U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Observations of ICE on NSTX-U and NSTX

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PPPL, Princeton, New Jersey
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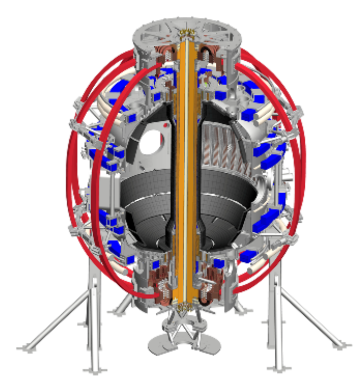
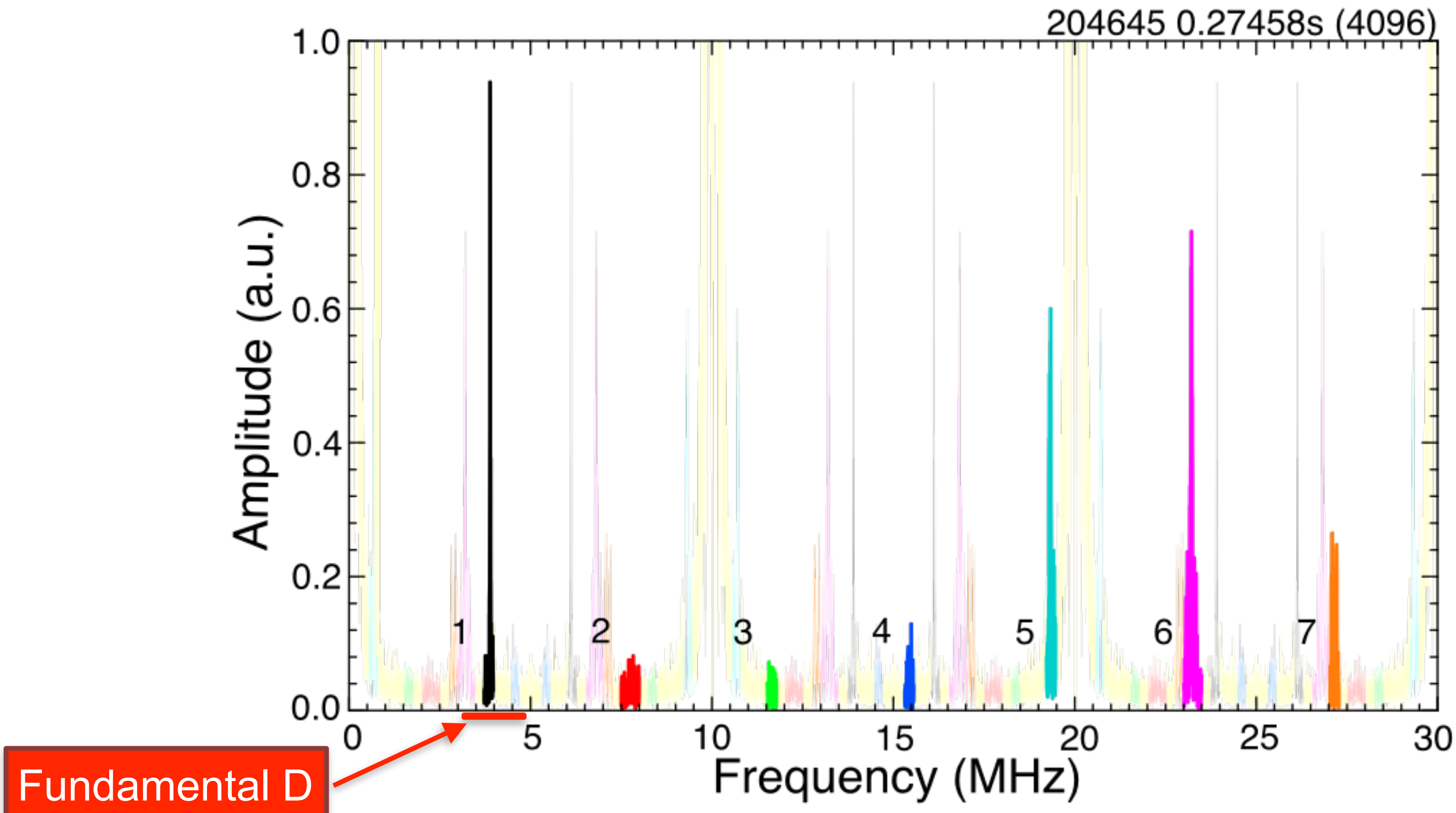
PPPL



Non-thermal emission in the ion-cyclotron range of frequencies is often observed in tokamaks

- Ion Cyclotron Emission (ICE) believed to originate in plasma edge from non-thermal fast ion population.
- Seen as narrow spectral peaks at fundamental, harmonics of f_{ci}.



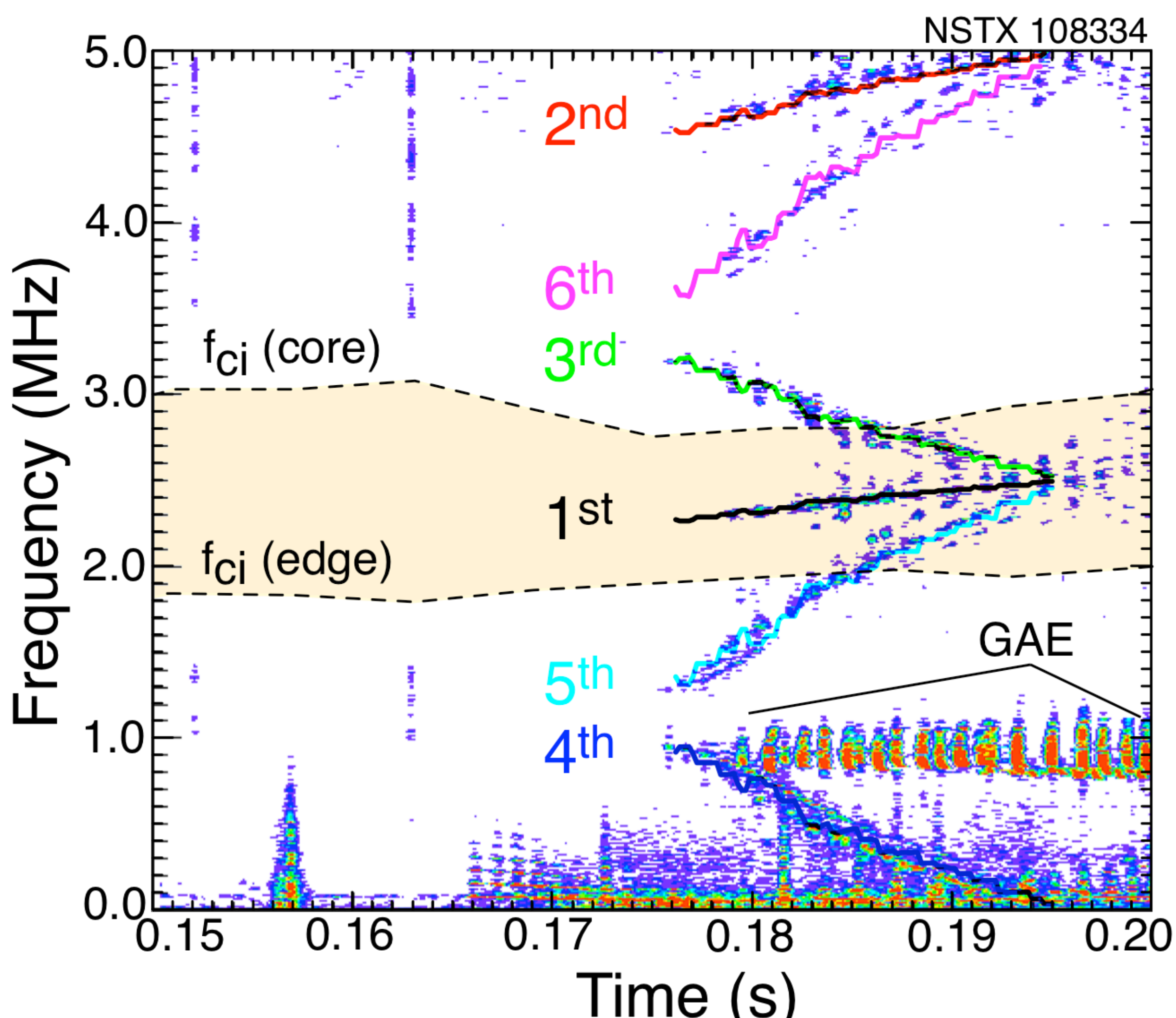
Recently there is renewed interest in ICE

- Original interest in ICE was mostly scientific curiosity,
  - ICE appears largely benign, but can it tell us something?
  - but, intensity can be correlated with fast ion populations, so potential cheap diagnostic of (fast ion something)?
- Theoretical understanding of ICE is still weak.
- Spherical tokamaks operate in a vastly different regime than conventional tokamaks,
  - f_{ci} much lower, closer to other characteristic frequencies
  - Larmor radius closer to plasma length scales.
- ICE on NSTX shows some interesting new behaviors, could guide theory?

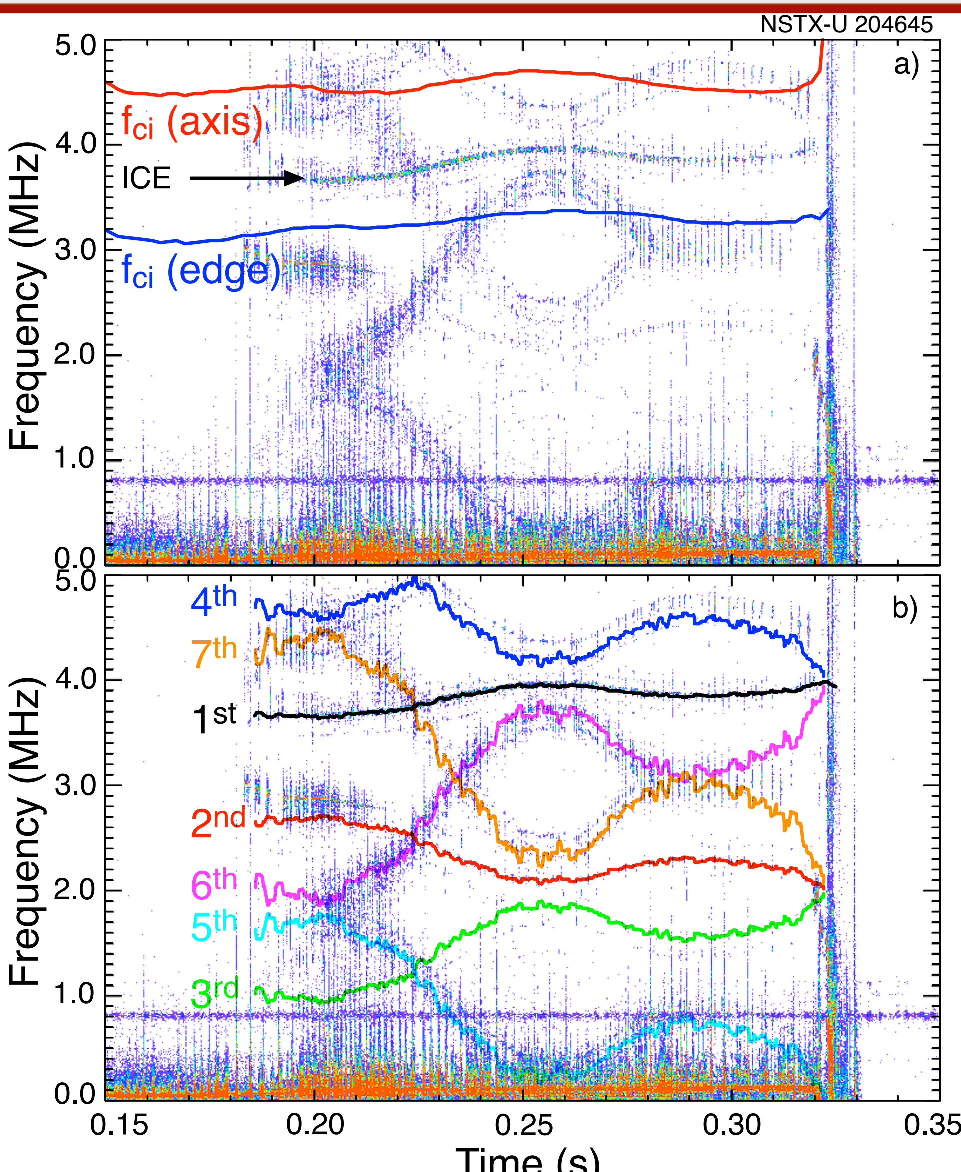
ICE was seen in early NSTX shots

- Some early campaigns had data acquired at 10 MHz.
  - higher harmonics were still aliased.
- Frequencies of aliased harmonics indicated by colored lines.
- ICE data for toroidal fields from 2.6 kG up to 5.9 kG.

$I_P \approx 0.8$ MA, $P_{NBI} \approx 1.7$ MW, $B_{tor} \approx 3.4$ kG



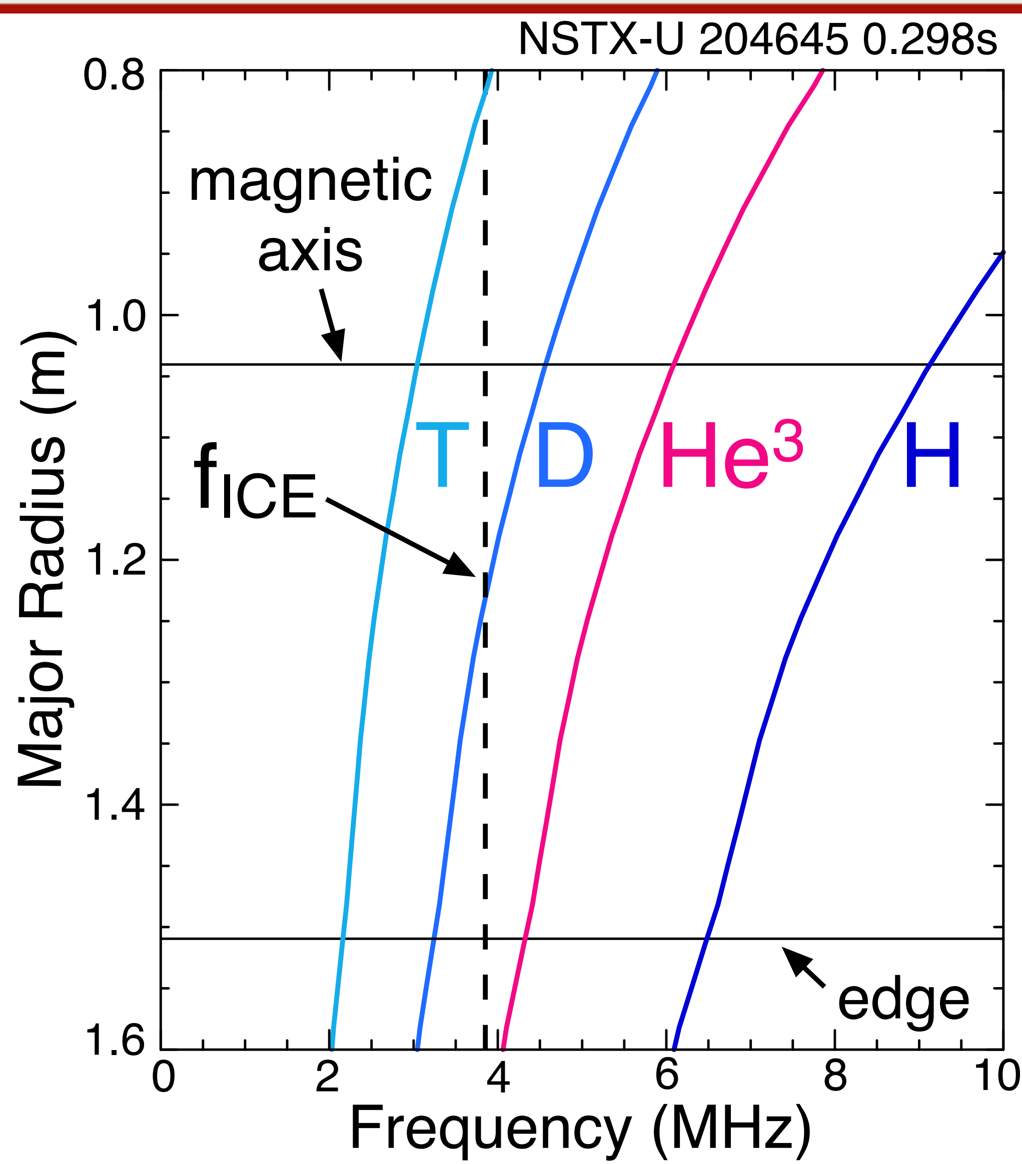
Observations of ICE on NSTX-U



- Many NSTX-U shots show modes in the frequency range from ≈ 3.6 MHz up to ≈ 4.3 MHz.
- ICE frequency higher than edge ω_{ci}, lower than axis ω_{ci}.
- ICE frequency modulation correlated with radial shift of plasma.
- Harmonics up to the 7th have been seen (but aliased).

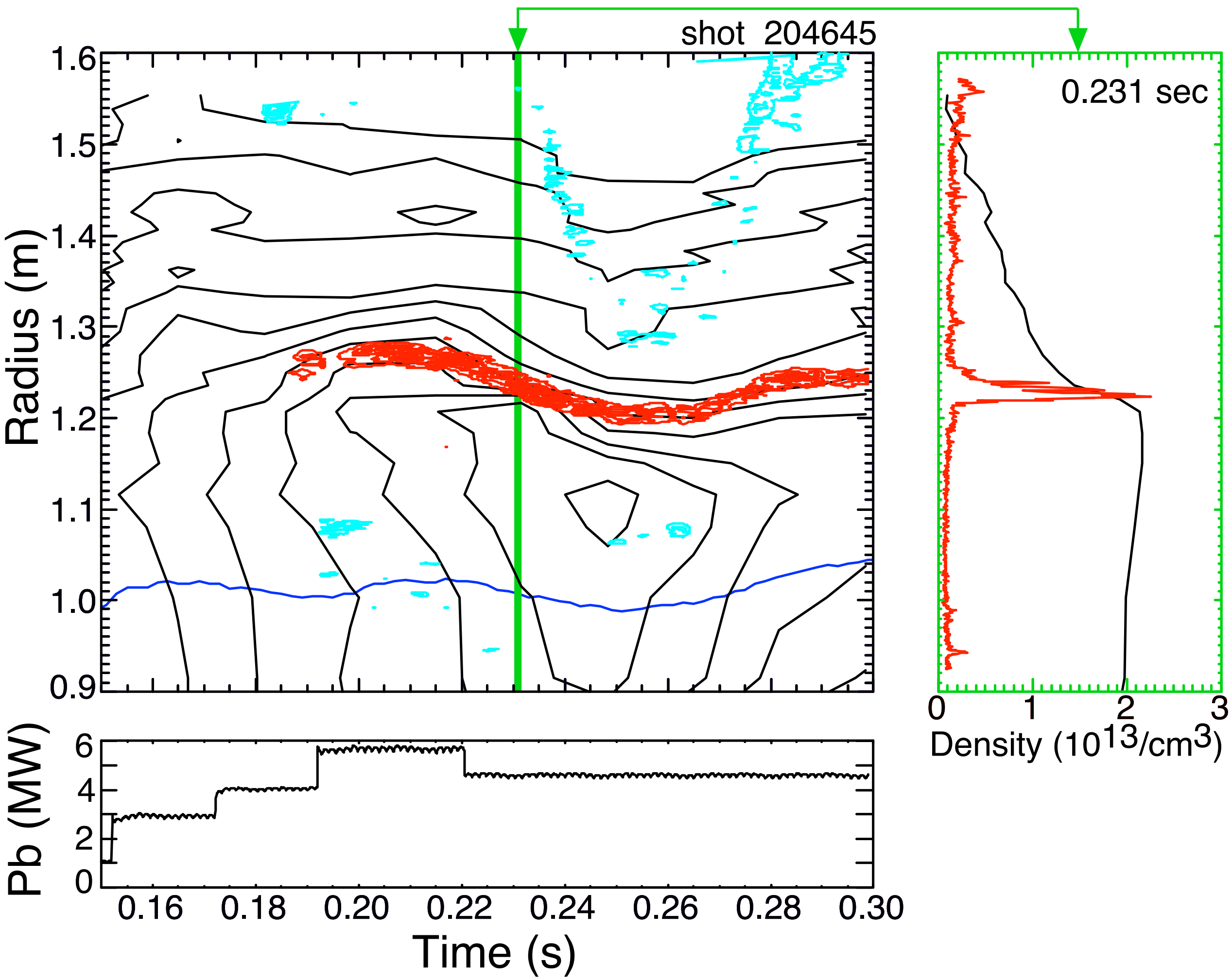
ICE appears to originate from D beam ions

- Cyclotron frequency ranges of the principal energetic ion species, compared to the measured ICE frequency.
- Only D seems consistent with ICE frequency.
- But ICE frequency is higher than edge D cyclotron frequency.
- Might be down-shifted by as much as 0.45 MHz?



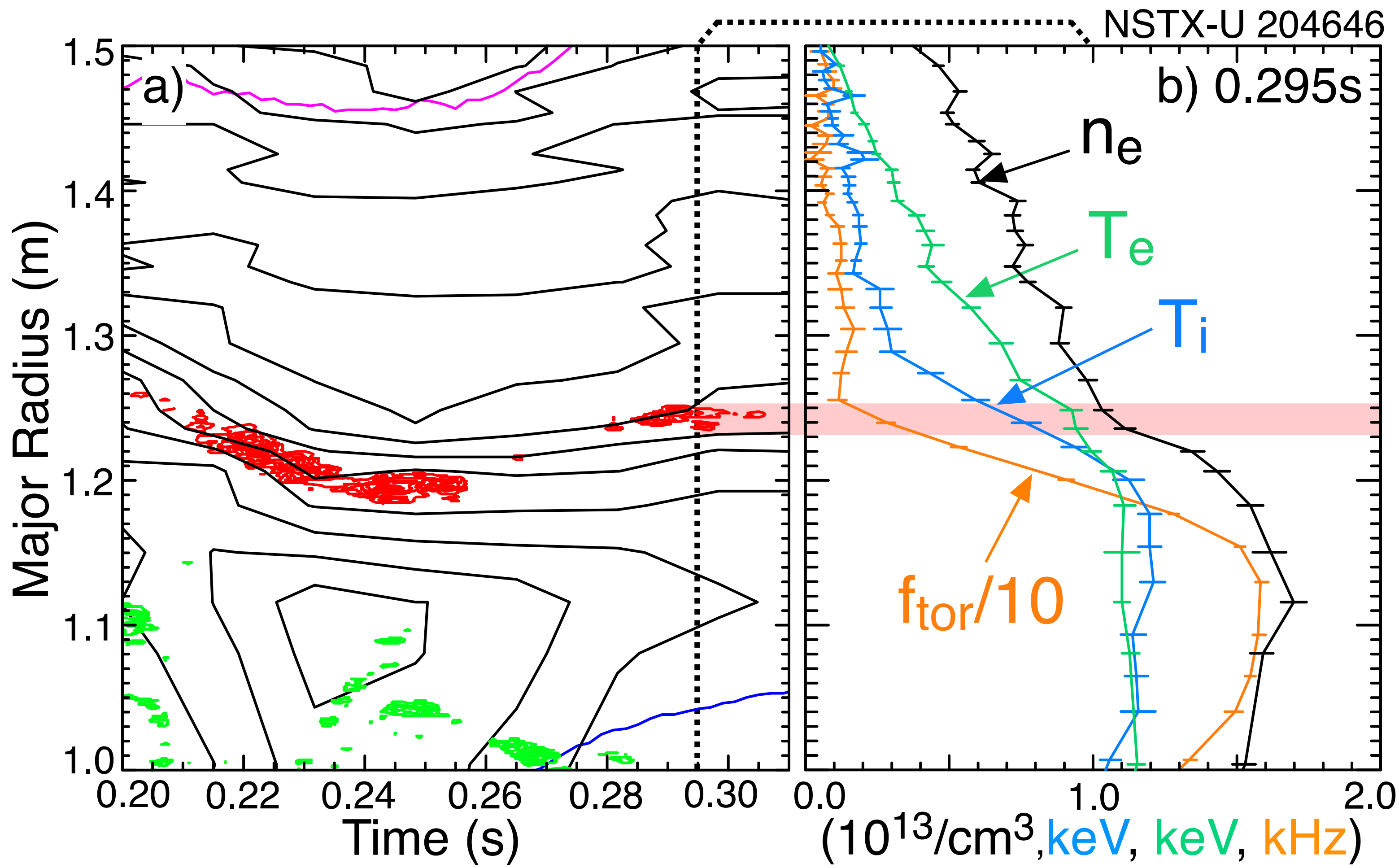
'ICE' frequency doesn't map to edge

- Maps to about half radius, at a "transport barrier".



- Are CAE less localized in STs?
- Up-shift/down-shift relatively greater in Spherical tokamaks?
- Is correlation with ITB coincidental?
- Frequency wobble is from plasma motion.

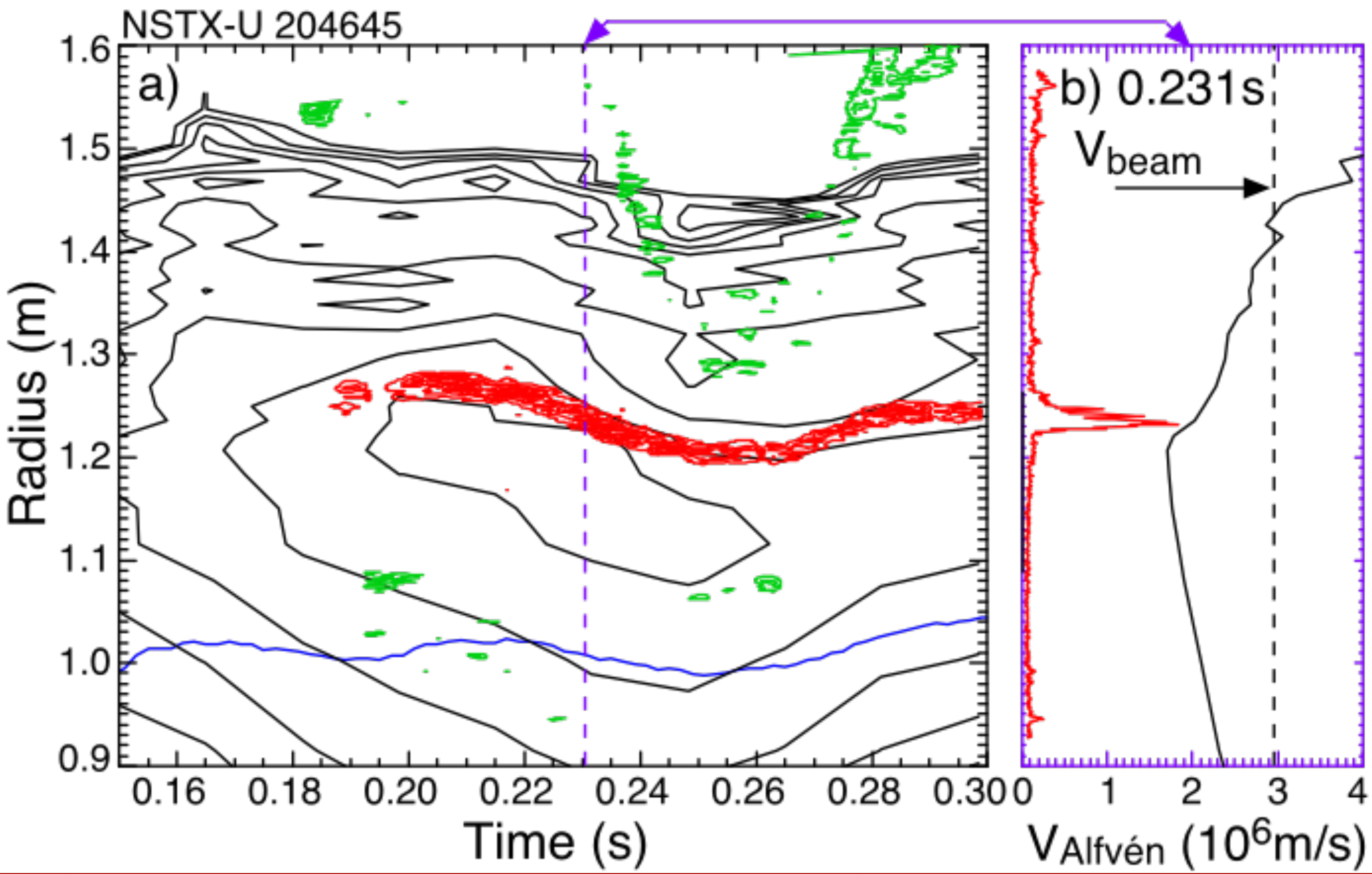
Emission location also correlated with ion temperature and velocity transport barriers



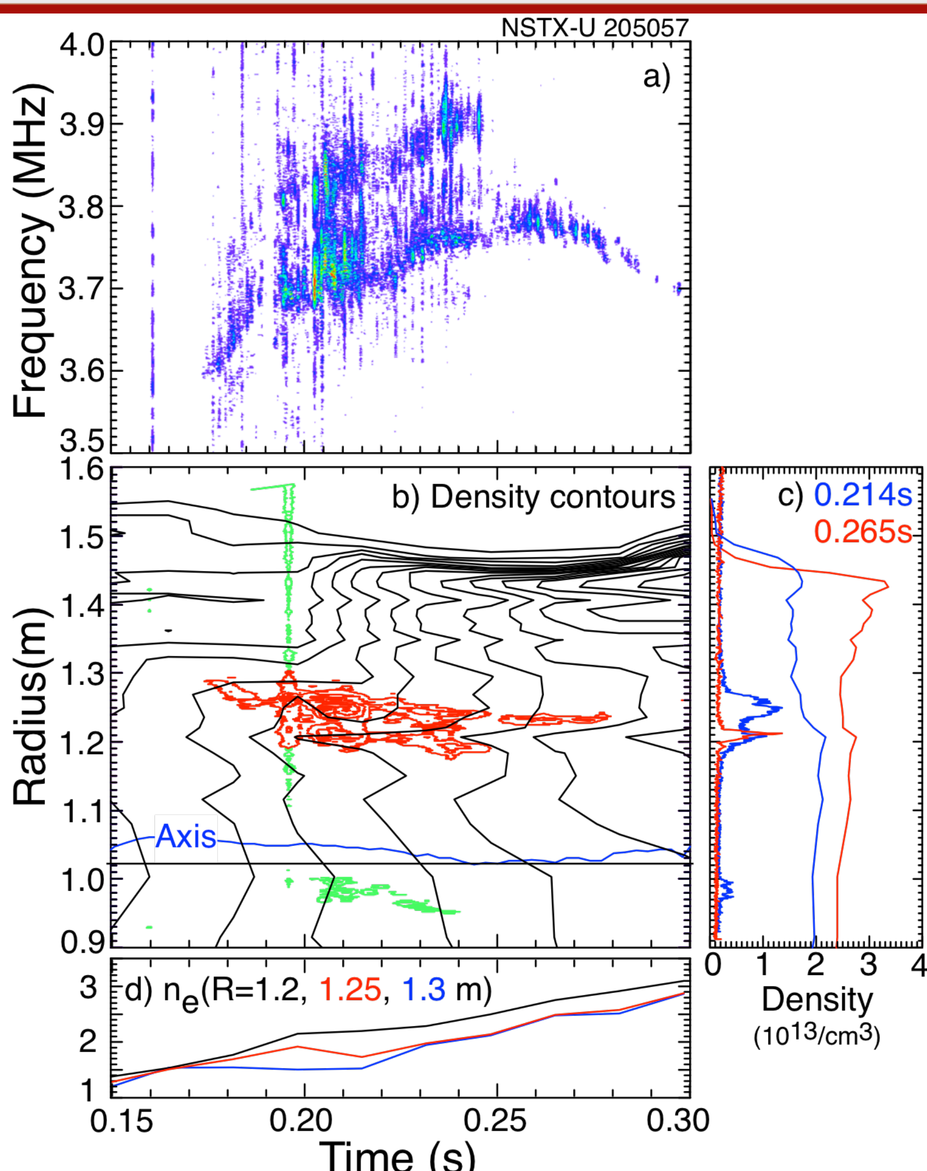
- Why velocity!! What does that have to do with fast ions?

Emission location also correlated with a minimum in $V_{Alfvén}$

- Emission is more ‘localized’ than fast ions, $\rho_{fast} \approx 7 - 20$ cm.
- High mode coherence suggests that it is an eigenmode.



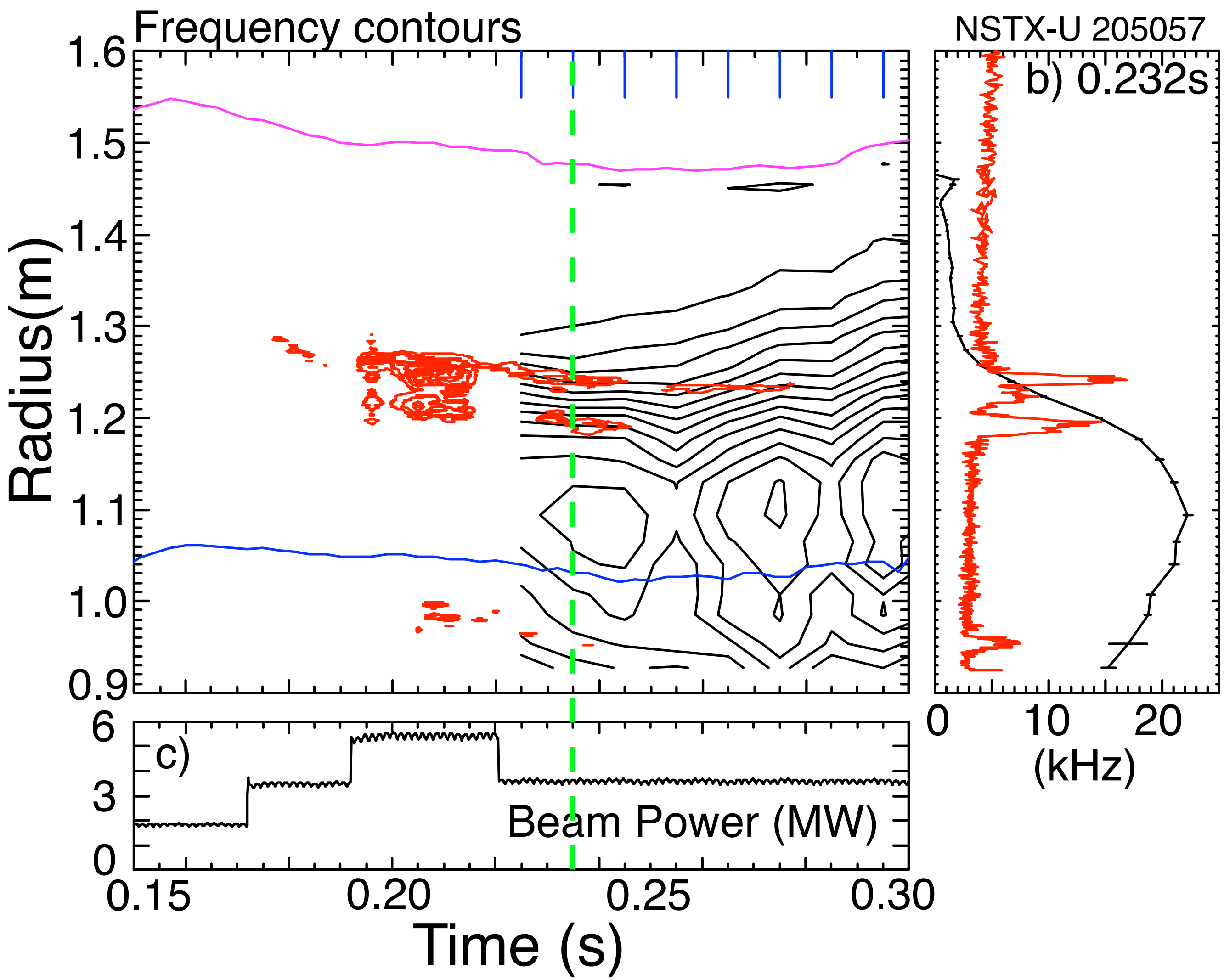
ICE frequency doesn't fall with increasing density



- Density nearly doubles, frequency *increases*.
- Density profile nearly flat, but mode still localized near local, stronger density gradient.
- Is mode is a type of energetic particle mode (EPM); frequency depends on some feature in fast ion distribution?

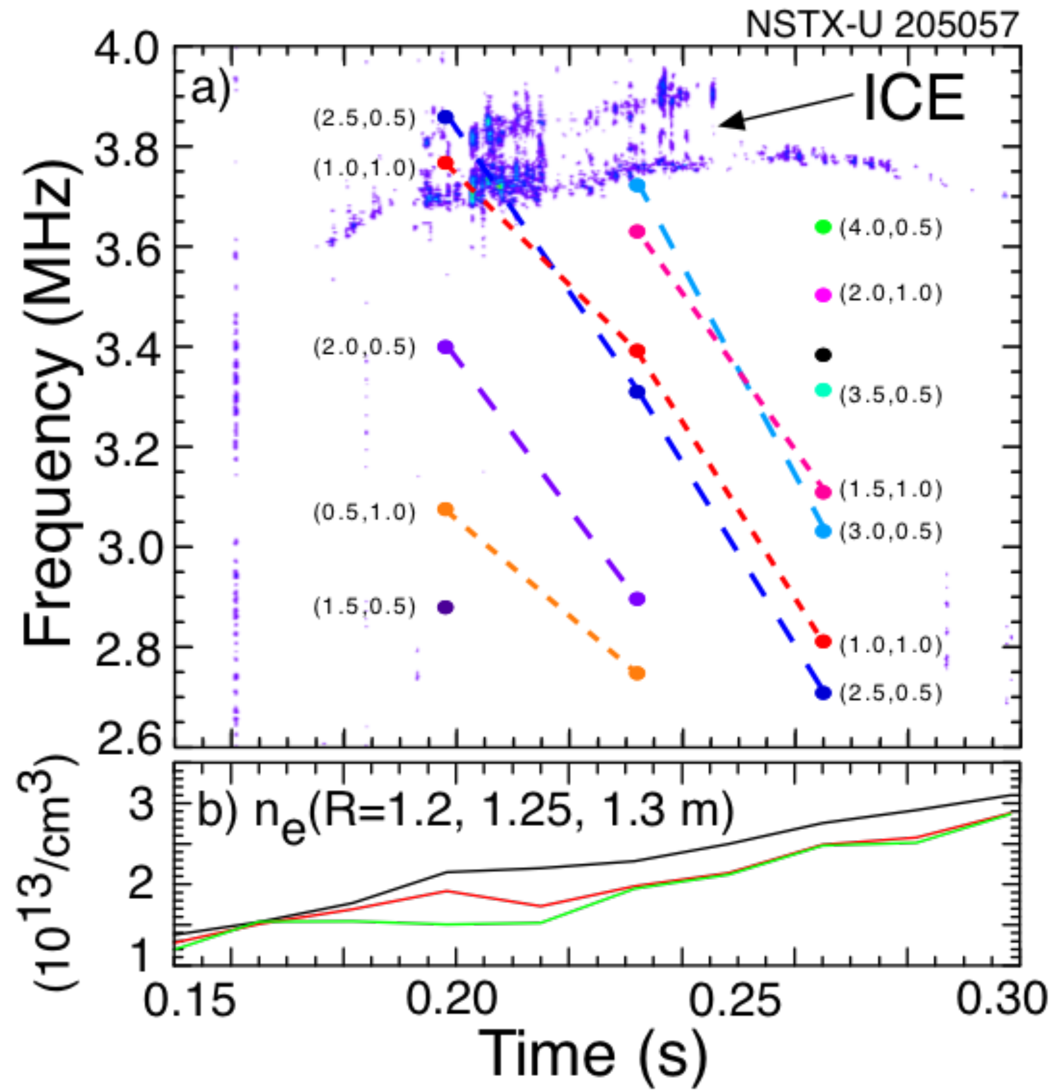
ICE location correlated with velocity gradient

- As velocity gradient smooths out, ICE fades.



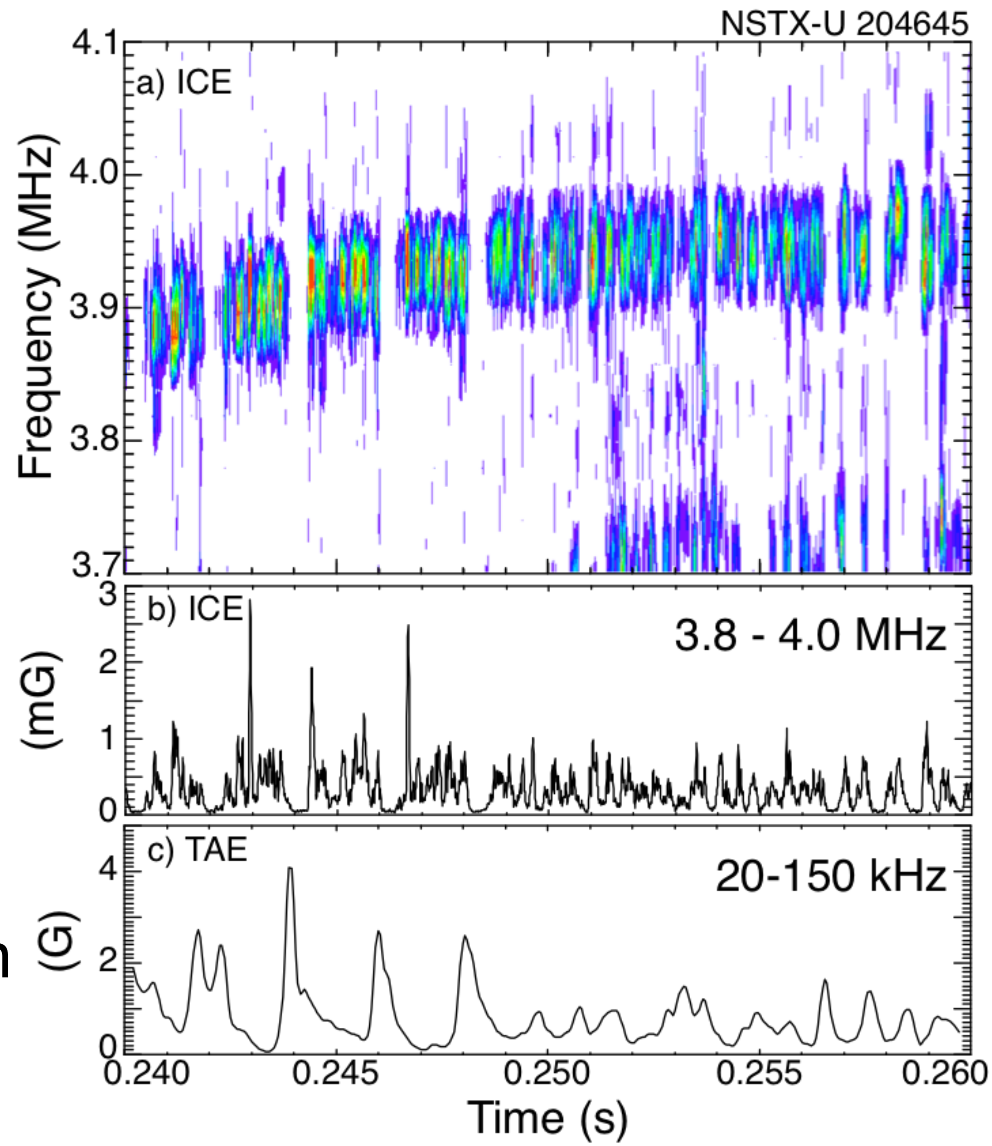
n=-1 CAE frequency evolution

- Frequency spacing is about right.
- Moderately high m or s to get to observed frequency.
- Eigenmode code is not valid close to cyclotron frequency, though.



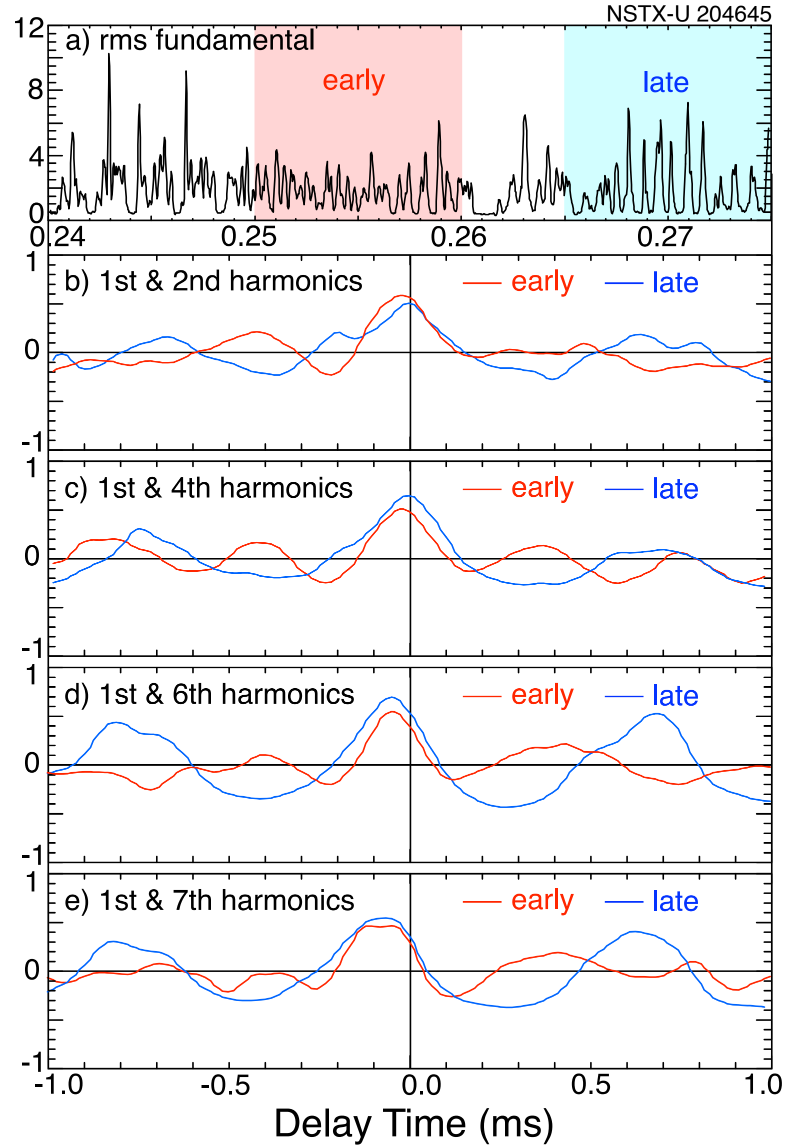
ICE comes in irregular bursts

- Spectrogram of magnetic fluctuations showing bursts of Ion Cyclotron emission,
- rms amplitude of the ICE bursts shows irregular spike heights, periods,
- rms amplitude of lower frequency Toroidal Alfvén eigenmodes shows correlation with quiescent ICE periods.



Higher harmonic bursts lead lower harmonic bursts by ≈ 50 μs

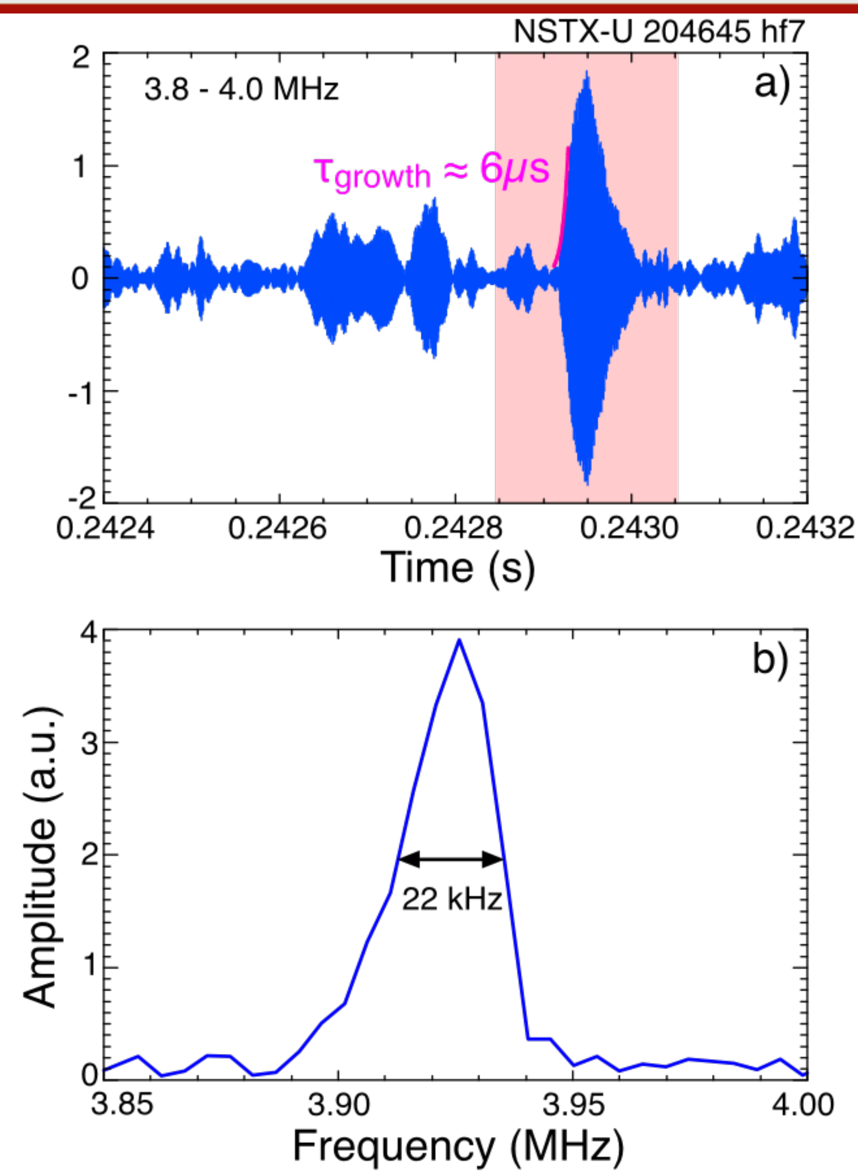
- Cross-correlation of fundamental ICE rms fluctuations with 2nd, 4th, 6th and 7th ICE harmonics.
- Red curves are time-delay correlations done in first time window indicated in top figure by pink band.
- Blue curves are correlations done in second time window indicated by blue band.



ICE bursts have borderline slow growth?

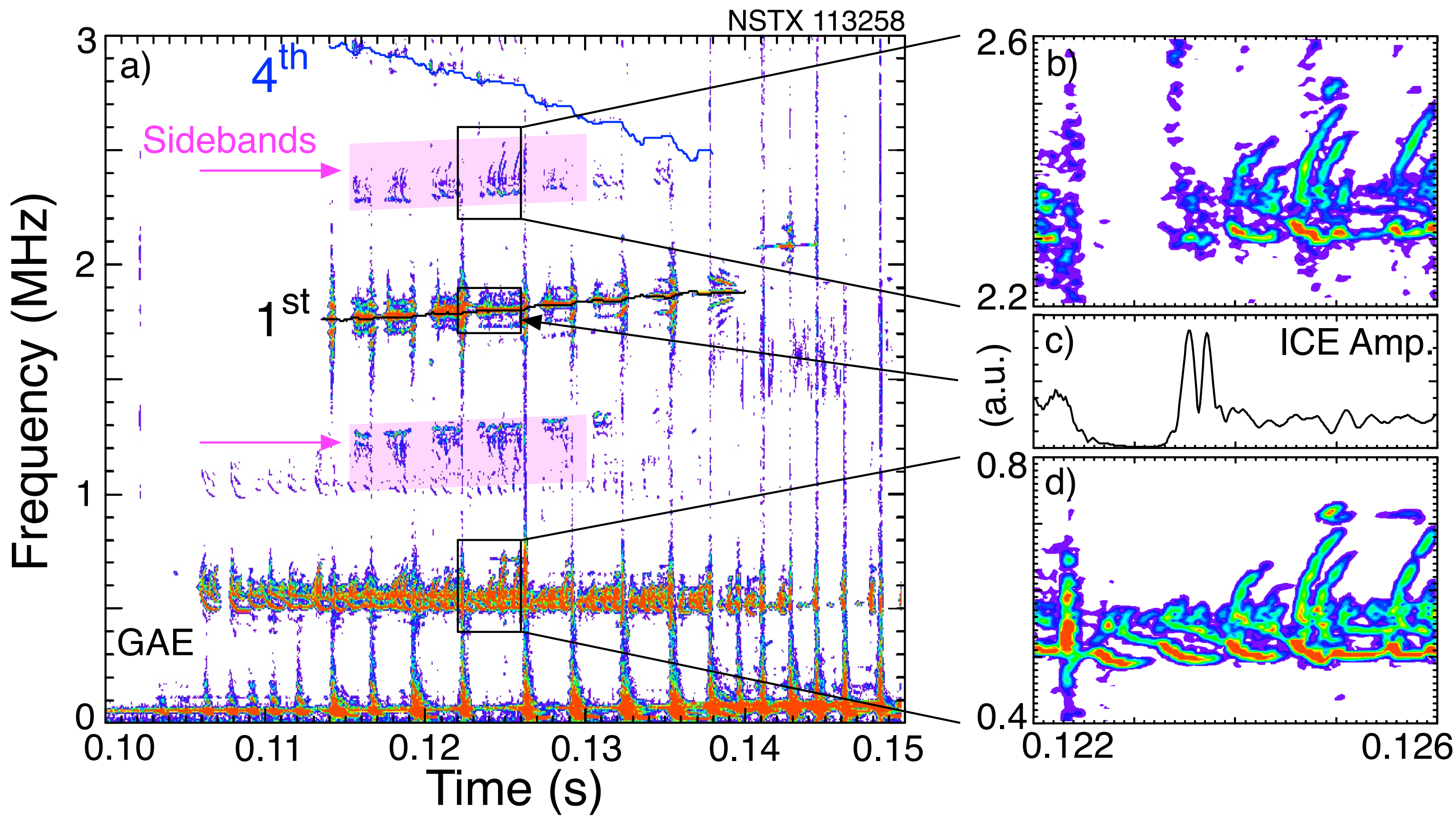
- Toroidal transit time for 90 kV beam ion is ≈ 2 μs, rise time of bursts is ≈ 6 μs

- Width of frequency peak consistent with burst period or growth time – modes are very temporally coherent.

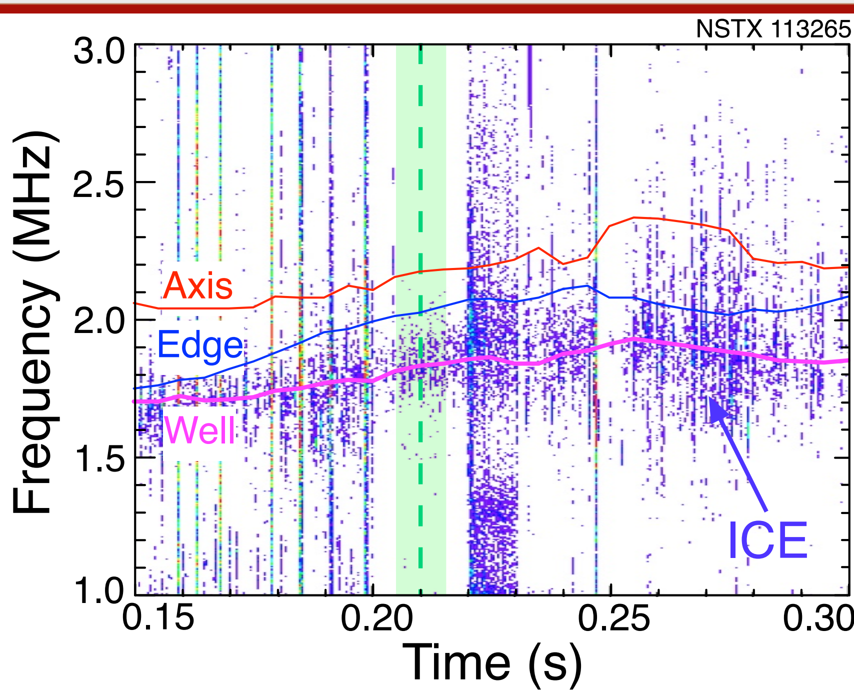


Non-linear, 3-wave interaction between ICE and GAE suggests both are waves?

- Strong fundamental ICE with weak harmonics at low field (2.6 kG) and strong GAE activity result in sidebands to fundamental ICE.

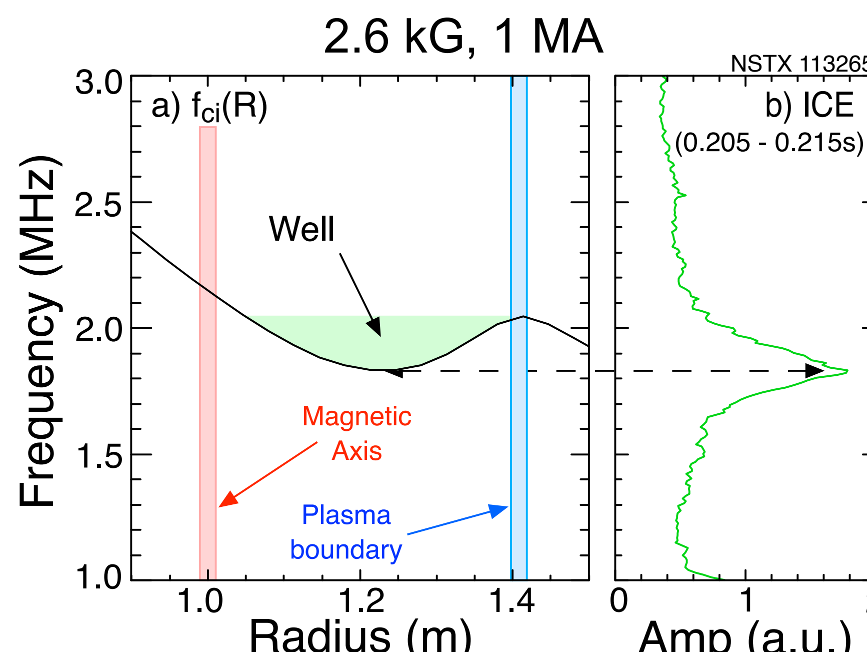


ICE is seen in shots with magnetic well

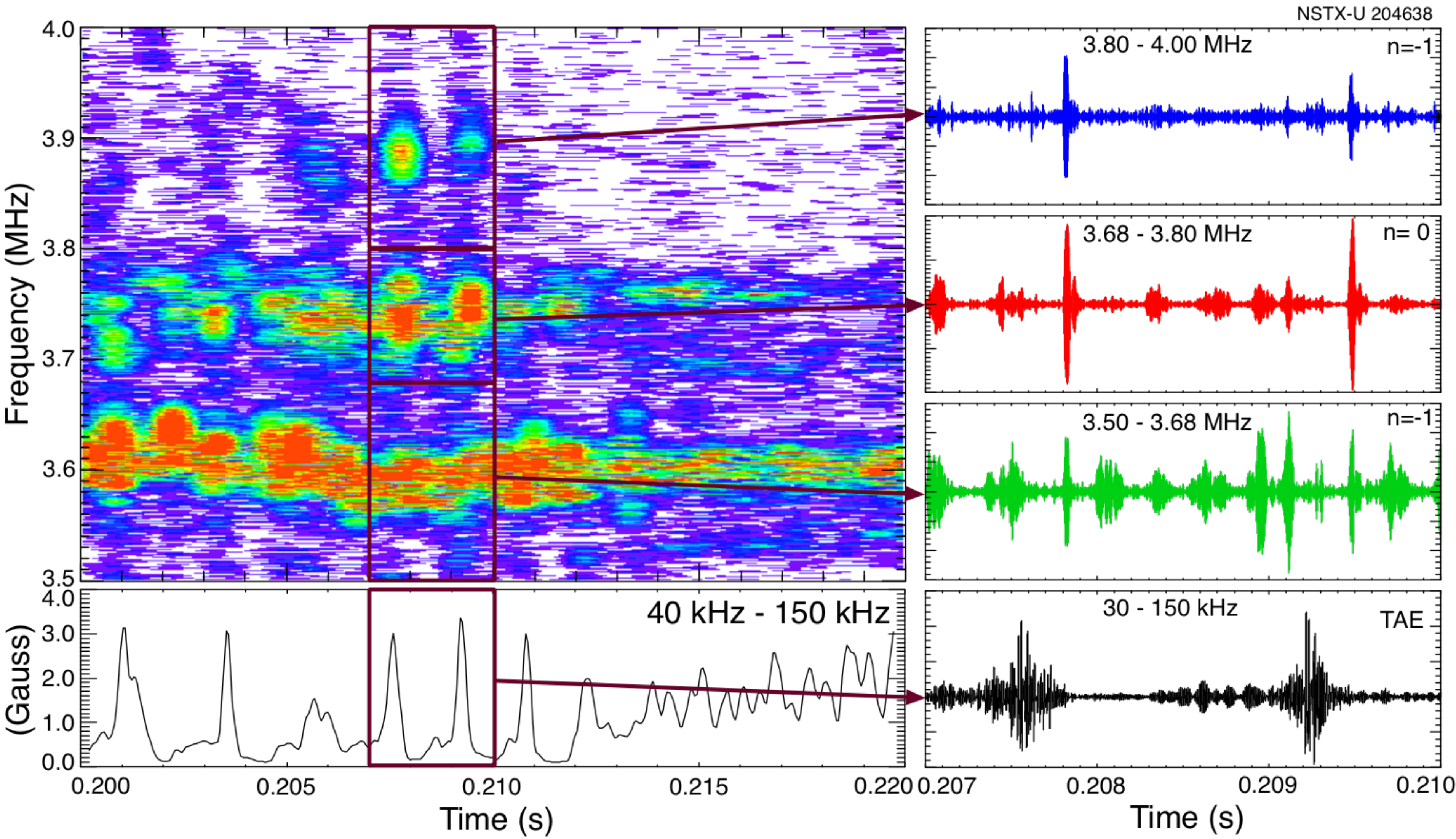


- Spectrum is broad with a peak in amplitude at a frequency below edge cyclotron frequency (magenta curve).

- ICE spectrum can't be mapped to radius as before
  - [R(f_{ci}) is double valued].
- Peak frequency maps to bottom of magnetic well.

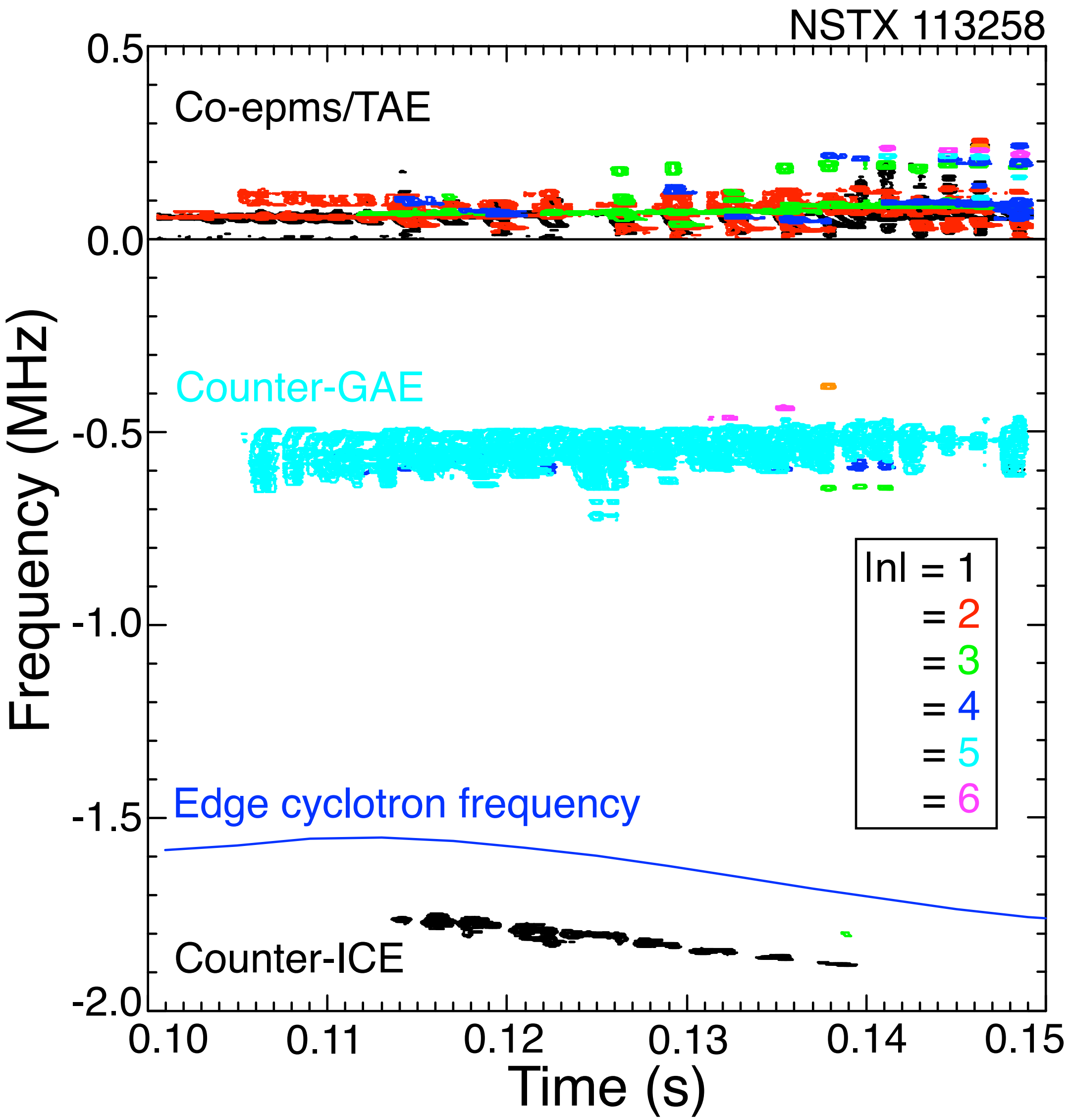


Doublet and triplets are fairly common



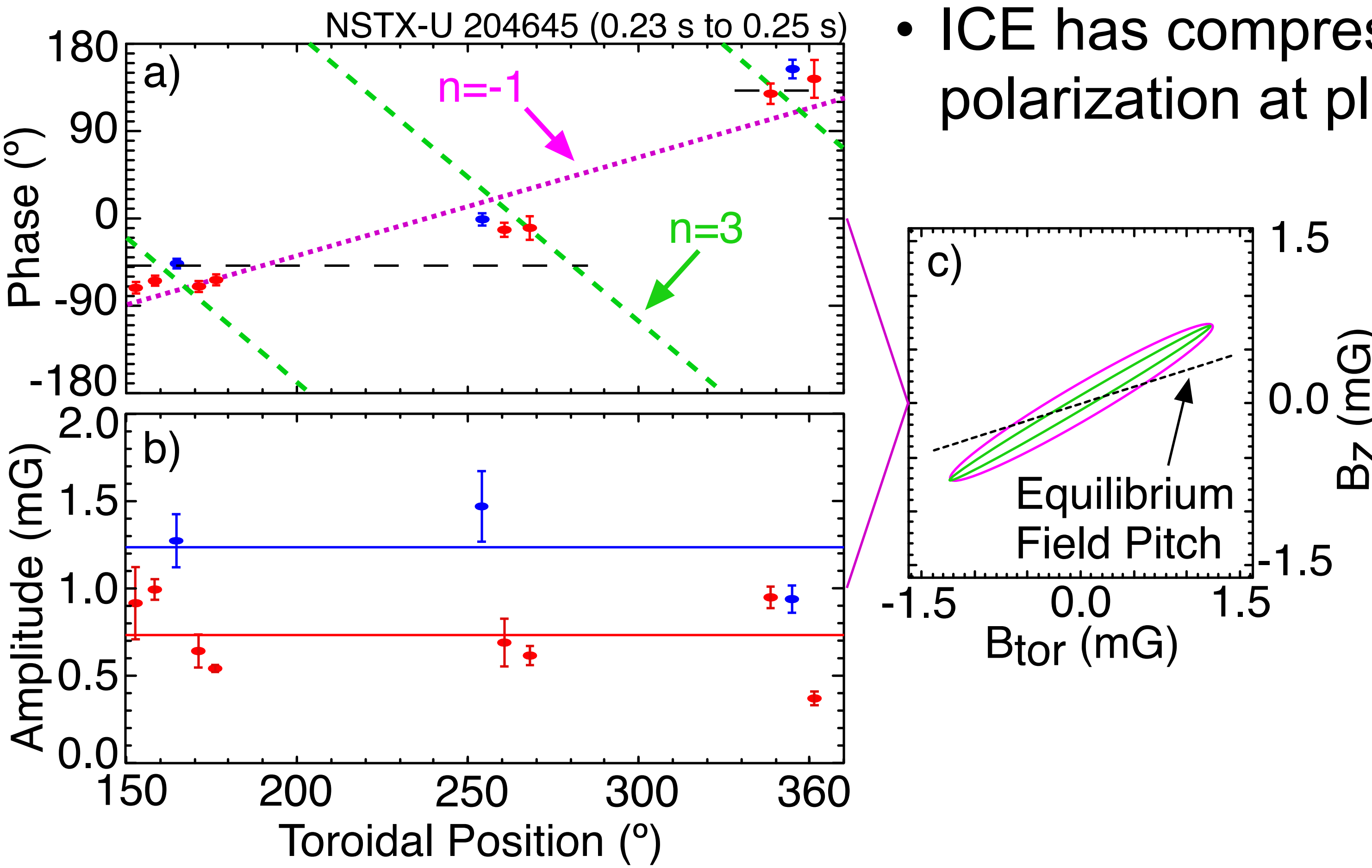
ICE is best fit with n=-1

- Data from NSTX-U fast array can have uncertainty of ±4 in n-identification (due to array layout).
- Older, low field (2.6 kG) shot from NSTX where high-n array (HN) give clear identification as n=-1.
- Negative frequencies are counter-propagating.
- Doppler shift up to 450 kHz



ICE is spatially coherent, long wavelength

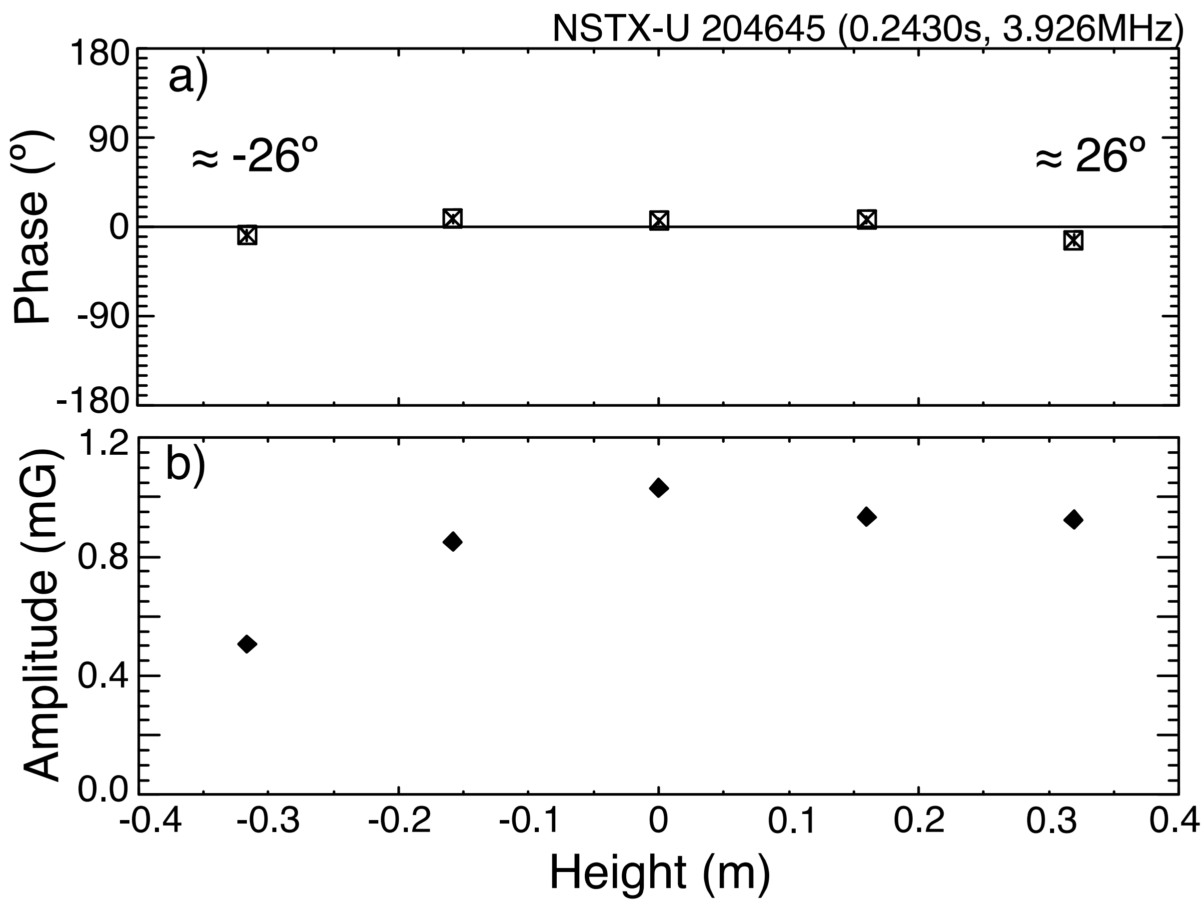
- ICE is best fit with n=-1 (ctr-propagating), but n=±1 and n = 3 are also reasonable fits.



- ICE has compressional polarization at plasma edge.

Poloidal structure less certain? More variable?

- Poloidal wavelengths mostly long, standing waves?



Poloidal structure less certain? More variable?

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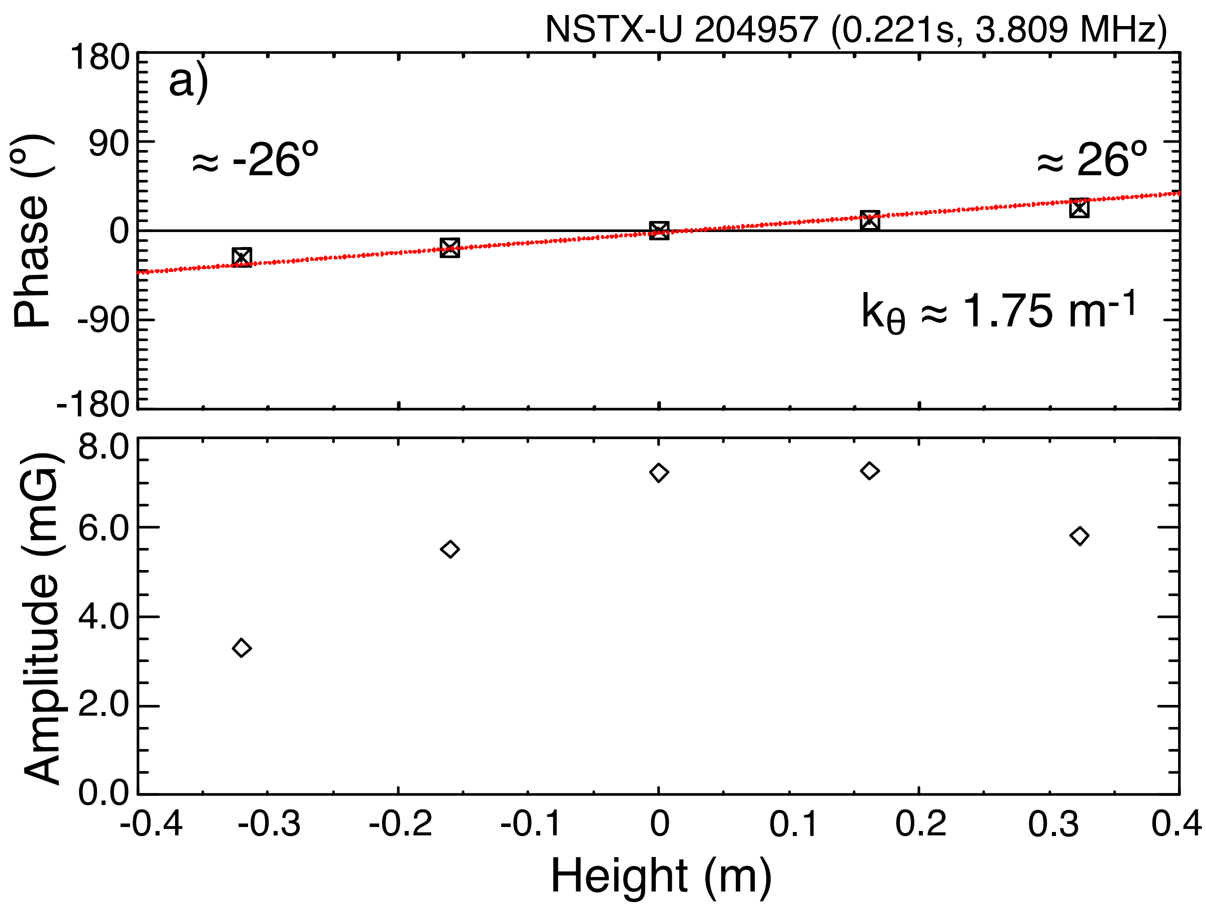
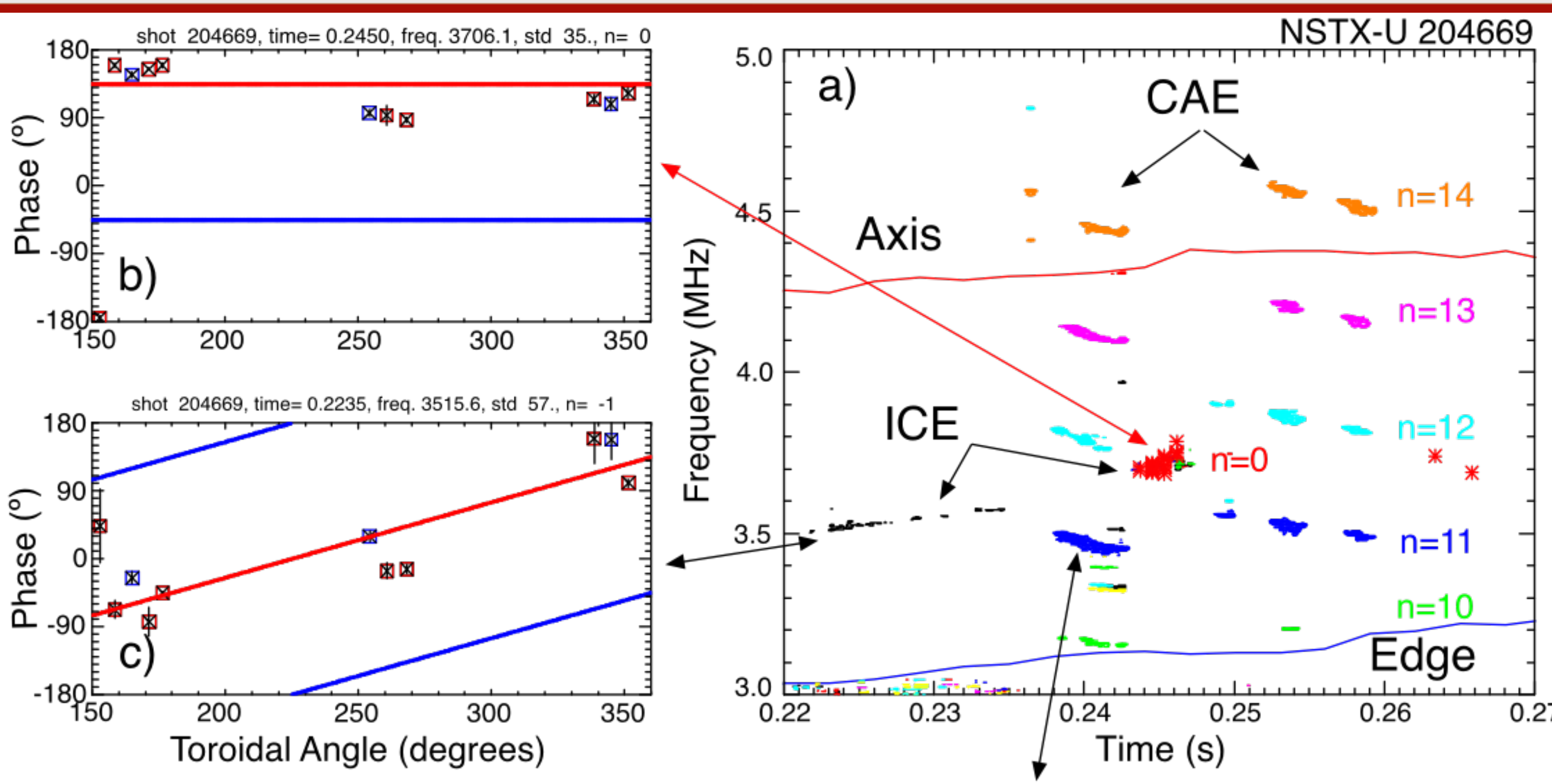
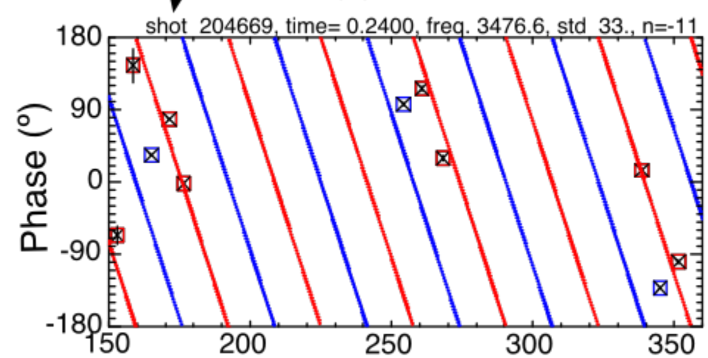


CAE and ICE can co-exist

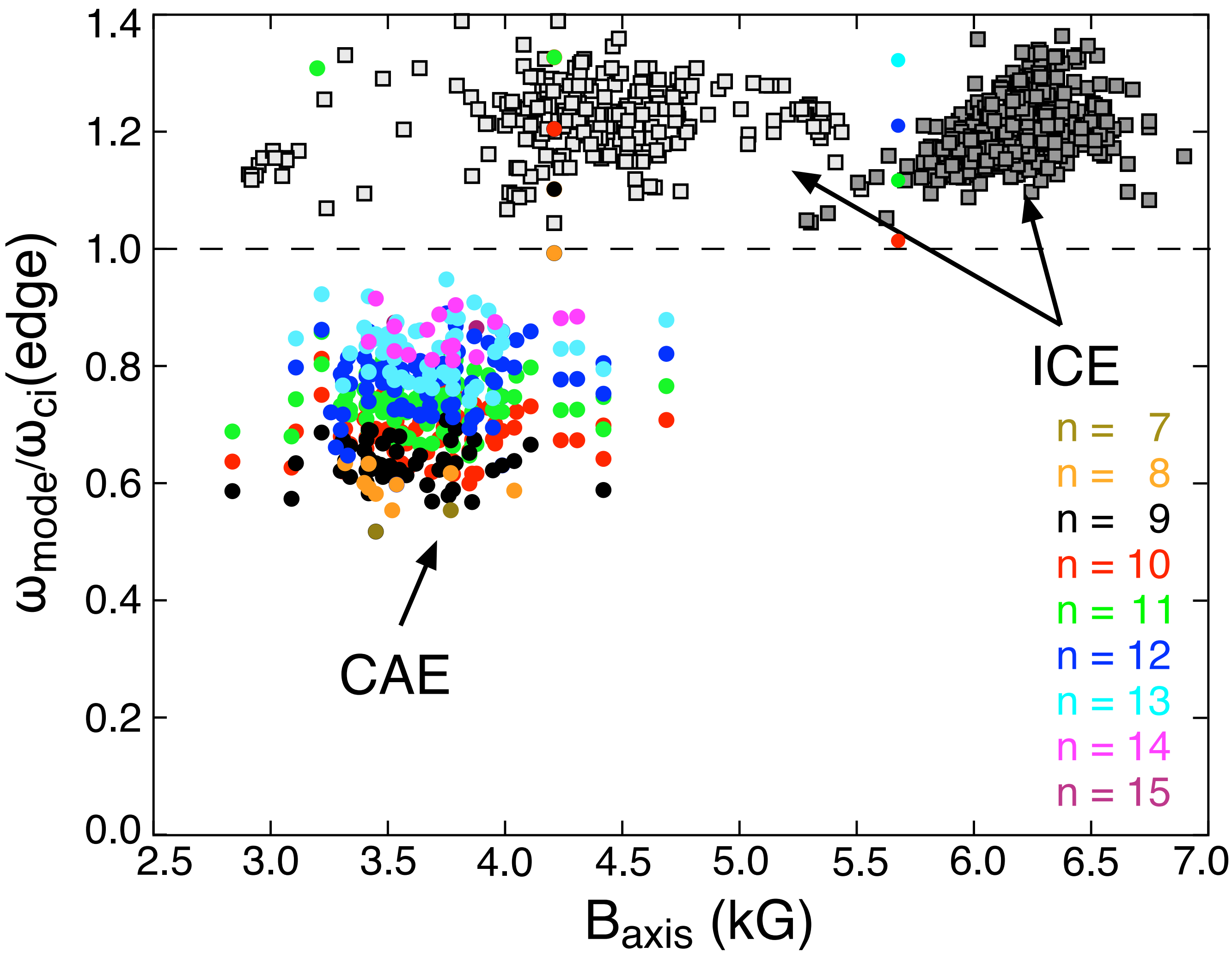




- CAE are high-n, co-propagating.
- ICE is low n, ctr-propagating (or not propagating).

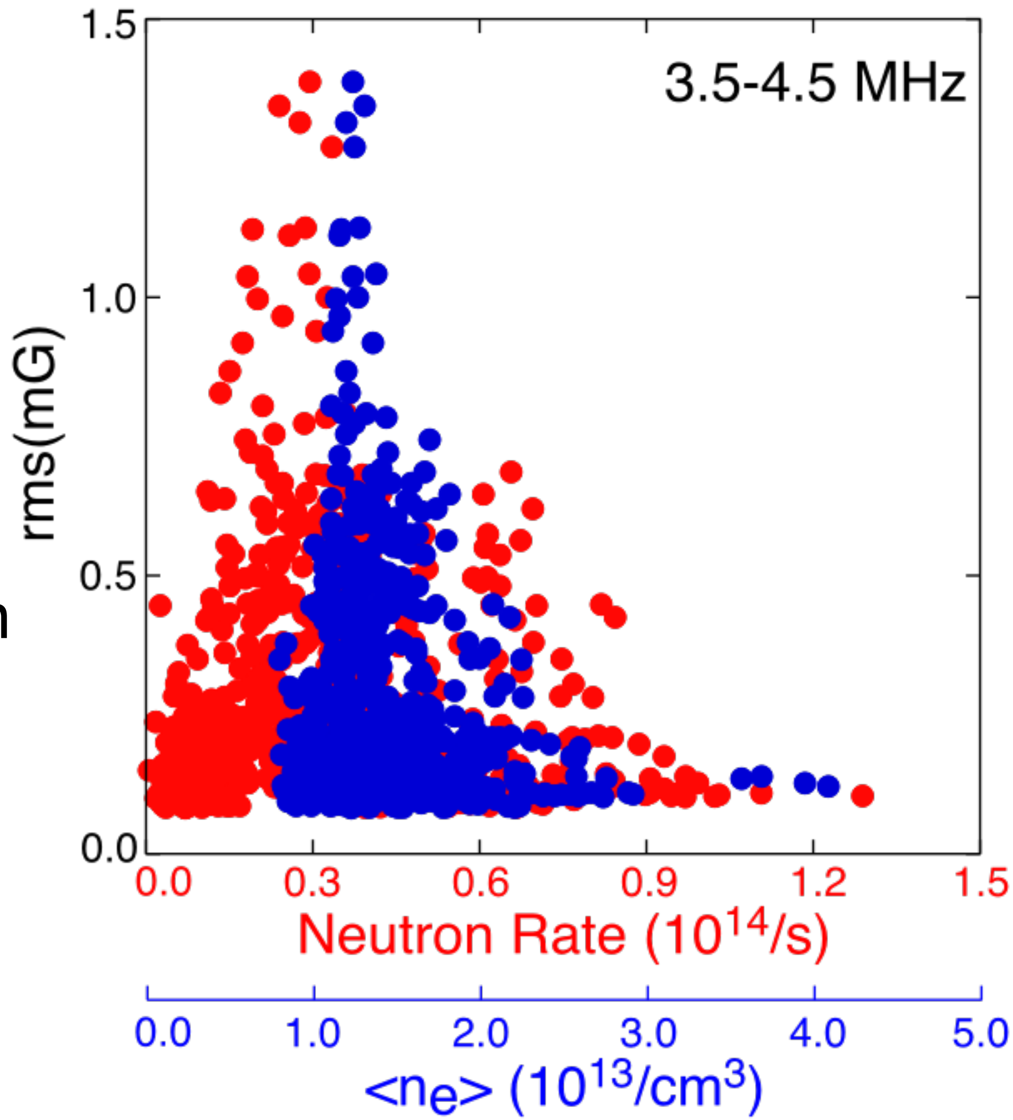
ICE frequency above edge ω_{ci}

- CAE frequency is typically below the edge ω_{ci}, but it can be higher.



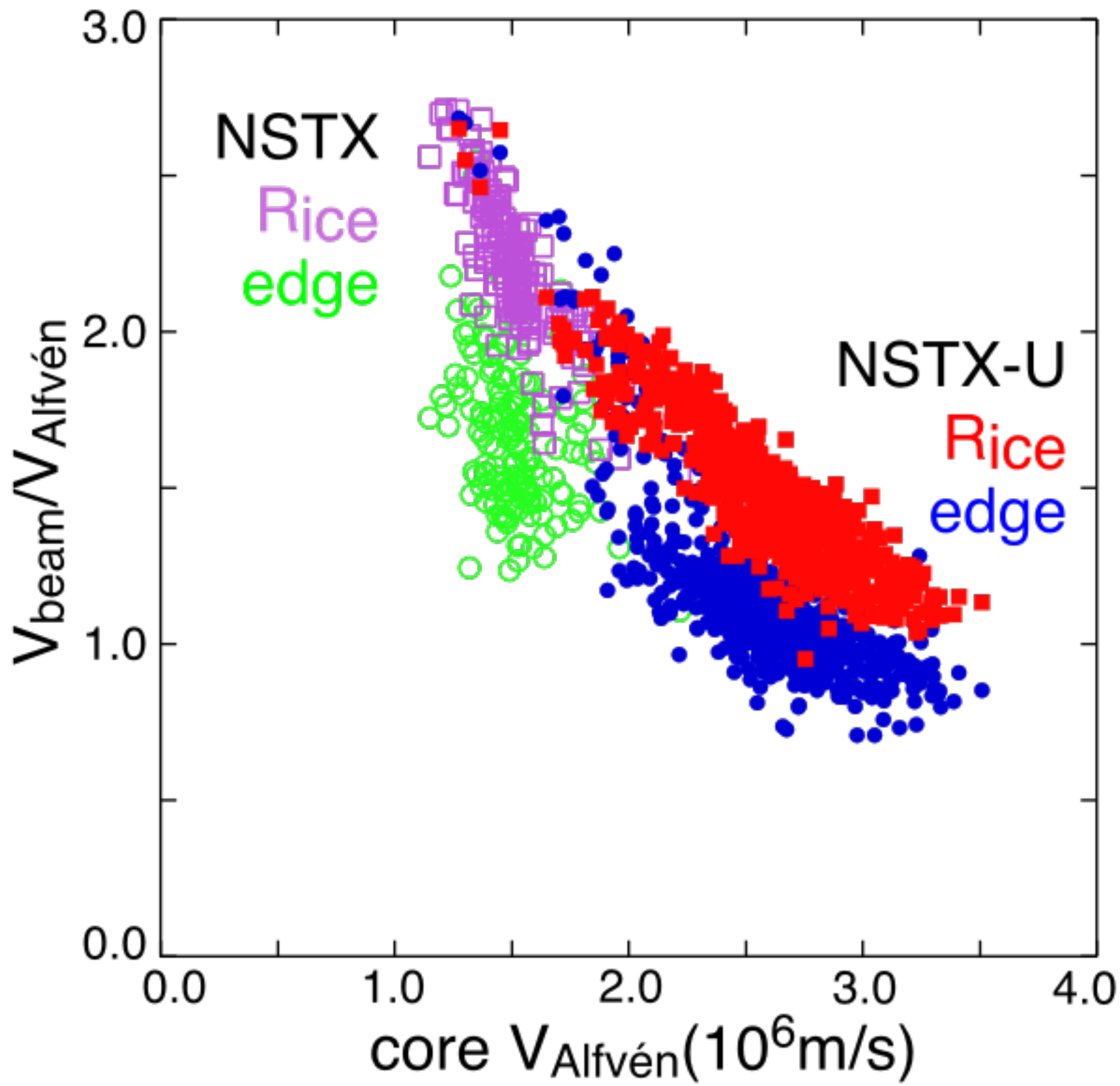
Not obviously correlated with 'total' fast ion density (neutron rate)

- Correlation of ICE intensity with neutron rate (red points) and density (blue points)
- Possibly consistent with TFTR observations.
- JET correlation was for fusion products.
- May be correlated with edge beam density?



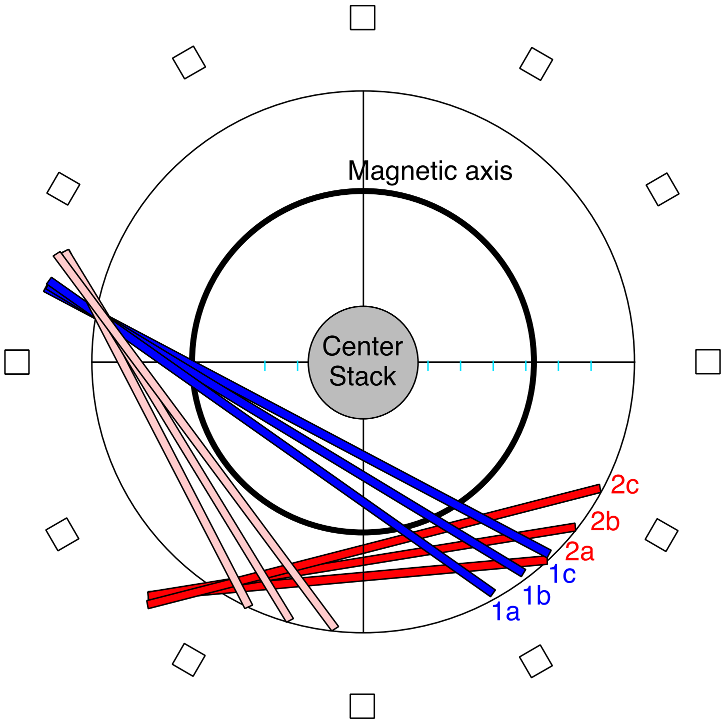
$V_{beam}/V_{Alfvén}$ typically > 1

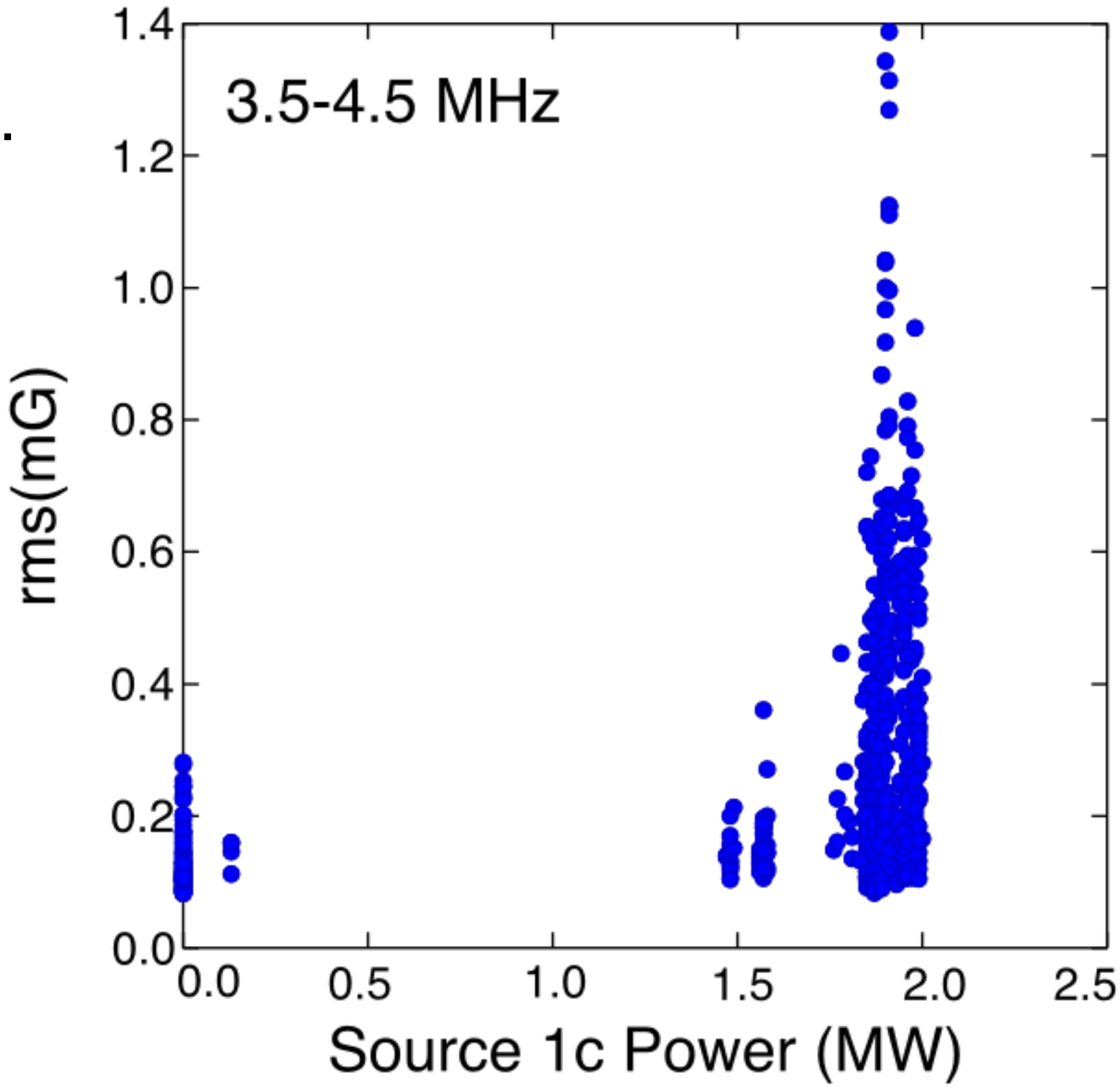
- Consistent with CAE interpretation of ICE.
- Calculated for an average density, full beam energy.
- Difficult to get this parameter < 1 in NSTX.
- Maybe in the future...



Curious correlation with source 1C

- A lot of "operational" correlations in database.





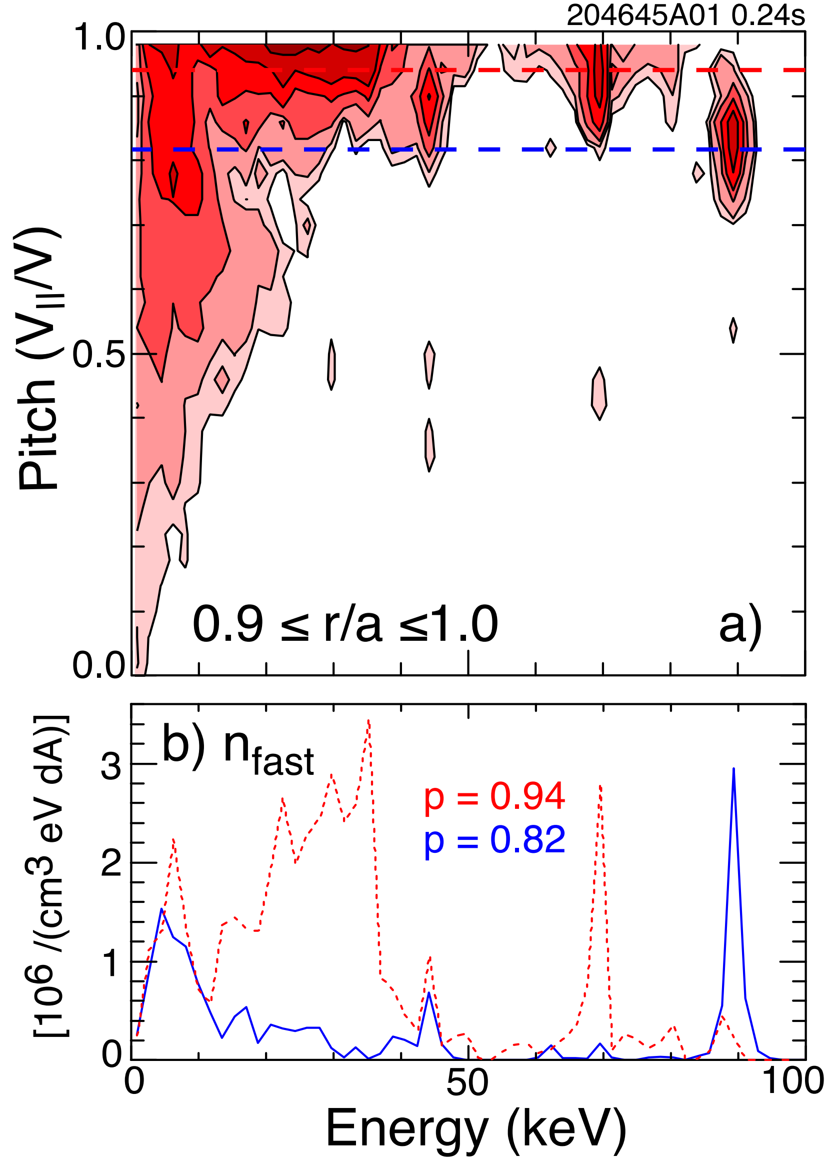
- Didn't see this in NSTX.

Fairly narrow “beams” in edge of plasma

- Beam ion distribution function in plasma edge showing bump-on-tails at the beam injection energies of 80 kV and 90 kV.

- Barely confined orbits of beam ions which were deposited deeper in plasma.

- As they slow down, they move radially inward - none further out to move to this location at lower energy.



Summary of observations (1)

- Emission in the ion-cyclotron range of frequencies (ICE) is seen from NSTX and NSTX-U plasmas.
- ICE frequency maps to about a/2 (on-axis ICE reported previously),
  - often close to an internal density-ion temperature-rotation transport barrier,
    - strongest correlation is with velocity
    - does rotation velocity define effective plasma edge?
- ICE frequency maps to bottom of magnetic well, when present, and is less 'coherent' than in non-well shots.
- ICE is spatially coherent, with n = -1 or n = 0.

(red, blue (more significant?) and magenta are new results)

Summary of observations (2)

- The ICE is bursty, with typical burst durations of $\approx 50\mu s$.
- Harmonics up to 7th have been seen, higher harmonic bursts slightly precede lower harmonic bursts, often higher harmonics appear to be weaker.
- Fine splitting of ICE at harmonic frequencies is seen; three or more frequency peaks with splitting of ≈ 4%.
- ICE co-exists with Compressional Alfvén eigenmodes.
- ICE frequency doesn’t scale with density.
- Strongest ICE seen with most perp. beam line (NSTX-U).