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

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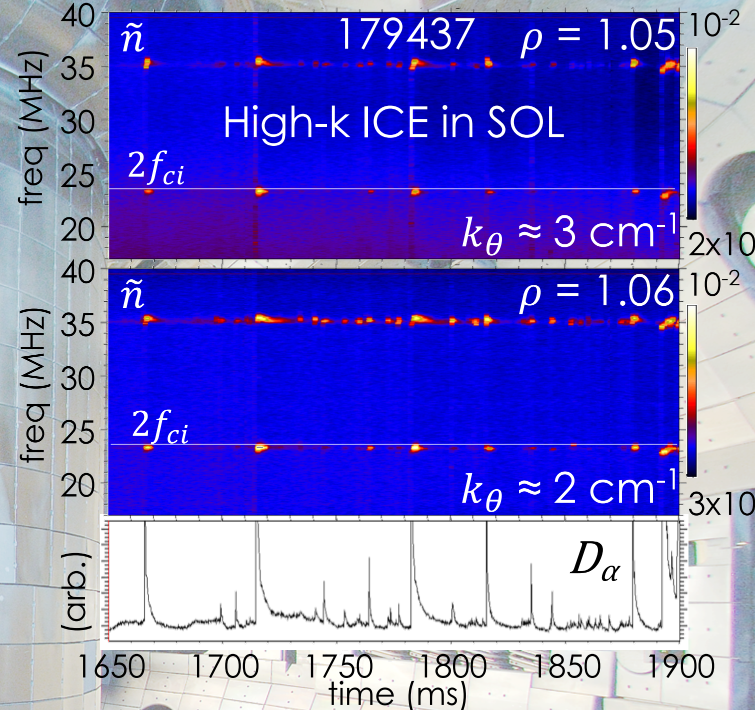

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Ion cyclotron range beam driven instabilities may cause thermal transport & be used for fast-ion diagnosis

- **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 instabiliy (MCI)** [Dendy, PoP 1994 p. 1918; N.N. Gorelenkov NF 2003]
  - drive from distribution gradient w/resp. to $\boldsymbol{v}_\perp$ (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

Highlights

- 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

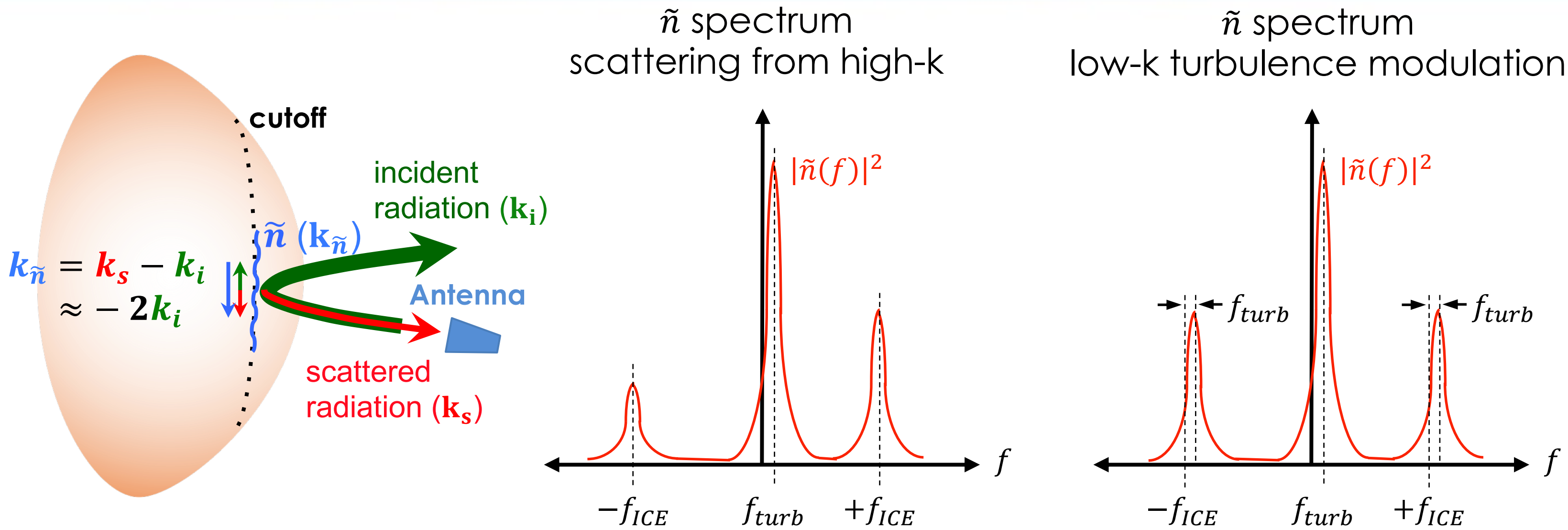
- **DBS measurements show ICE $\tilde{n}$ at $2f_{ci}$ & $3f_{ci}$ in the edge of DIII-D plasmas, at the top of the pedestal and in the SOL.**
  - Edge magnetic also show ICE $\tilde{\boldsymbol{b}}$ at $2f_{ci}$ & $3f_{ci}$ but the observed modes not the same as those observed by DBS
- **The observed 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: $\Delta R \gtrsim$ ¾ cm
  - Top of pedestal: $\Delta R \gtrsim 7$ 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 $\tilde{\boldsymbol{n}}$ with *f* ≈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

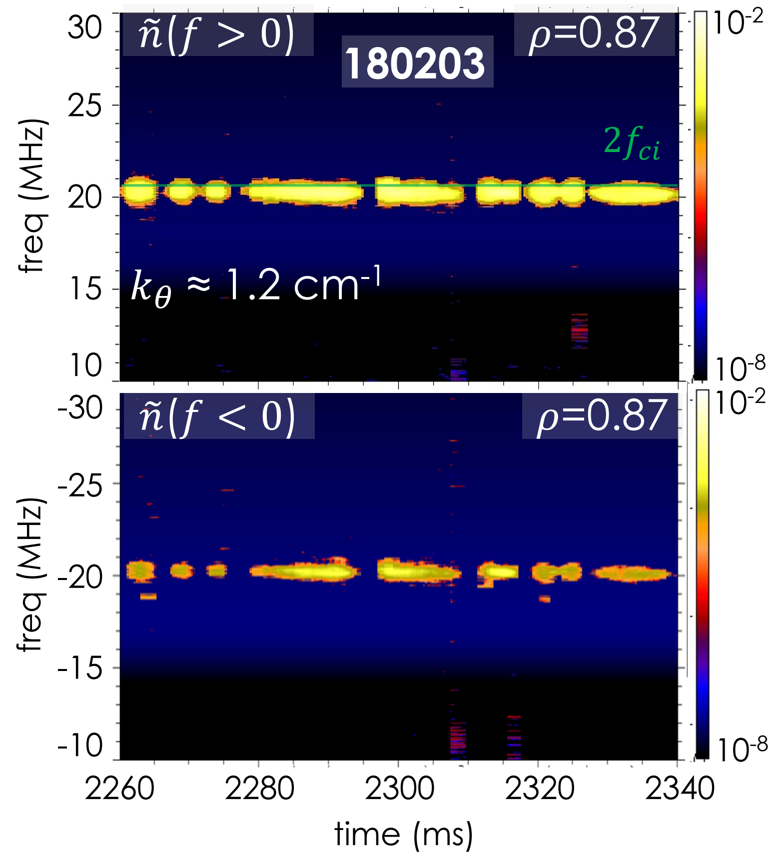


- **DBS => $\tilde{n}$ measured via scattering in two ways:**
  1) Low-k (k_θ << 1 cm^{-1}) mode ($f = f_{ICE}$) modulates turbulence spectrum ($f = f_{turb}$) $\Rightarrow$ sidebands: $f_{\tilde{n}} = f_{turb} \pm f_{ICE}$
  2) High-k mode (k_θ ~ 1 – 10 cm^{-1}) scatters: $f_{\tilde{n}} = +f_{ICE}$ 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 $\mathbf{k}_s = \mathbf{k}_i + \mathbf{k}_{\tilde{n}}$**
  – $\omega_{\tilde{n}} \ll \omega_i, \omega_s \Rightarrow \mathbf{k}_{\tilde{n}} \approx -2\mathbf{k}_i$

Ion cyclotron emission observations

2nd harmonic ICE high-k observed at top of pedestal in H-mode

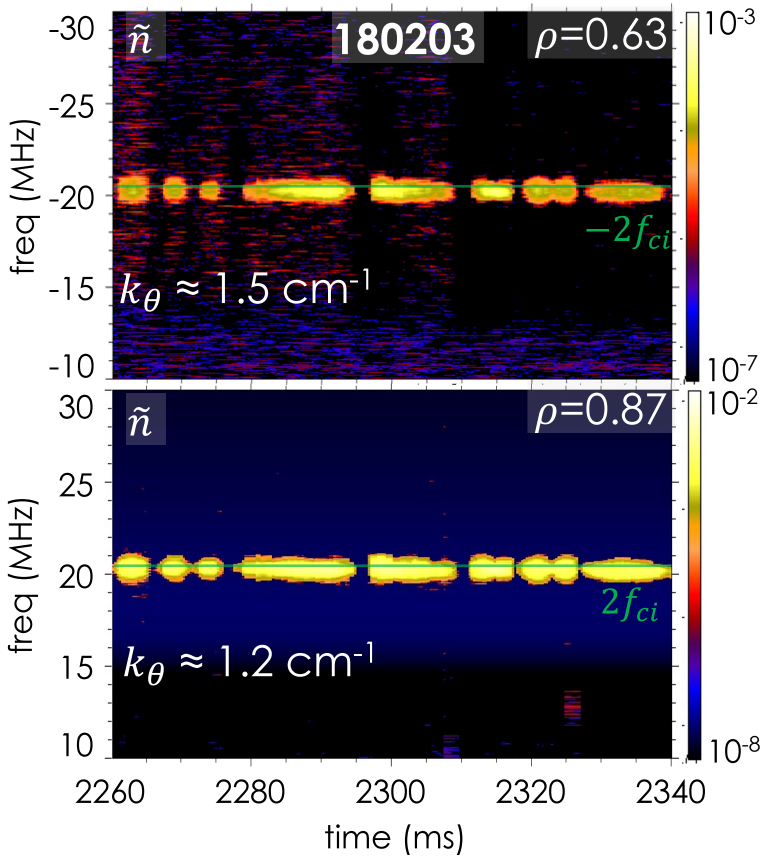
- **Deuterium H-mode, reverse B_T**
  - R_{midout} = 2.24 m, R_0 = 1.85 m
- **$\tilde{n}$ measured at ρ=0.87 = pedestal top**
- **$\tilde{n}$ peaks at ~ ±20.5 MHz ~ ± $2f_{ci}$**
  - $f_{ci} \approx$ 10.3 MHz, v_A ~ 3.4 x 10⁶ m/s
  - ρ_{fast} ~ 3 – 4 cm (species: D)
- **Peaks are caused by scattering from plasma wave**
  - Matching peaks at $f = f_+ > 0$ and $f = f_- < 0$ where $f_- = -f_+$
- **DBS scatters from k_θ = 1.2 cm⁻¹ ⇒ peak is high-k wave: cyclotron harmonic wave or electrostatic wave**
  - k_θ too large for Alfvén wave: ω/v_A~0.4 cm⁻¹



spectra are denoised by background subtraction

2nd harmonic ICE at pedestal-top observed to be radially broad

- **$2f_{ci}$ peak seen in 4 channels: ρ = 0.63 – 0.87**
  - same frequency all channels => "eigenmode" or propagating wave
  - strong peaks at $f = \pm 2\boldsymbol{f_{ci}}$
  - asymmetric power consistent with scattering: $\tilde{n}(+2\boldsymbol{f_{ci}}) \neq \tilde{n}(-2\boldsymbol{f_{ci}})$
- **ρ = 0.63 – 0.87 ⇒ radially broad: $\Delta R \gtrsim$ 7 cm = $a/6$ ($a = R_{midout} - R_0$)**
  - "≳" *because no measurements* $\rho > 0.87$
  - also, $\Delta R \gtrsim 2\rho_{fast}$



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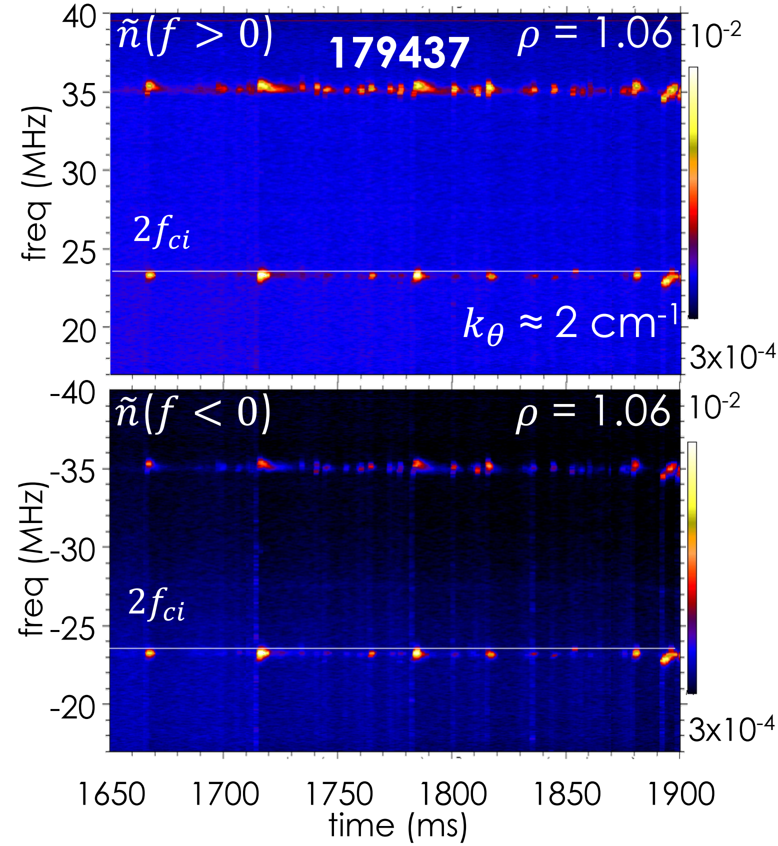
2nd & 3rd harmonic high-k ICE observed in H-mode scrape off layer (SOL)

- **Deuterium H-mode**
  - R_{midout}= 2.27 m, R_0 = 1.73 m
- $\tilde{n}$ **measured at** ρ**=1.06 = SOL**
- $\tilde{n}$ **peaks at ±23,±35 MHz ~ ±** $2f_{ci}$**,**$3f_{ci}$
  - ρ_{fast} ~ 2 cm (species: D)
  - f_{ci} ≈11.8 MHz, v_A ~ 1.2 x 10^7 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_θ **= 2 cm^{-1} ⇒ peak is high-k wave: cyclotron harmonic wave or electrostatic wave**
  - k_θ too large for Alfvén wave: ω/v_A~0.1 – 0.2 cm^{-1}



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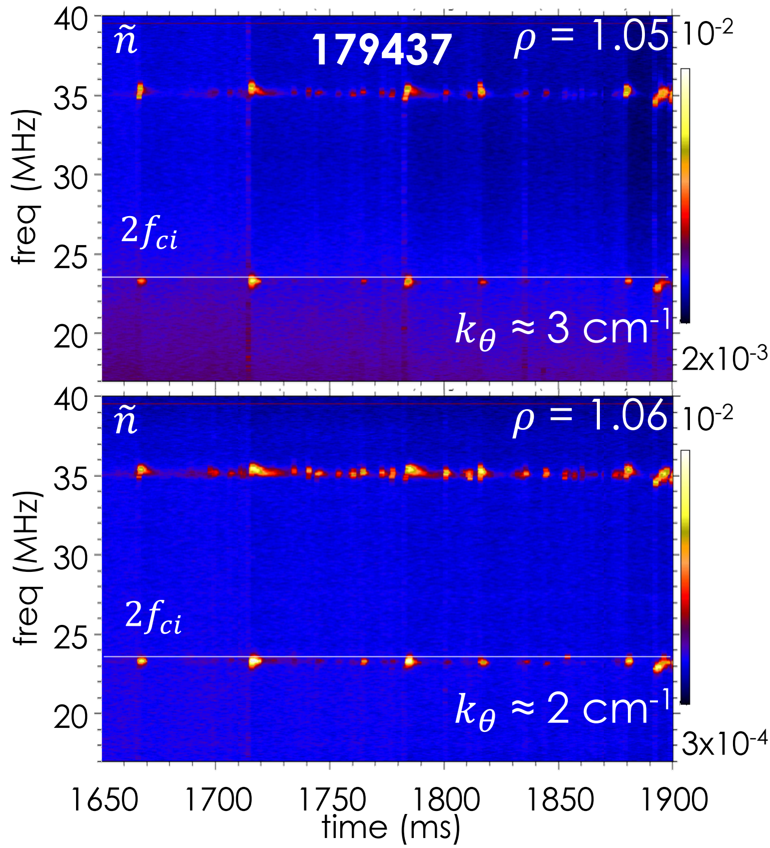
ICE in SOL observed to be radially extended

- $2f_{ci}, 3f_{ci}$ **peaks observed on 2 channels: ρ = 1.05, 1.06**
  - same frequency all channels => "eigenmode" or propagating wave
  - strong peaks at $f = \pm 2\boldsymbol{f_{ci}}$
  - asymmetric power consistent with scattering: $\tilde{n}(+2\boldsymbol{f_{ci}}) \neq \tilde{n}(-2\boldsymbol{f_{ci}})$
- **ρ = 1.05, 1.06 ⇒ $\tilde{\boldsymbol{n}}$ spatially extended: $\Delta R \gtrsim$ 3/4 cm**
  - *"≳" because only 2 channels available*



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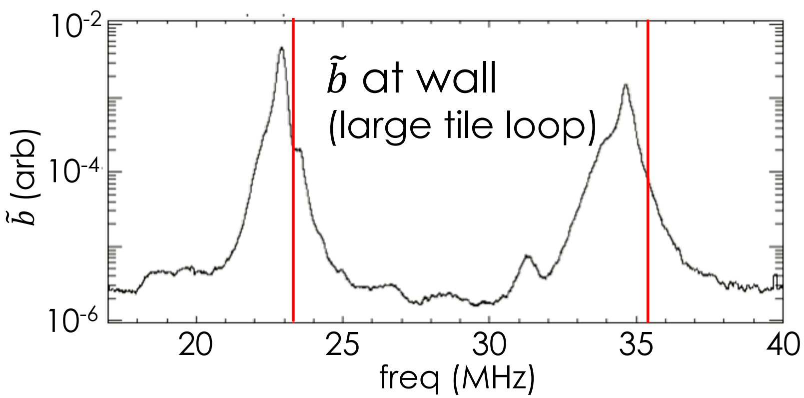
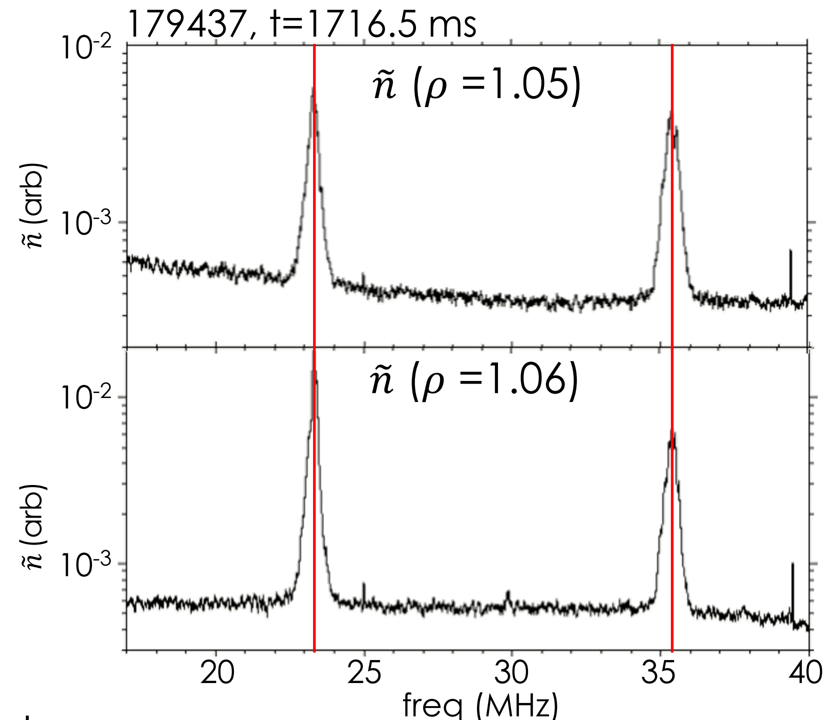
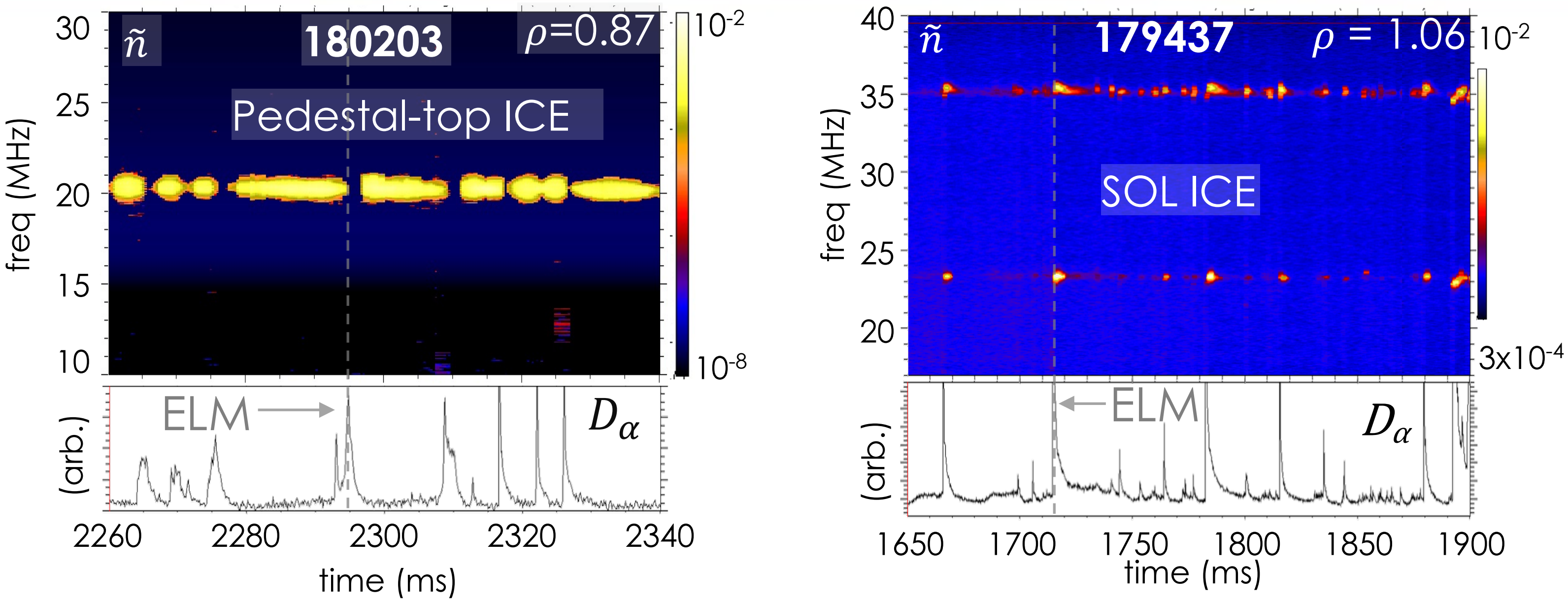
High-K ICE in SOL mode observed by DBS is confined to plasma





- $2f_{ci}$, $3f_{ci}$ **peaks observed in $\tilde{b}$ at wall**
- **$\tilde{n}$ and $\tilde{b}$ don't see same modes**
  - Peaks in $\tilde{b}$, $\tilde{n}$ differ by ~ ½ MHz
  - Tile loop probably sees fast Alfvén waves with long wavelength not detected by DBS: $\lambda = v_A/f \gtrsim$ 50 cm
  - $\tilde{n}$ is high-k wave.
- **$\tilde{n}$ 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_α 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_α spikes) ⇒ consistent with excitation by ejected fast-ions passing through SOL** [S. G. Thatipamula, PPCF 2016],[K. E. Thome, NF 2019]

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Conclusions

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