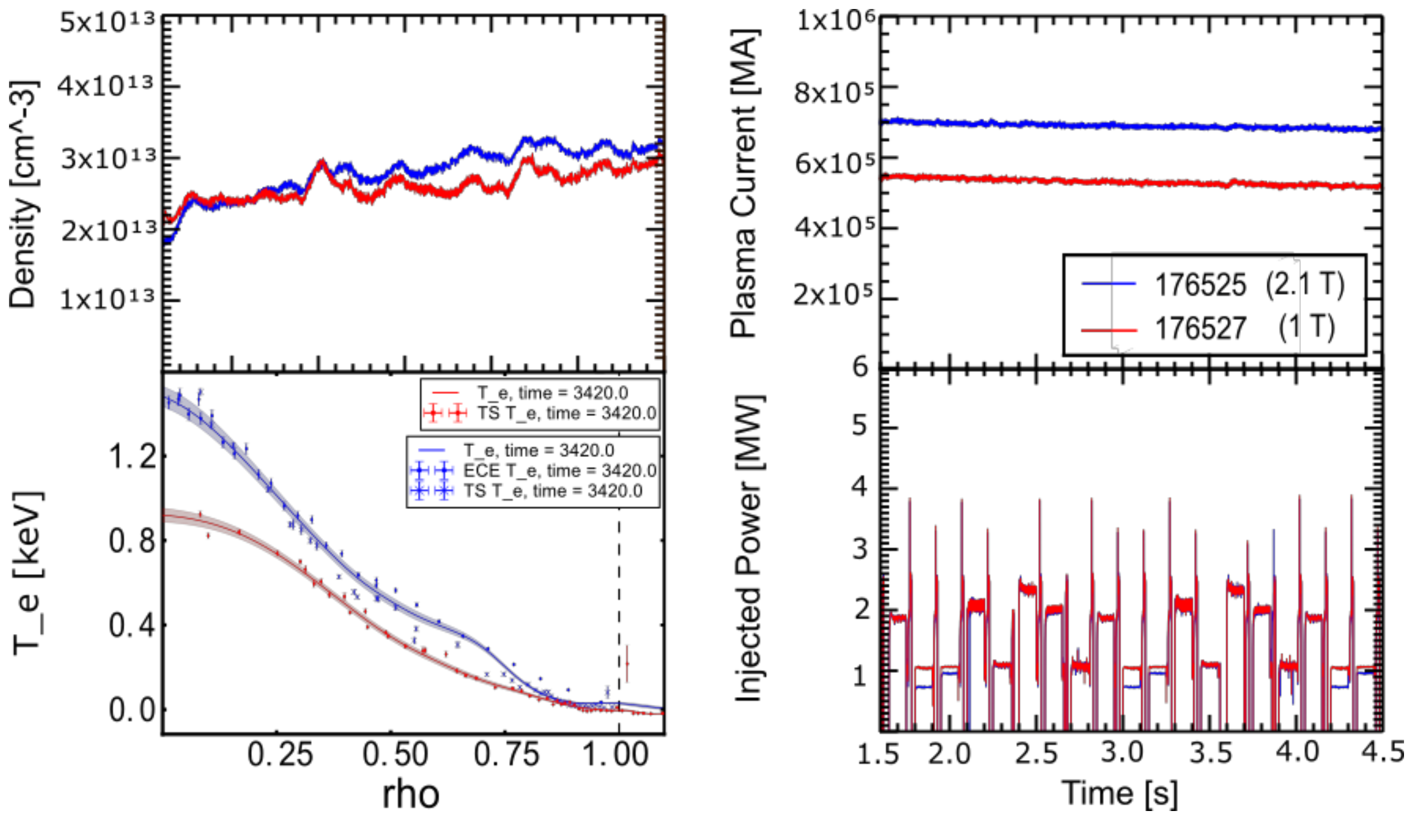
Distribution function changed through variation of neutral beam injection

- **Beam configurations altered to access different distribution functions**
  - Long pulses (~100 ms) used to drive instabilities
  - Cycled through beams on every shot
- **Some beam sources pulsed for ~10 ms for diagnostic purposes**

Beam Configurations Used	
Co-injecting	Counter-injecting
Tangential	Perpendicular
On-axis	Off-axis
Deuterium	Hydrogen
Variation of injection energy (50-81 keV)	

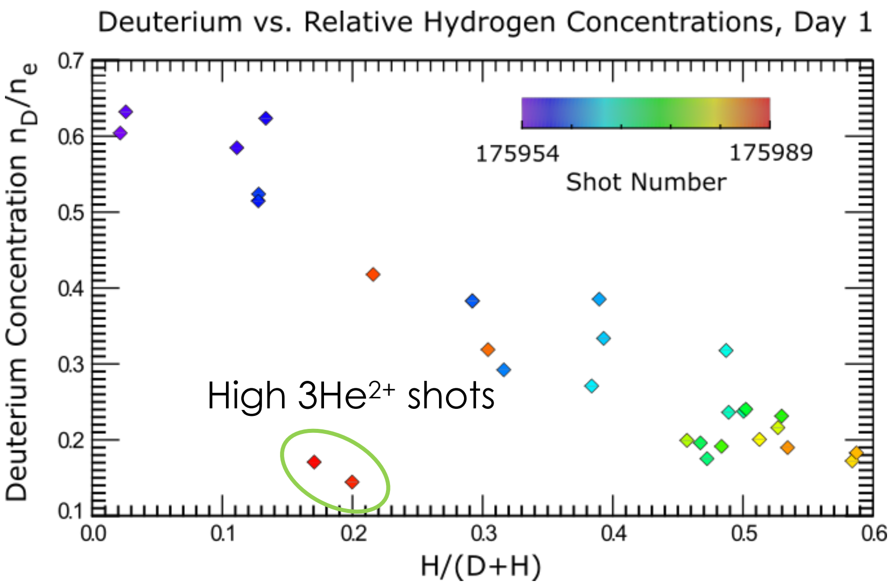


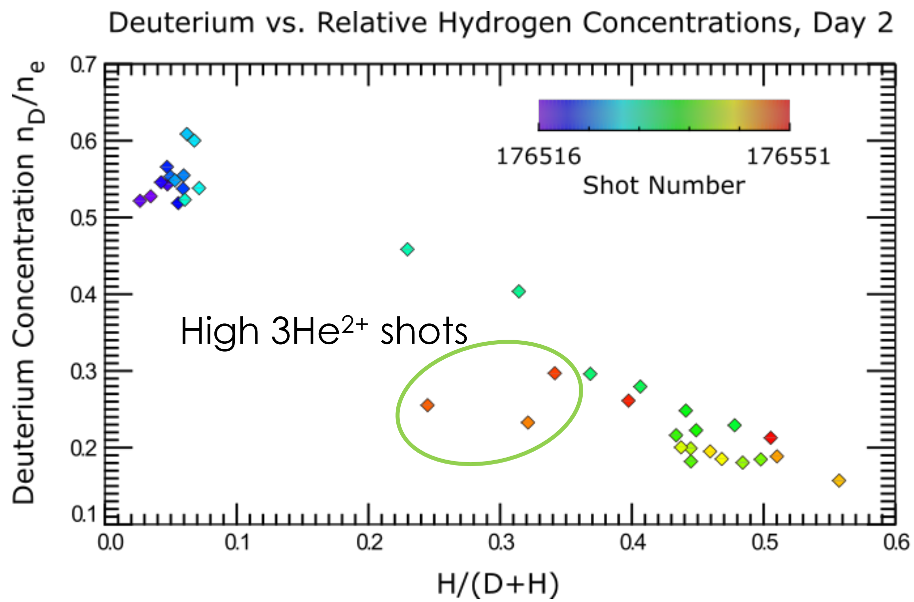
Plasma conditions chosen to mimic conditions seen in radiation belts



- **Low density, L-mode plasma served as "cold, dense background" from space observations**
- **B_T varied from 1-2.1 T to represent different belt regions**

Relative species concentrations monitored during both experiment days



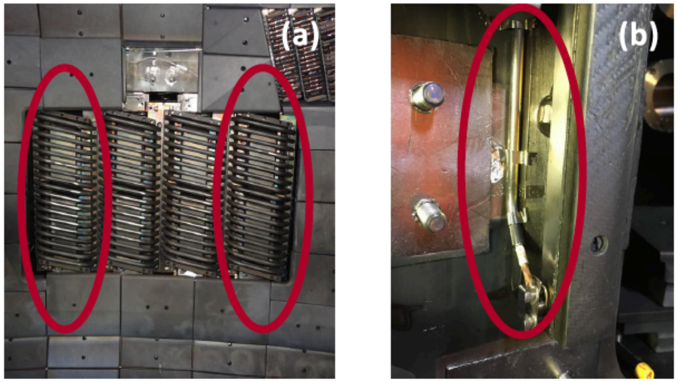


- **Space plasma observations are not limited to one species**
  - Different fast ion populations achieved by running beams both in deuterium and hydrogen
  - Background species altered through hydrogen puffing, with overall concentration rising throughout each experiment day
  - $3He^{2+}$ puffed for a few shots as well
- **Species concentrations affect frequency of ICE, and can either strengthen or hinder observed GAEs/CAEs***

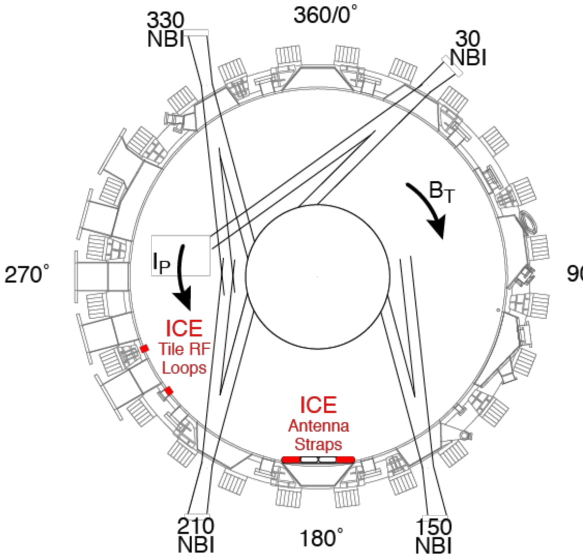
**Cannot currently distinguish between the two*

CAE and ICE measured with antennas on outer wall

- **Measurements made by both tile RF loops and antenna straps on outer wall[1]**
- **Located at midplane, various toroidal angles**
- **200 MHz digitization rate with low-pass filters to avoid aliasing**
- ***Upgrades planned!***
  - More toroidal loops to get mode number
  - Poloidal loop for basic polarization information
  - Faster digitization rate to get higher frequency whistler waves



a) ICRF antenna straps
b) Tile loops (more of these to be installed)

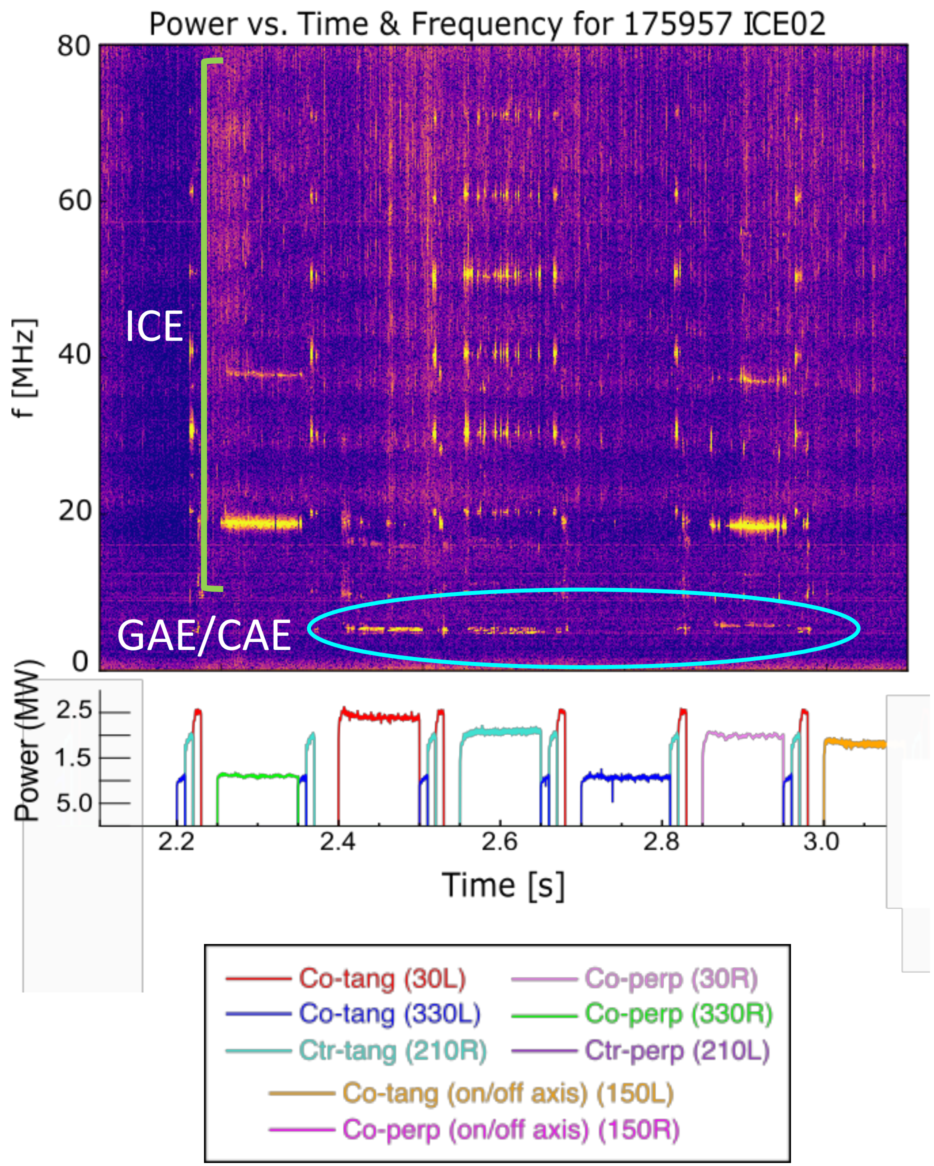


[1] Thome et al., Rev. Sci. Instrum., 89, 101102, (2018).

EFFECTS ON GAEs/CAEs

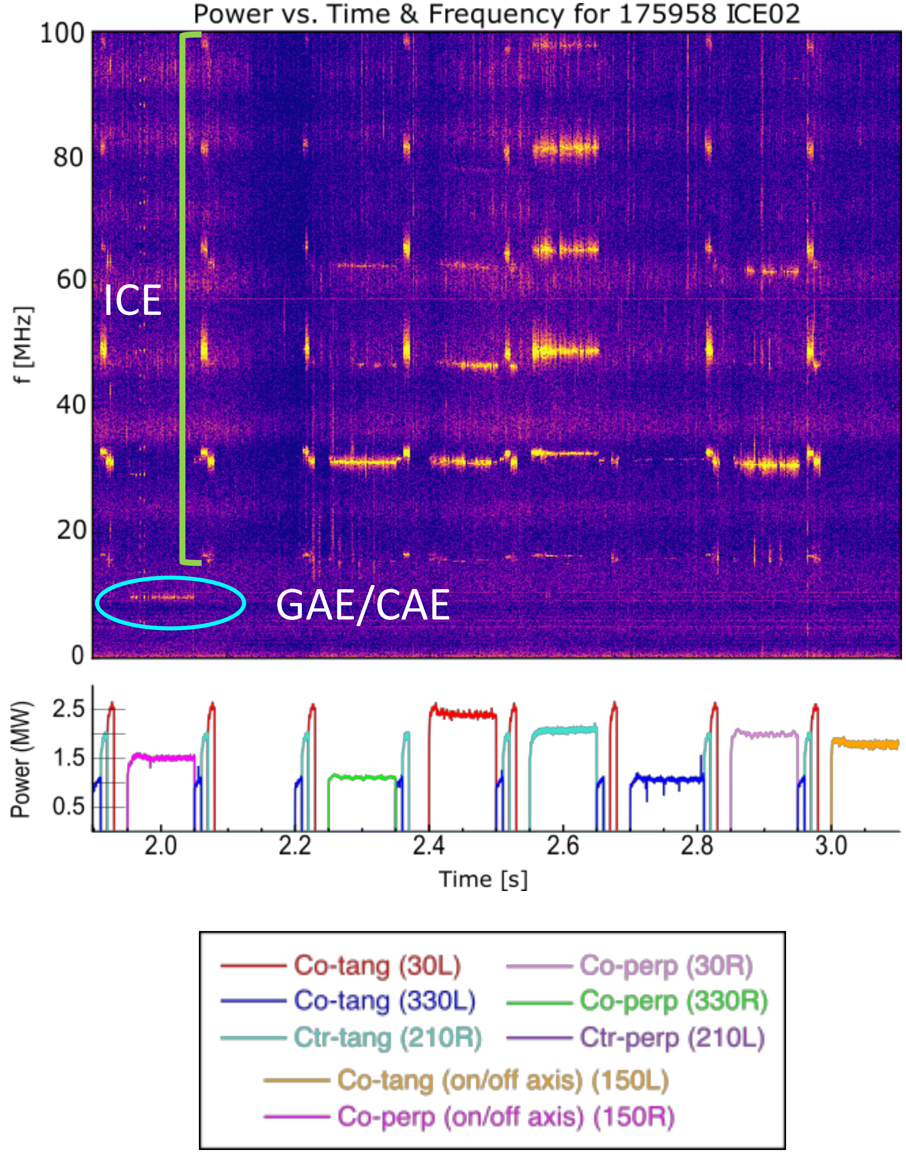
Low field pure deuterium shot shows modest GAE/CAE and ICE activity

- **Baseline deuterium shot with B_T = 1.25 T**
- **GAE/CAE (~$0.6f_{cd}$) observed on 3/6 beam geometries**
  - Strongest signals excited by high-powered co-perp injecting beams
- **Relatively weak ICE excited on 3/6 beam geometries**
  - Co-perp 2^{nd} harmonics have strongest emission
  - Up to 5^{th} harmonic excited by ctr-tang

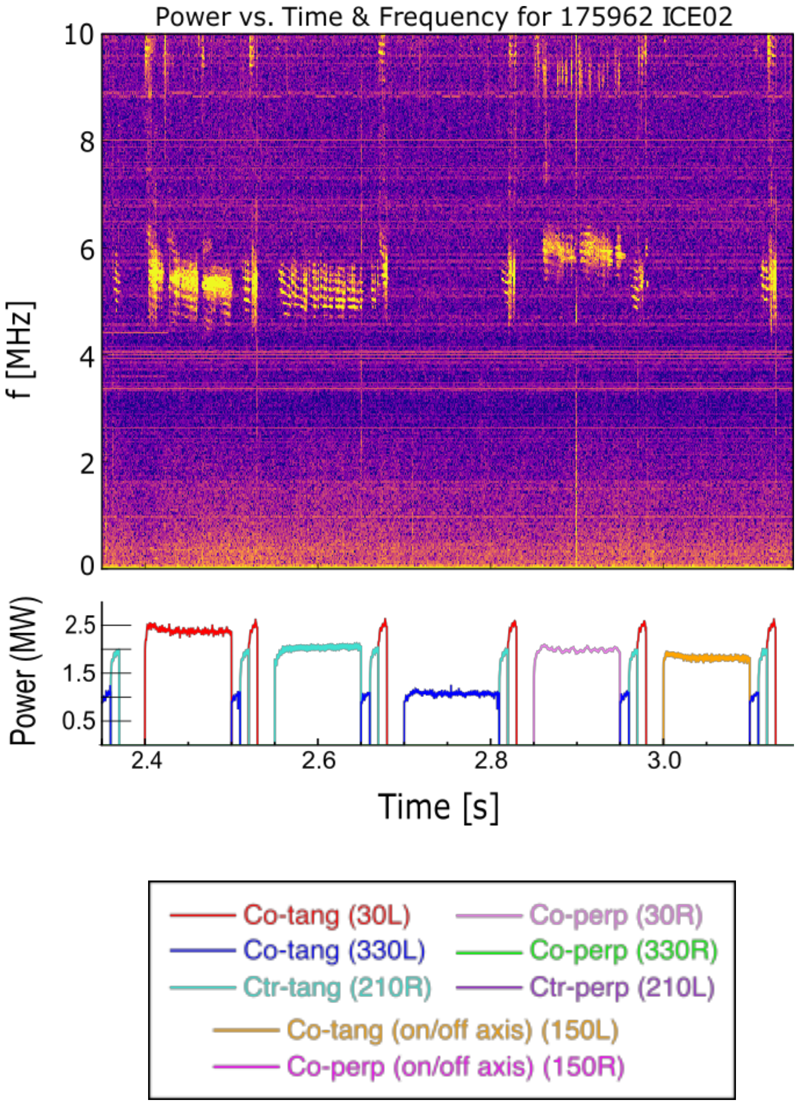


High field pure deuterium shot sees decline in GAE/CAE activity

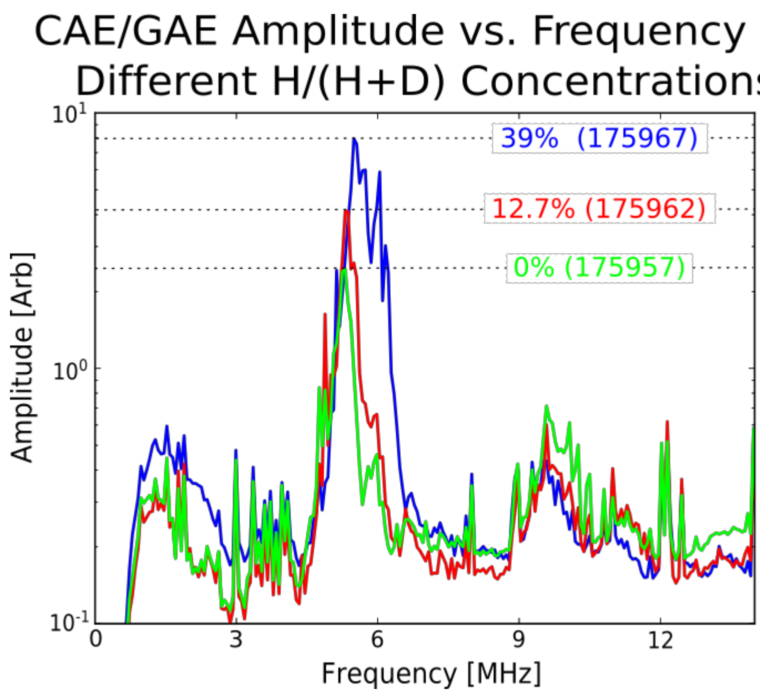
- B_T increased to 2.1 T
- GAE/CAE activity from off-axis co-perp beam only
- Co-injecting tang., co-perp., and off-axis tang. excite ICE
    - 2nd harmonics strongest
    - Up to 4th harmonic observed
- Counter-perp excites ICE slightly higher than on-axis f_{cD}
    - 3rd harmonic has highest amplitude
    - Reaches higher harmonics than co-injecting beams



GAE/CAE activity increases with thermal hydrogen concentration at 1.25 T



- High voltage co-tang and co-perp along with ctr-tang beams consistently show GAE/CAE activity
- Secondary higher-frequency (~f_{cD}) signal from high-powered co-perp
- Contrasts with previous results on MAST[1]

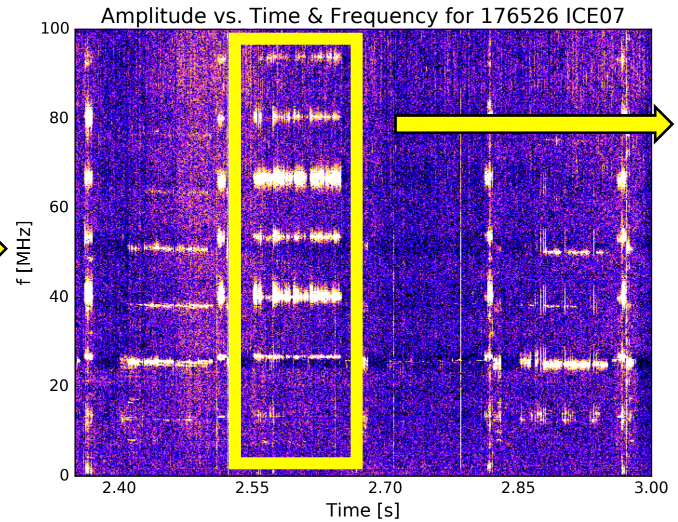


[1] H J C Oliver et al 2014 Plasma Phys. Control. Fusion 56 125017

ICE DATABASE AND ANALYSIS

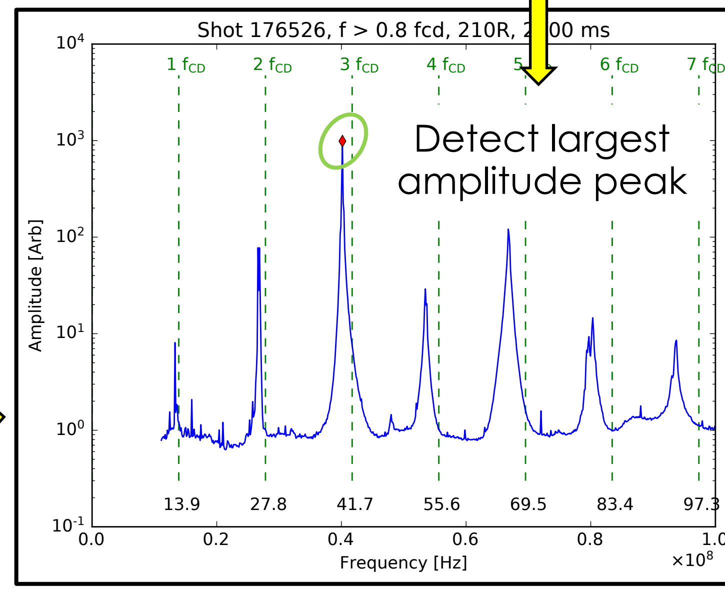
Large number of shots and beam pulses lends itself to nice database

FFT raw ICE data



Time average over beam pulse

Split into frequency regions above & below f_{CD}

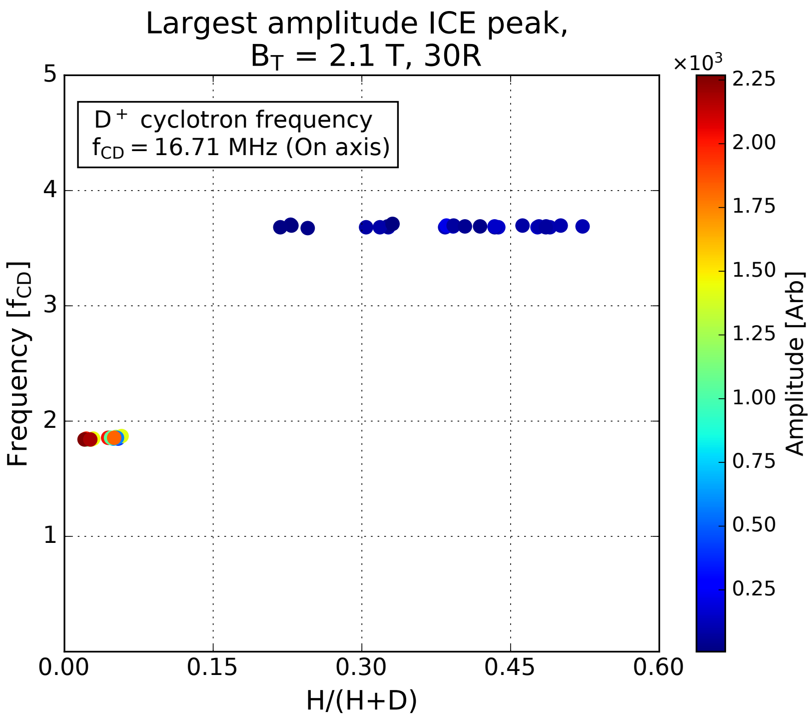


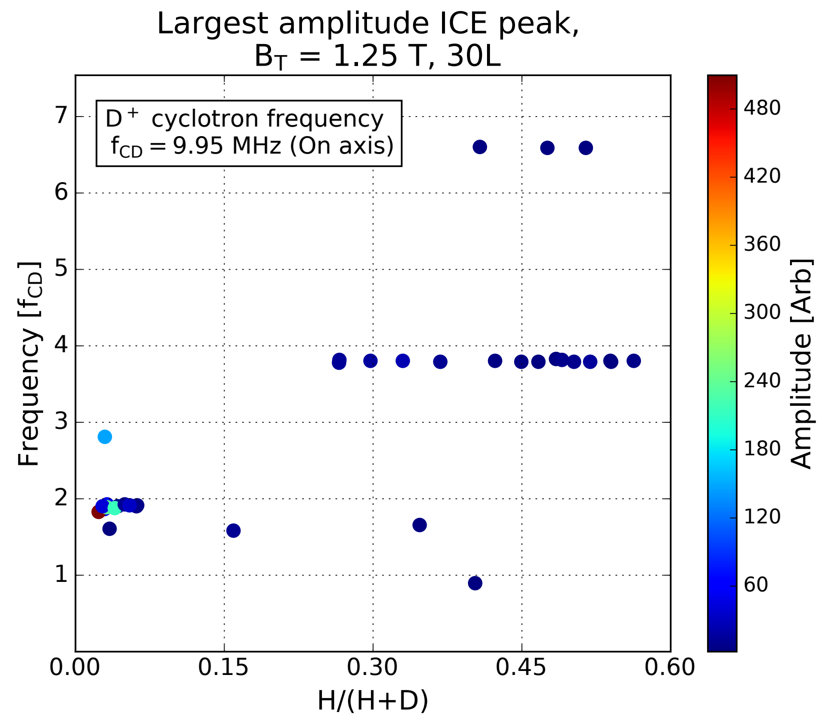
- **Initial analysis of ICE dominant harmonic dependence on species mix, B_T, etc.**
- **Future analysis:**
  - Detect multiple harmonics and track evolution
  - Follow frequency spreading of signals

Collect peak info along with H/(H+D) ratio, B_T, density, and more

DATABASE!

Addition of hydrogen shifts dominant ICE harmonic excited by high-powered co-beams

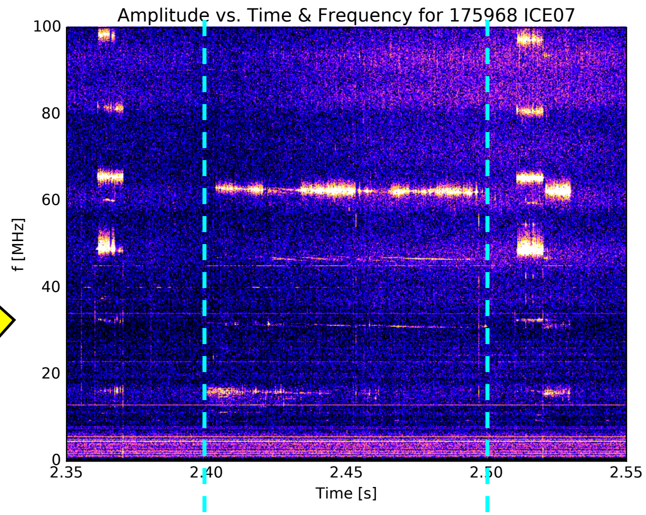




- **High-power co-injecting beams start off with 2nd deuterium cyclotron harmonic being the strongest**
- **Later shots with hydrogen show 4th deuterium harmonic (or 2nd hydrogen harmonic) being dominant for a range of hydrogen concentrations**
  - These signals have consistently lower amplitudes than those from purely deuterium plasmas

Signals from co-injecting beams dependent on both B_T and hydrogen concentration

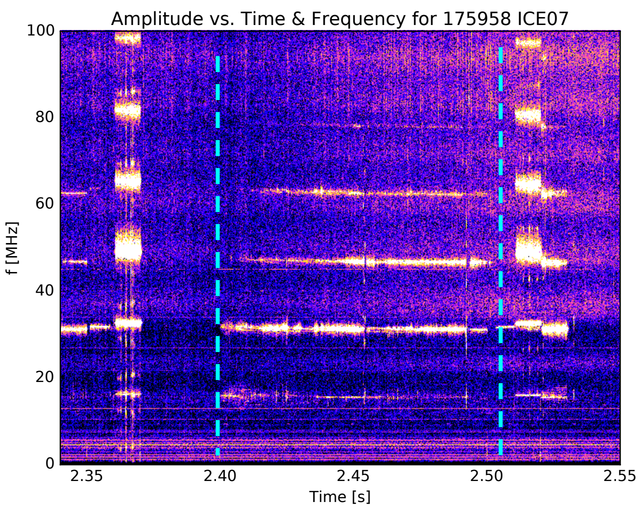
High B_T, appreciable hydrogen concentration (mean H/(H+D) ~ 38%)

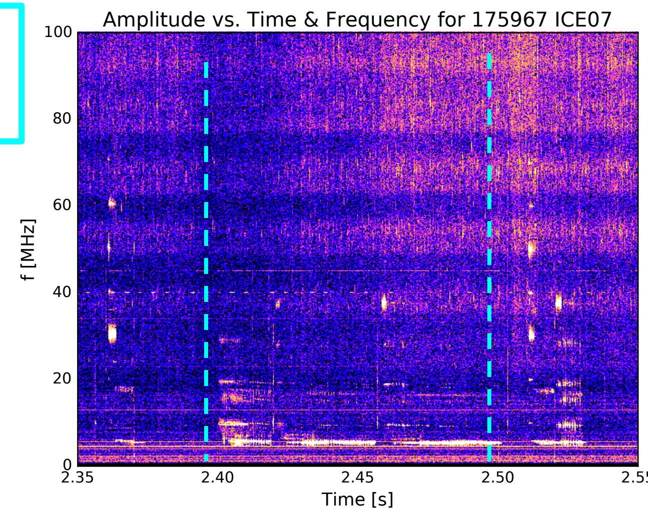


Lower hydrogen concentration generates more harmonics with appreciable amplitude

Lower B_T almost eliminates ICE signals entirely, lower frequency signals become prevalent

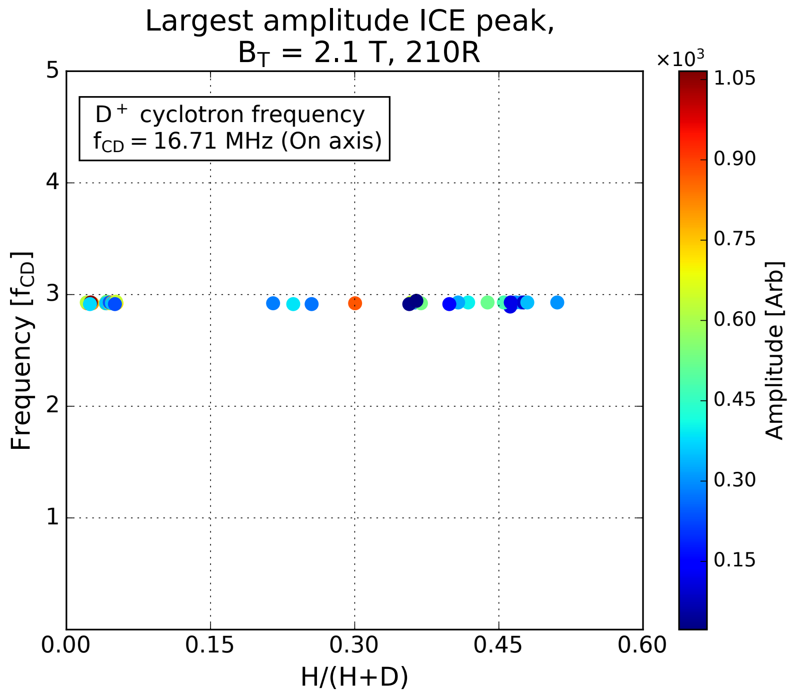
High voltage co-tang beam pulse

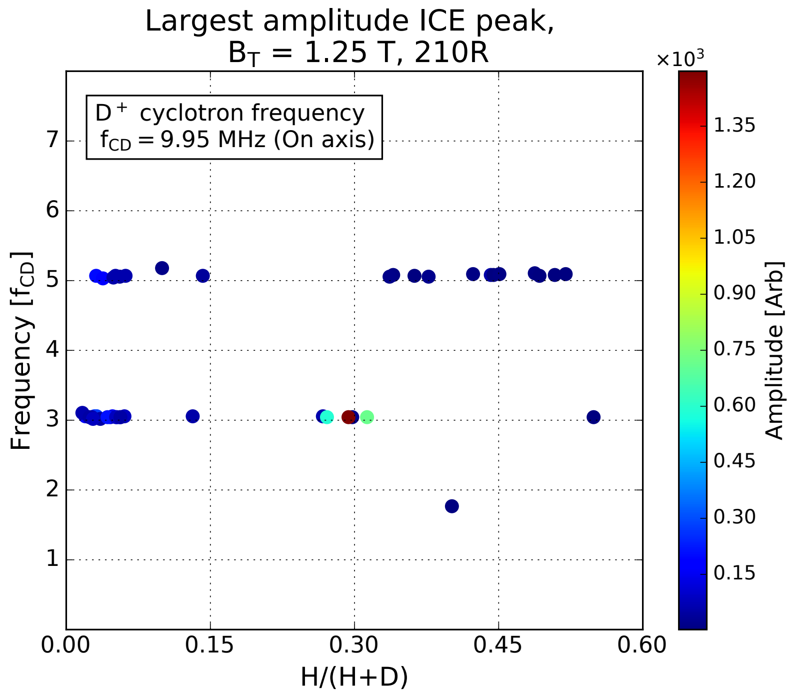




Hydrogen does not change dominant harmonic for counter-injecting beams

- **Addition of hydrogen has no obvious affect on frequency of dominant harmonic for counter-injecting beams**
- **Peaks have smaller shift in frequency from f_{CD} harmonics than ICE from co-injecting beams**





FUTURE WORK

Future Work and Goals

- **More accurate diagnosis and analysis of hydrogen profile**
  - Comparison/validation of main ion concentrations through improved CER techniques and TAE frequency calculation
  - Adaptation of current TRANSP model to look at hydrogen-heavy distribution functions
  - Use verified distribution functions to analyze wave-particle conditions to find gradients that drive observed instabilities
- **More detailed analysis of database of instability activity vs. relative hydrogen concentration**
- **Inclusion of $3He^{2+}$ puffing shots in analysis and effects thereof**
- **Future experiments may include more detailed mode information due to ICE diagnostic upgrade**

Distribution functions obtained need to be verified through FIDA comparison

OMFIT → **TRANSP** NUBEAM → FIDASIM A Neutral Beam and Fast-ion Diagnostic Modeling Suite

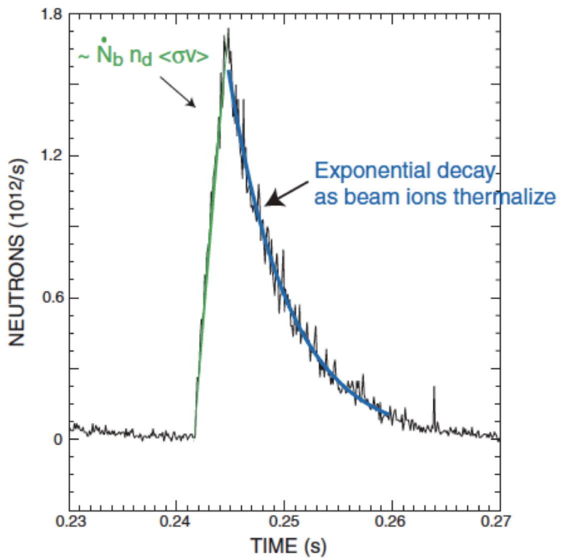
- **OMFIT[1] used to fit density, temperature, and other profiles**
- **TRANSP with NUBEAM module used to calculate distribution function**
  - Calculated neutron rate compared against the experimental rate
  - Bulk ion species changed in accordance with hydrogen concentration
- **Mixed species capabilities need to be incorporated into FIDASIM[2,3]**
- **TRANSP calculated distribution functions need to be fed through FIDASIM, whose output will be compared to spectra seen in experiment**

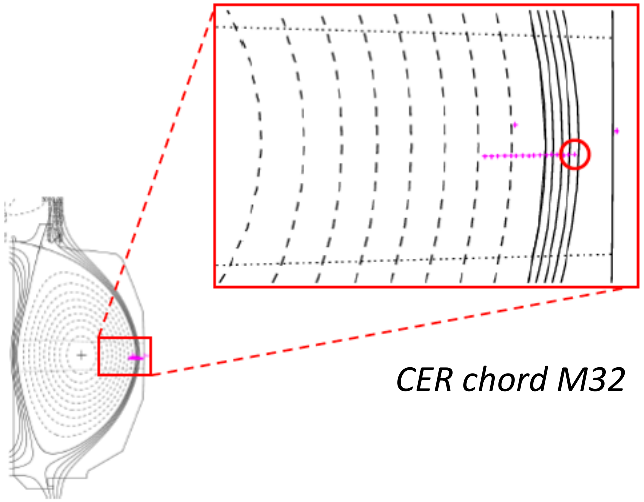
[1] O. Meneghini; L. Lao, Plasma Fusion Res. 8, 2403009 (2013)
[2] L. Stagner, B. Geiger, and W. Heidbrink, 10.5281/zenodo.1341369
[3] Heidbrink, W., Liu, D., Luo, Y., Ruskov, E., & Geiger, B. *Comput. Phys. Commun.*, 10(3) (2011).

BACKUP SLIDES

Beam-blipping and CER main-ion fitting in SOL used for n_D and n_H measurements

- **Fitting rate of exponential decay of neutron rate after beam blip[1]**
  - $\dot{I}_N = \dot{N}_D n_D \langle \sigma v \rangle$
  - $\dot{N}_D$, $\langle \sigma v \rangle$ constant, known
  - Fit to calculate $\dot{I}_N$
- **Relative hydrogen concentration H/(H+D) found through fitting cold emission for CER chord in scrape off layer**
  - Additional work being done to fit more detailed profiles
- **TAE frequency investigated as means to infer mass density**
  - Acceptable agreement but too inaccurate to be reliable



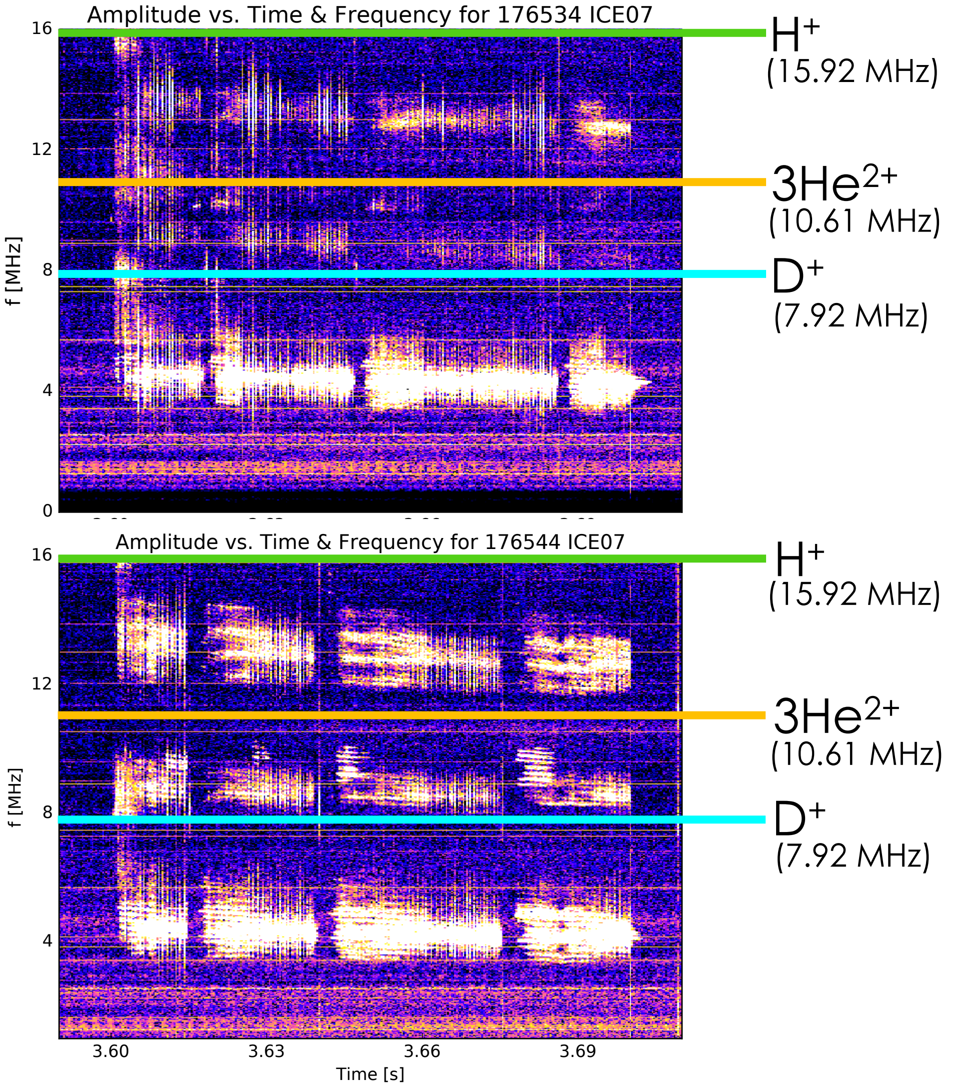


CER chord M32

[1] W.W. Heidbrink et al 2003 Nucl. Fusion 43 883

Possibly three emission bands for GAEs/CAEs when H^+, D^+, $3He^+$ present

- **$3He^{2+}$ puffed at end of day when H^+ and D^+ present in similar concentrations**
- **CAE/GAE-looking signals appear in bands for high-power co-perp beam pulse**
  - H^+ and $3He^{2+}$ f_{ci}
  - Weaker signal between $3He^{2+}$ and D^+ f_{ci}
  - Usual sub-f_{cD} GAEs/CAEs
- **Future work:**
  - Detect multiple lower-frequency peaks to see these emission bands



Top: Mixed H^+ and D^+ shot

Bottom: H^+, D^+, and $3He^{2+}$ all present