Novel Internal Measurements and Analysis of Ion Cyclotron Frequency Range Fast-ion Driven Modes Advance Predictive Capability for Fast-ion Transport in Burning Plasmas

by
NA Crocker, SX Tang, KE Thome, JB Lestz, EV Belova, AI Zalzali, RO Dendy, WA Peebles, K Barada, R Hong, TL Rhodes, G Wang, L Zeng, TA Carter, GH DeGrandchamp WW Heidbrink and RI Pinsker

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Ion cyclotron range beam driven instabilities may cause thermal transport & be used for fast-ion diagnosis

- Ion cyclotron emission (ICE) at $f_{cb}$ harmonics frequently observed, typically with beam heating or significant fusion products (see e.g. review [K. McClements, NF 2015])
- Leading theory: ICE driven by Doppler-shifted cyclotron resonance with fast ions – aka magnetoacoustic cyclotron instability (MCI) [Dendy, PoP 1994 p. 1918; N.N. Gorelenkov NF 2003]
  - drive from distribution gradient w/resp. to $v_\perp$ (anisotropy)
  - fast Alfven waves ($k_\perp \rho_f \ll 1$) & cyclotron harmonic waves ($k_\perp \rho_f \gtrsim 1$)
- Electrostatic non-beam driven instabilities possible (see refs. in [R. Dendy, PoP 1994 p. 3407])
  - must learn to distinguish from MCI
- MCI waves may cause thermal transport or “energy channeling”
  - see [Y. I. Kolesnichenko, NF 2020] and Refs. therein
- “spectroscopy” using MCI waves constrains inferred fast-ion energy spectrum/spatial distribution
  - Indicates presence of resonant ions and anisotropy at resonance
• DBS measurements show ICE $\tilde{n}$ at $2f_{ci}$ & $3f_{ci}$ in the edge of DIII-D plasmas, at the top of the pedestal and in the SOL.

• The observed ICE $\tilde{n}$ is shown to be high-k cyclotron harmonic waves or electrostatic waves

• The ICE $\tilde{n}$ is shown to be radially extended, consistent with eigenmode or propagating wave
Preview of conclusions

• DBS measurements show ICE $\tilde{n}$ at $2f_{ci}$ & $3f_{ci}$ in the edge of DIII-D plasmas, at the top of the pedestal and in the SOL.
  – Edge magnetic also show ICE $\tilde{b}$ at $2f_{ci}$ & $3f_{ci}$ but the observed modes not the same as those observed by DBS

• The observed ICE $\tilde{n}$ is shown to be high-k cyclotron harmonic waves or electrostatic waves

• The ICE $\tilde{n}$ is shown to be radially extended, consistent with eigenmode or propagating wave:
  – SOL: $\Delta R \gtrsim \sqrt[3]{4} \text{ cm}$
  – Top of pedestal: $\Delta R \gtrsim 7 \text{ cm} \approx 0.2a, \approx 2\rho_{fast}$

• The stability of the ICE $\tilde{n}$ is influenced by ELMs consistent with drive by fast-ions and fast-ion ejection by ELMs
  • SOL: $\tilde{n}$ transiently excited during ELM as ejected fast-ion pass through
  • Pedestal-top: $\tilde{n}$ transiently damped during ELM as edge fast-ions depleted
Measurement technique
Ion cyclotron range fluctuations measured with two instruments

- **DBS system measures** $\tilde{n}$; recently modified to extend frequencies to ion cyclotron range
  - 8 frequency DBS system: 55 – 75 GHz [W. A. Peebles, RSI 2010]
    - Core to edge depending on equilibrium $n_e$ and $B$ profiles
    - modified to split signals into low (LF) and high (HF) frequency bands using diplexer
    - HF DBS sensitive to $\tilde{n}$ with $f \approx 16$ – 75 MHz
      - DC-47 MHz anti-alias filters
- **Array of loops on wall measures edge ion cyclotron range** $\tilde{b}_\phi$
  (1 – 200 MHz)
  - for results reported here, see [K. E. Thome, RSI 2018]
  - for recent upgrades enhancing ICE structure measurement capability, see [G. H. DeGrandchamp, RSI 2021]
DBS system measures $\tilde{n}$ via scattering of mm-waves from plasma waves

- **DBS => $\tilde{n}$ measured via scattering in two ways:**
  1) Low-k ($k_\theta \ll 1$ cm$^{-1}$) mode ($f = f_{ICE}$) modulates turbulence spectrum ($f = f_{turb}$) $\Rightarrow$ sidebands: $f_{\tilde{n}} = f_{turb} \pm f_{ICE}$
  2) High-k mode ($k_\theta \sim 1 - 10$ cm$^{-1}$) scatters:
     $f_{\tilde{n}} = +f_{ICE}$ or $-f_{ICE}$
     - propagating make at only $f > 0$ or $f < 0$

- **Scattering governed by Bragg rules:** $\omega_s = \omega_i + \omega_{\tilde{n}}$ and $k_s = k_i + k_{\tilde{n}}$
  - $\omega_{\tilde{n}} \ll \omega_i, \omega_s \Rightarrow k_{\tilde{n}} \approx -2k_i$
Ion cyclotron emission observations
2\textsuperscript{nd} harmonic ICE high-k observed at top of pedestal in H-mode

- Deuterium H-mode, reverse $B_T$
  - $R_{\text{midout}} = 2.24 \text{ m}$, $R_0 = 1.85 \text{ m}$
- $\tilde{n}$ measured at $\rho=0.87 = \text{pedestal top}$
- $\tilde{n}$ peaks at $\pm 20.5 \text{ MHz}$ $\sim \pm 2 f_{ci}$
  - $f_{ci} \approx 10.3 \text{ MHz}$, $v_A \sim 3.4 \times 10^6 \text{ m/s}$
  - $\rho_{fast} \sim 3 - 4 \text{ cm}$ (species: D)
- Peaks are caused by scattering from plasma wave
  - Matching peaks at $f = f_+ > 0$ and $f = f_- < 0$ where $f_- = -f_+$
- DBS scatters from $k_\theta = 1.2 \text{ cm}^{-1}$ $\Rightarrow$ peak is high-k wave: cyclotron harmonic wave or electrostatic wave
  - $k_\theta$ too large for Alfvén wave: $\omega/v_A \sim 0.4 \text{ cm}^{-1}$

spectra are denoised by background subtraction
2\textsuperscript{nd} harmonic ICE at pedestal-top observed to be radially broad

- $2f_{ci}$ peak seen in 4 channels: 
  \[ \rho = 0.63 - 0.87 \]
  - same frequency all channels => “eigenmode” or propagating wave
  - strong peaks at $f = \pm 2f_{ci}$
  - asymmetric power consistent with scattering: $\tilde{n}(+2f_{ci}) \neq \tilde{n}(-2f_{ci})$

- $\rho = 0.63 - 0.87 \Rightarrow$ radially broad:
  \[ \Delta R \gtrsim 7 \text{ cm} = a/6 \ (a = R_{midout} - R_0) \]
  - “$\gtrsim$” because no measurements \[ \rho > 0.87 \]
  - also, $\Delta R \gtrsim 2\rho_{fast}$

spectra are denoised by background subtraction
2nd & 3rd harmonic high-k ICE observed in H-mode scrape off layer (SOL)

- **Deuterium H-mode**
  - $R_{midout} = 2.27 \text{ m}, R_0 = 1.73 \text{ m}$
- $\tilde{n}$ measured at $\rho = 1.06 = \text{SOL}$
- $\tilde{n}$ peaks at $\pm 23, \pm 35 \text{ MHz} \sim \pm 2f_{ci}, 3f_{ci}$
  - $\rho_{fast} \sim 2 \text{ cm}$ (species: D)
  - $f_{ci} \approx 11.8 \text{ MHz}, v_A \sim 1.2 \times 10^7 \text{ m/s}$
- **Peaks are caused by scattering from plasma wave**
  - Matching peaks at $f = f_+ > 0$ and $f = f_- < 0$ where $f_- = -f_+$
- **DBS scatters from** $k_\theta = 2 \text{ cm}^{-1}$ $\Rightarrow$ peak is high-k wave: cyclotron harmonic wave or electrostatic wave
  - $k_\theta$ too large for Alfvén wave: $\omega / v_A \sim 0.1 - 0.2 \text{ cm}^{-1}$
ICE in SOL observed to be radially extended

- $2f_{ci}, 3f_{ci}$ peaks observed on 2 channels: $\rho = 1.05, 1.06$
  - same frequency all channels $\Rightarrow$ “eigenmode” or propagating wave
  - strong peaks at $f = \pm 2f_{ci}$
  - asymmetric power consistent with scattering: $\tilde{n}(+2f_{ci}) \neq \tilde{n}(-2f_{ci})$

- $\rho = 1.05, 1.06 \Rightarrow \tilde{n}$ spatially extended: $\Delta R \gtrsim 3/4 \text{ cm}$
  - “$\gtrsim$” because only 2 channels available

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High-K ICE in SOL mode observed by DBS is confined to plasma

- $2f_{ci}$, $3f_{ci}$ peaks observed in $\tilde{b}$ at wall
- $\tilde{\bar{n}}$ and $\tilde{b}$ don't see same modes
  - Peaks in $\tilde{b}$, $\tilde{\bar{n}}$ differ by $\sim 1/2$ MHz
  - Tile loop probably sees fast Alfvén waves with long wavelength not detected by DBS: $\lambda = v_A/f \gtrsim 50$ cm
  - $\tilde{\bar{n}}$ is high-k wave.
- $\tilde{\bar{n}}$ modes not seen by tile loops on wall suggests confinement to plasma consistent with expectation for electrostatic or cyclotron harmonic wave
Edge ICE stability observed to be influenced by ELMs, consistent with fast-ion drive and fast-ion ejection by ELMs

- **ELMs eject fast ions from the edge** [M. García-Muñoz, NF 2013]
- Pedestal-top ICE amplitude transiently damps during ELMs ($D_\alpha$ spikes) ⇒ consistent with depletion of edge fast-ions that excite the ICE by ejection [Cottrell NF 1993]
- SOL ICE amplitude transiently jumps during ELMs ($D_\alpha$ spikes) ⇒ consistent with excitation by ejected fast-ions passing through SOL [S. G. Thatipamula, PPCF 2016], [K. E. Thome, NF 2019]
Conclusions

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