

Probing Marginally Confined Energetic Ions Using Polarization-Resolved Ion Cyclotron Emission Measurement in KSTAR

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Acknowledgements

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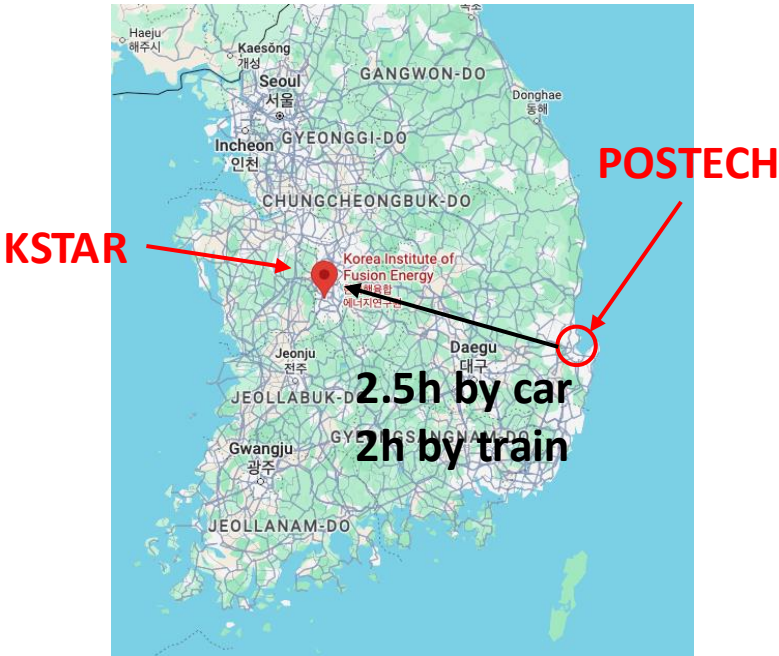
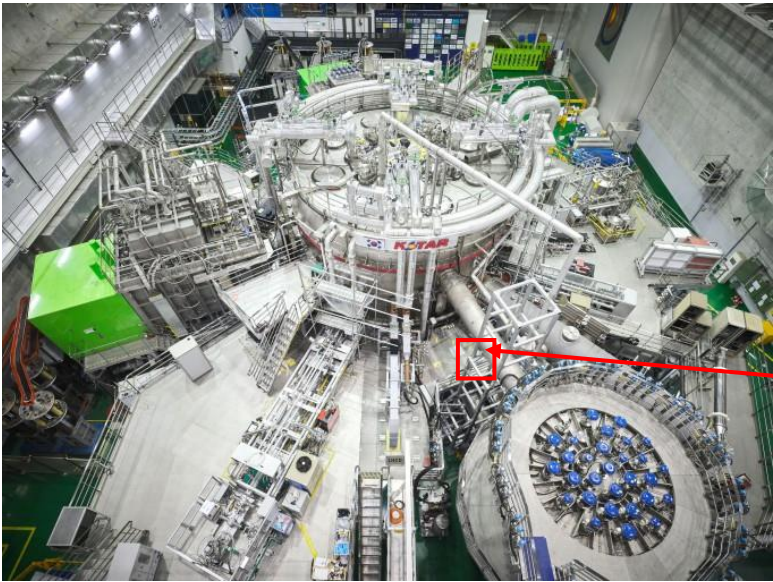


QST : Andreas Bierwage

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- I. **Energetic-particle diagnostics** for future fusion plasmas
- II. **Ion Cyclotron Emission(ICE)** as an energetic-particle diagnostic
- III. Polarization-resolved ICE measurement in KSTAR Experiment
- IV. ICE-based energetic-ion inference and comparison with other diagnostics
- V. Summary and outlook

KSTAR Tokamak

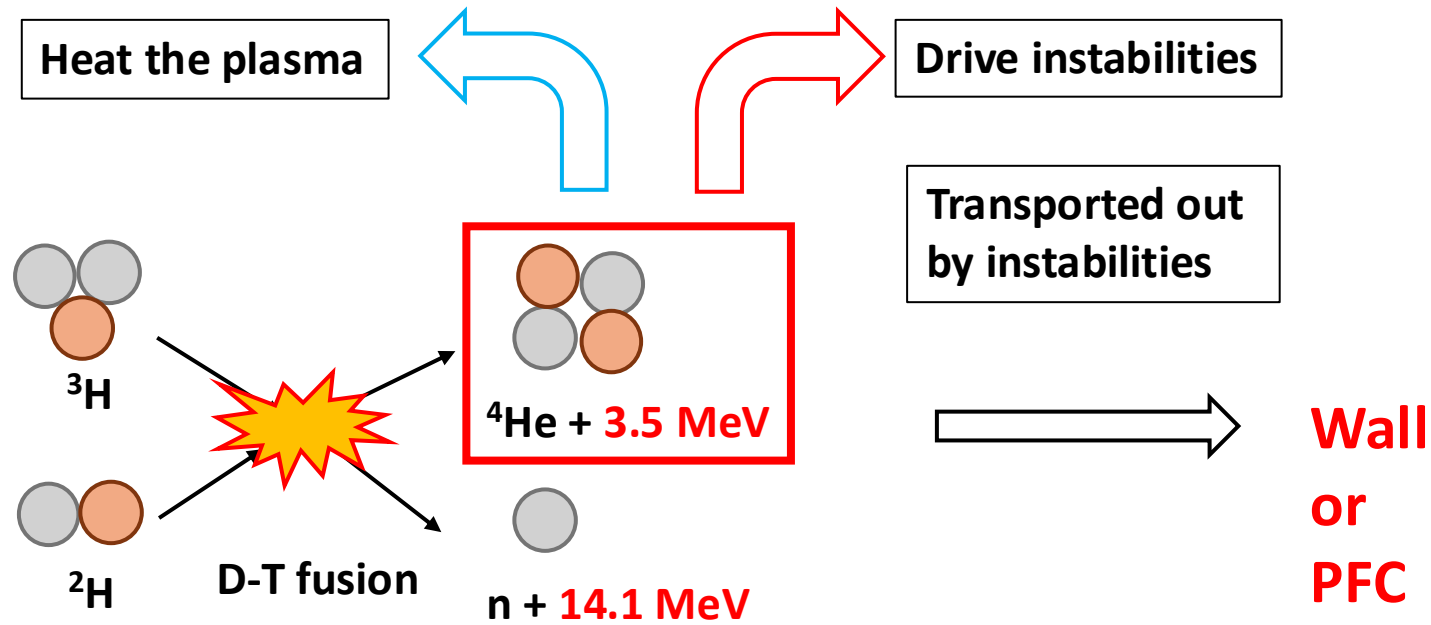


- Major radius : 1.8m, Minor radius : ~0.5m
- Operation : 2008 - Present
- B field strength : up to 3.5T @ 1.8m
- Heating power : 10MW (2 NBI, 4ECH)
- Major, height : Physics, 1.8m (😊 kg)
- Operation : 2000 – present
- Strength : Deadlift 100kg 🤖

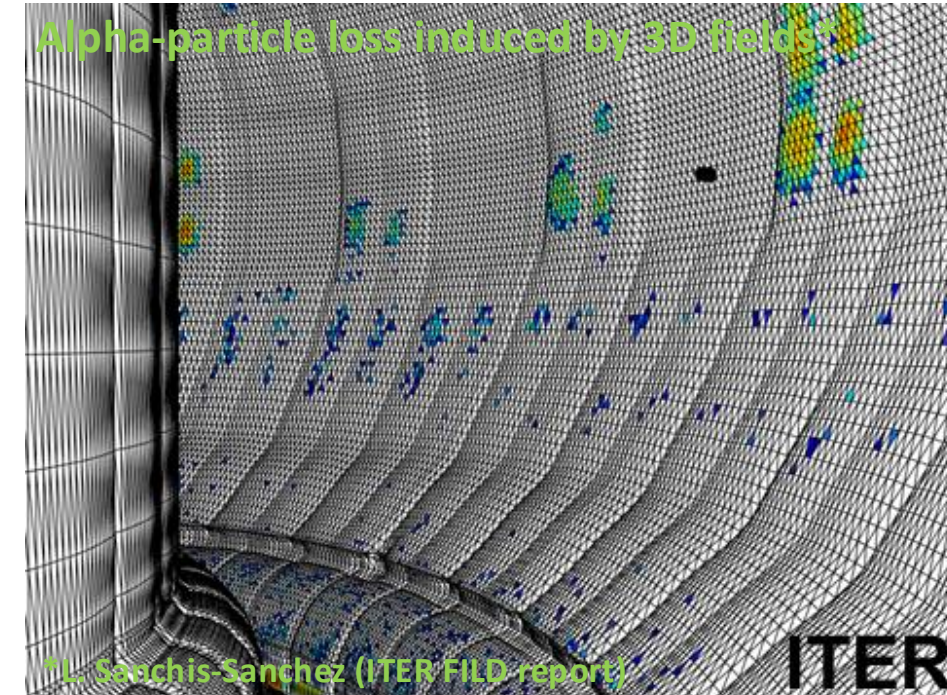


I. Energetic-particle diagnostics for future fusion plasmas

Energetic particles in a fusion plasma



- Helium born at 3.5 MeV, 1.3×10^7 m/s, 4% of light speed
- Confined in a tokamak by strong magnetic fields
- Heat the plasma by collisions



Energetic particles

- 😊 • Heat the plasma by collisions
- 😱 • Drive instabilities
- 😱 • Transported out by instabilities
- 😱 • PFC degradation

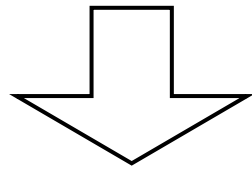
Why diagnostics is difficult in future fusion devices

Harsh Operating Environment :

- High neutron flux
- High radiation levels
- Strong magnetic field
- High heat loads

Reliability and robustness :

- Maximizing machine availability
- Minimizing maintenance downtime

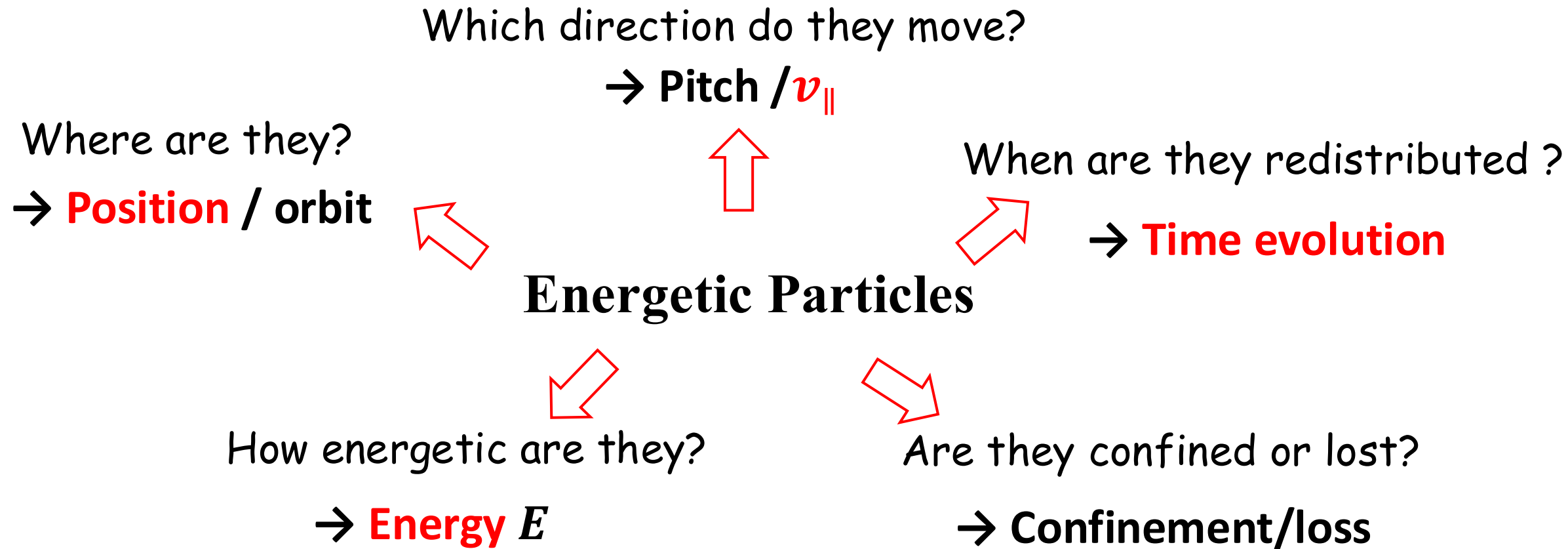


Robust and reliable diagnostics are essential for fusion devices



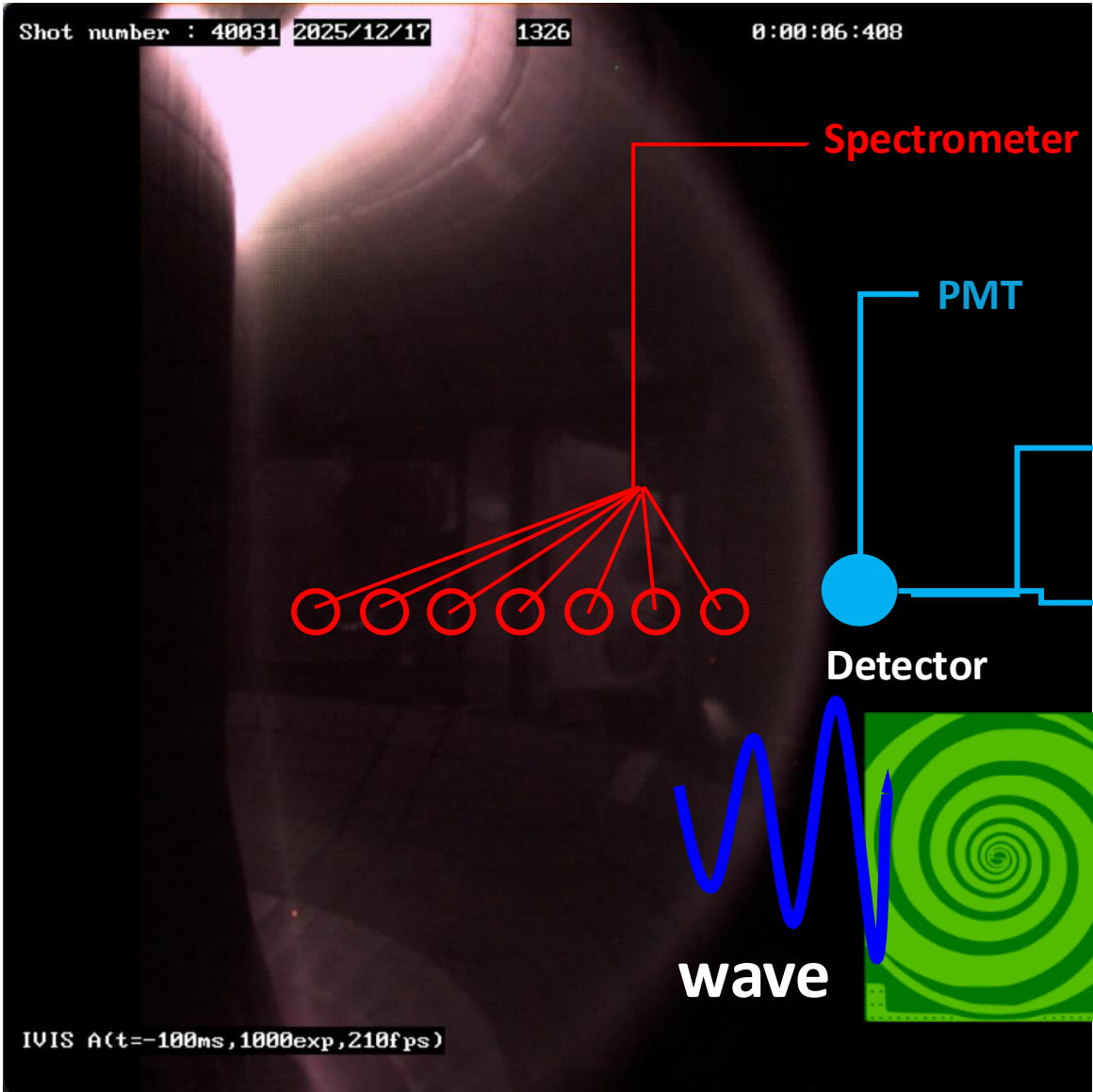
KSTAR PFC damage

What do we need to measure about energetic particles?



→ A Useful EP diagnostic should provide information on energy, pitch, location, and redistribution

EP diagnostics and where RF fits



Diagnostics	Typical information
-------------	---------------------

→ **FIDA** : Velocity-space / fast-ion distribution

→ **FILD** : Escaping fast ions

**Neutron
gamma** : Fusion-product
energetic-ion reaction signatures
In progress

→ **NPA** : Energetic neutral / ion information
In progress

→ **RF** : fast temporal response, wave/EP interaction,
Passive measurement

II. Ion Cyclotron Emission(ICE) as an energetic-particle diagnostic

RF Diagnostics

❑ Non-invasive, easy-to-install, small foot-print, **radiation tolerant**, cost-efficient

→ **suitable for burning plasma diagnostics**

❑ Broadband and fast-wave detection:

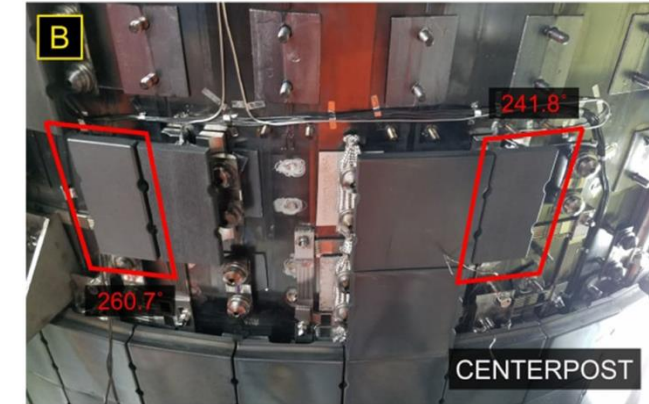
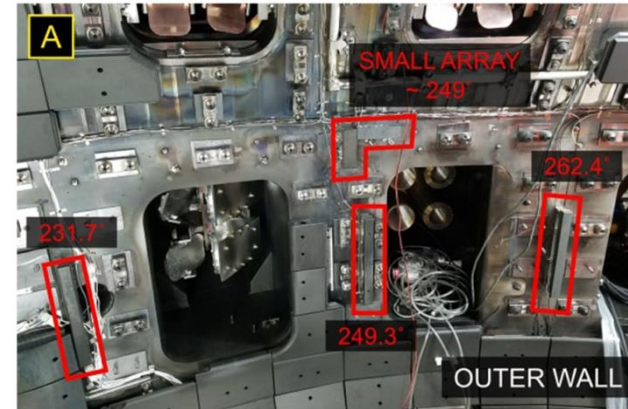
❑ EP-driven Alfvén waves

❑ Ion-cyclotron harmonic emissions (ICEs)

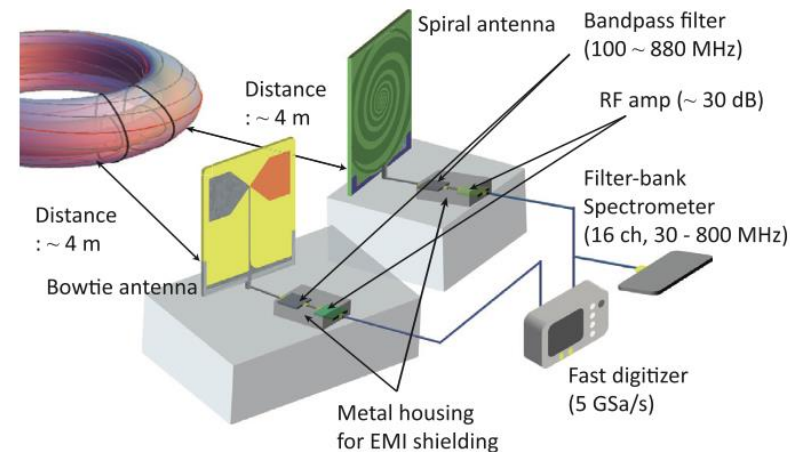
❑ RE-driven Whistler waves

❑ MHD activity

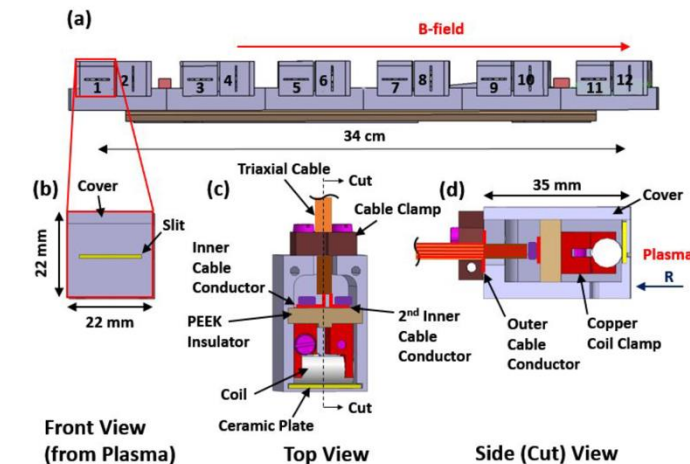
❑ Several antenna configurations:
conducting loops, dipole antennas,
spiral antennas, B-dot probes



In-vessel loop installed in DIII-D*



Broadband RF diagnostics system in KSTAR**



In-vessel B-dot probe installed in ASDEX-U***

*G.H. Degrandchamp et al., RSI 2021

** M.H. Kim et al., NF 2018

*** R. Ochoukov et al., RSI 2015

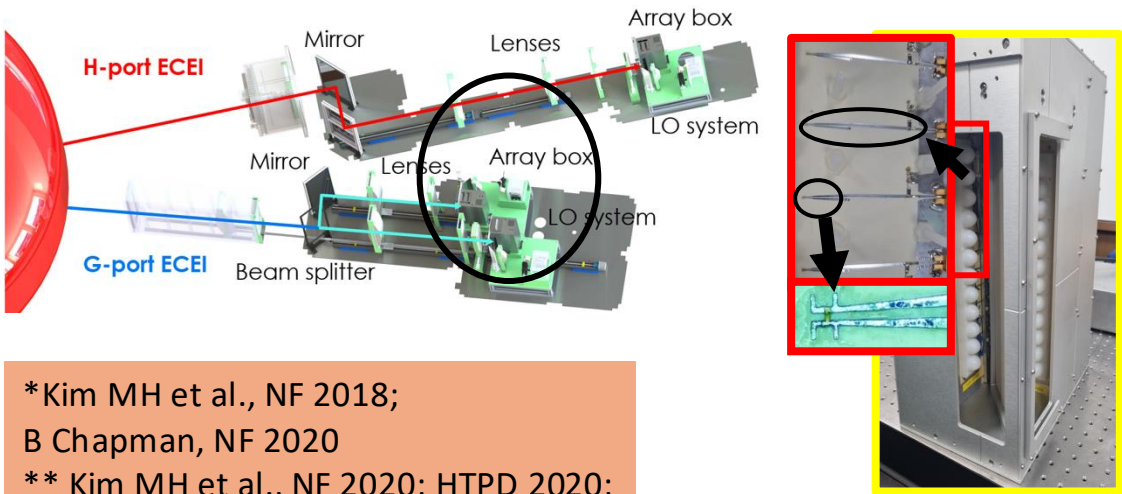
KSTAR RF Diagnostics

KSTAR

(1) Broadband spiral antenna (0.1-0.88 GHz)*

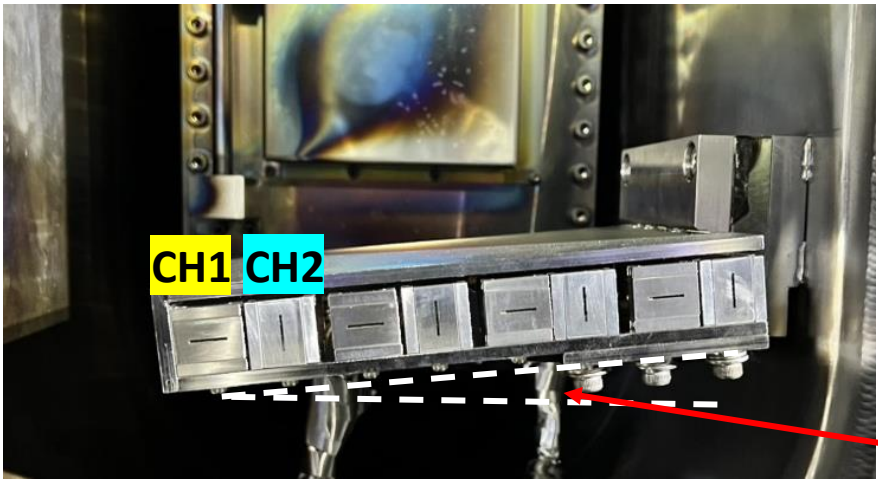


(2) mm-wave antenna array (0.5-6.5 GHz)**

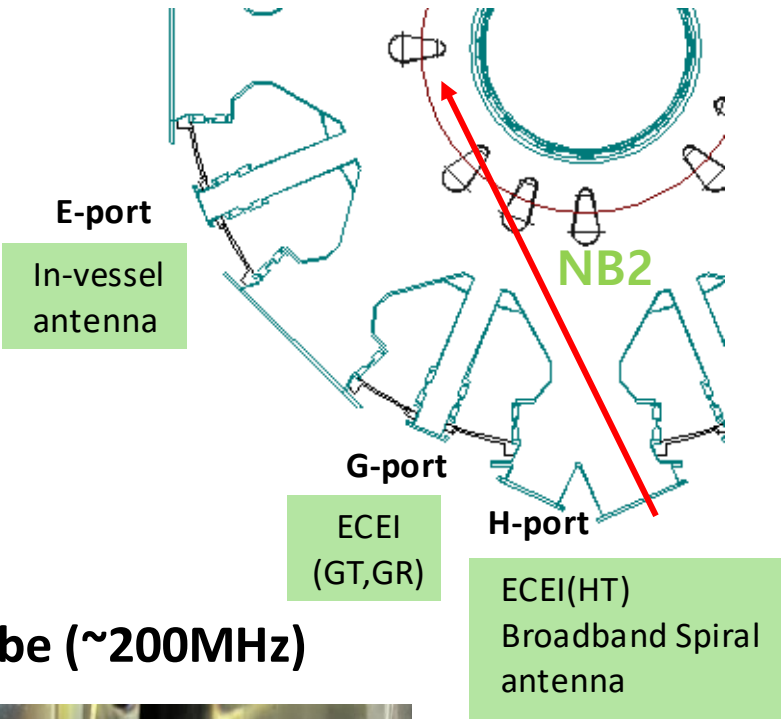


*Kim MH et al., NF 2018;
B Chapman, NF 2020
** Kim MH et al., NF 2020; HTPD 2020;
Kim DG et al. RSI 2024

(3) In-vessel B-dot probe (~200MHz)

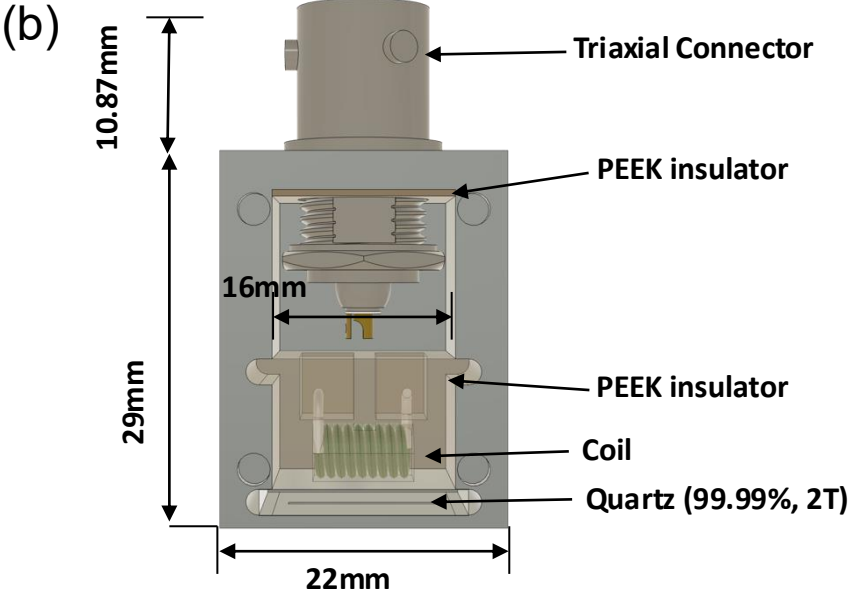
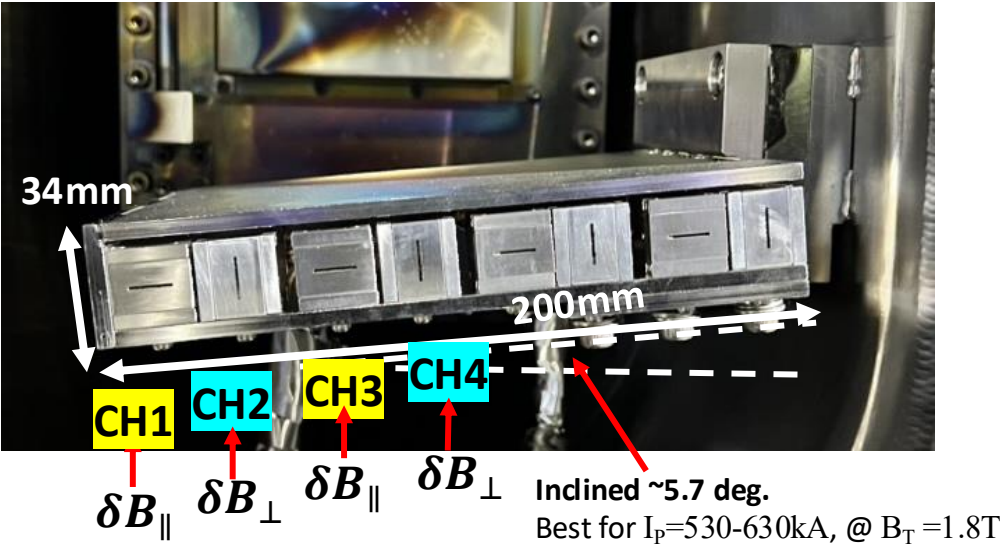


(Best for $I_p = 530-630$ kA, @ $B_T = 1.8$ T)

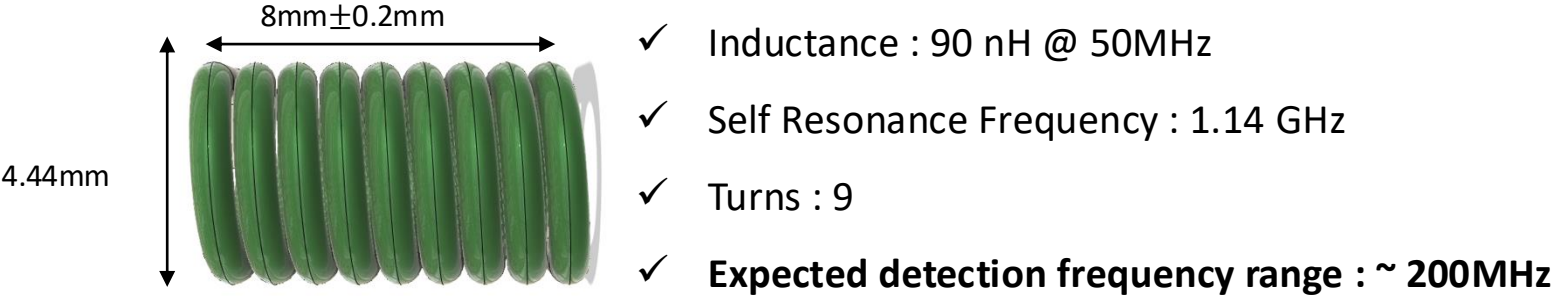


Inclined ~5.7 deg.

In-vessel B-dot probe array in KSTAR

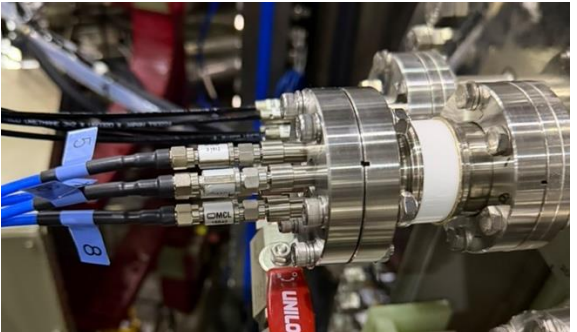
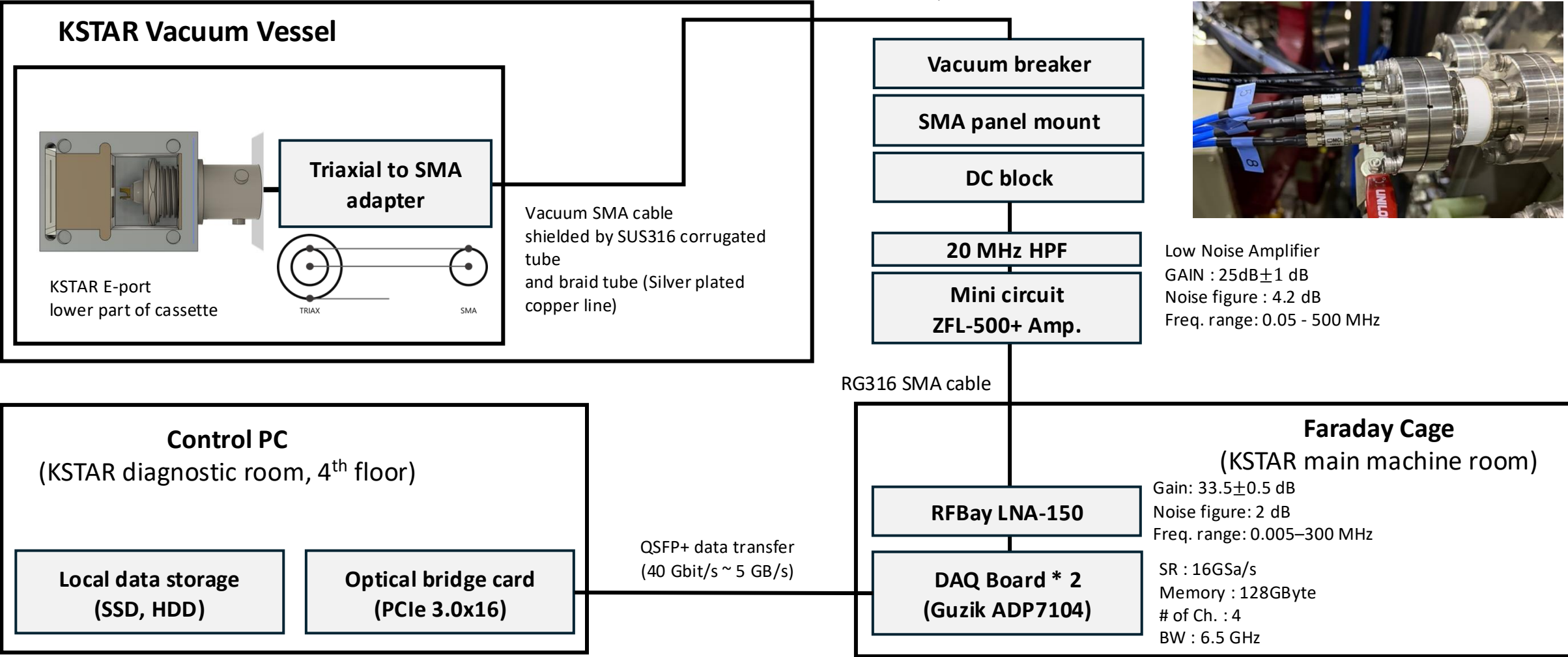


- The B-dot arrays focus on **RF emissions below 200 MHz**, including **low-harmonic ICE** and Alfvén waves.
- By comparing the phase between channels in each direction, wave **properties** can be analyzed.



S.Hong et al., HTPD 2026, RSI (Under Review)

DAQ Schematic In-vessel B-dot probe



S.Hong et al., HTPD 2026, RSI (Under Review)

Ion Cyclotron Emission

- ❑ In a magnetized plasma, energetic ions gyrate at:

$$f_{ci} = \frac{zq_i B}{2\pi m_i} \quad \rho_L = \frac{m_i v_{\perp}}{zeB}$$

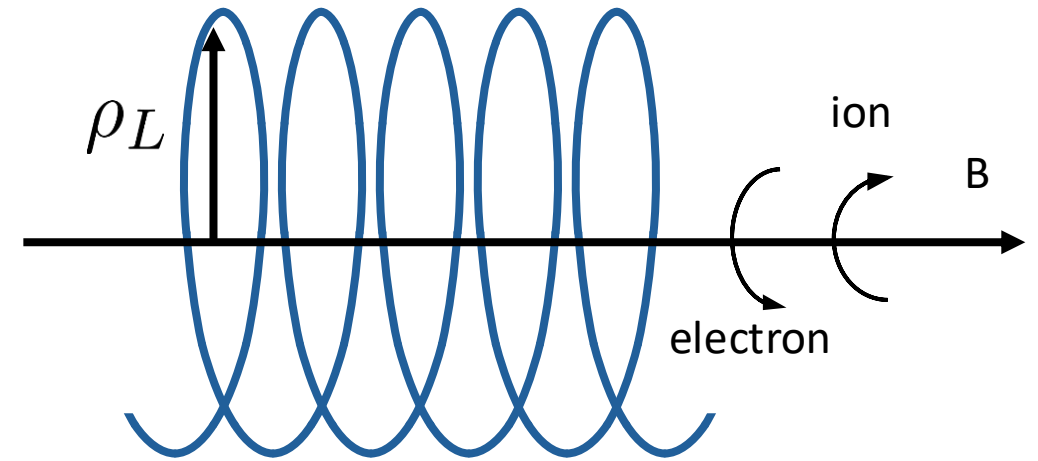
- ❑ When the **resonance** condition is satisfied,

$$\omega - k_{\parallel} v_{\parallel} = n\Omega_{ci} \quad (n = 1, 2, \dots)$$

EM waves are emitted near resonance.

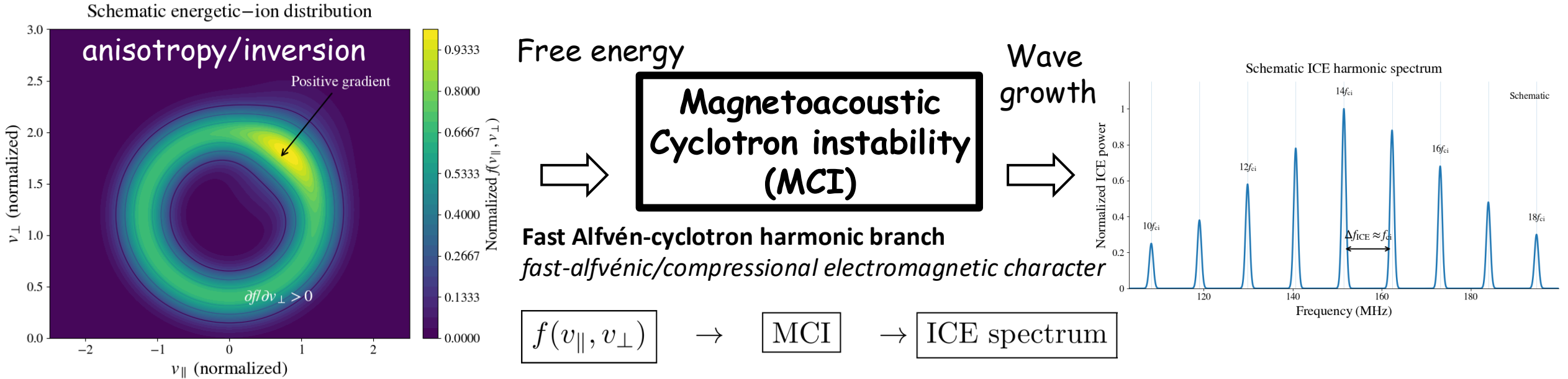
- ❑ $P_{ICE} \propto |J_n(k_{\perp} \rho_L)|^2$, and growth requires $\frac{\partial f}{\partial v_{\parallel}} > 0$ or $\frac{\partial f}{\partial v_{\perp}} > 0$ (anisotropy/inversion).

- ❑ **Free energy (anisotropy/inversion) → wave growth → spontaneous emission → ICE**



* D'Inca, Rodolphe. *Ion cyclotron emission on ASDEX Upgrade*. Diss. Imu, 2014.

From energetic ions to diagnostic information in ICE



What can we learn from ICE?

Harmonic spacing

$$\Delta f_{\text{ICE}} \sim f_{ci}$$

→ Species / local B
→ Candidate emission region

Phase/Polarization

$$\Delta \phi / \Delta r \rightarrow k$$

→ Propagation
→ Wave properties

Doppler-Shifted resonance

$$\omega - k_{\parallel} v_{\parallel} = l \omega_{ci}$$
$$\Rightarrow v_{\parallel} \rightarrow E_{\parallel}$$

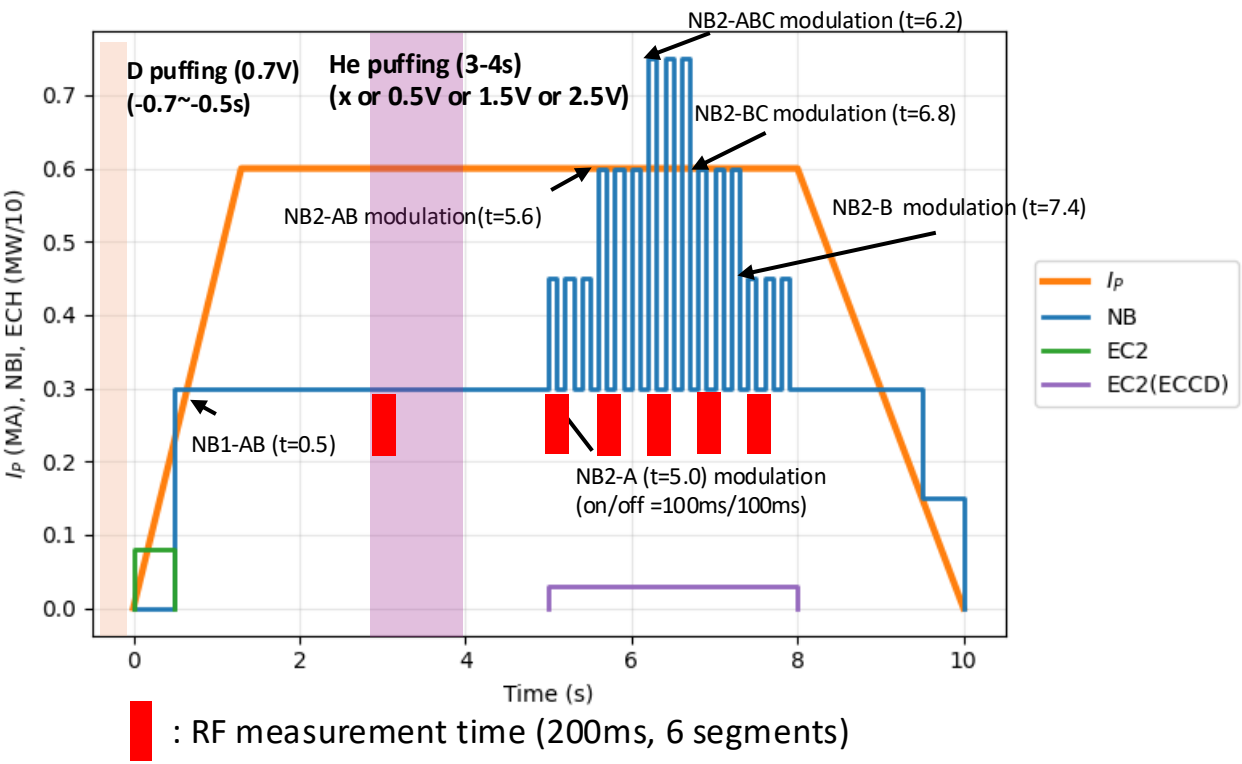
Spectrum intensity

→ sensitive to EP distribution / composition

Dendy et al., Phys. Fluids 1993
B. S. Schmidt et al. POP 2023
Cook et al. PPCF 2013
O. Samant et al. NF 2024

III. Polarization-resolved ICE measurement in KSTAR Experiment

KSTAR experimental scenario

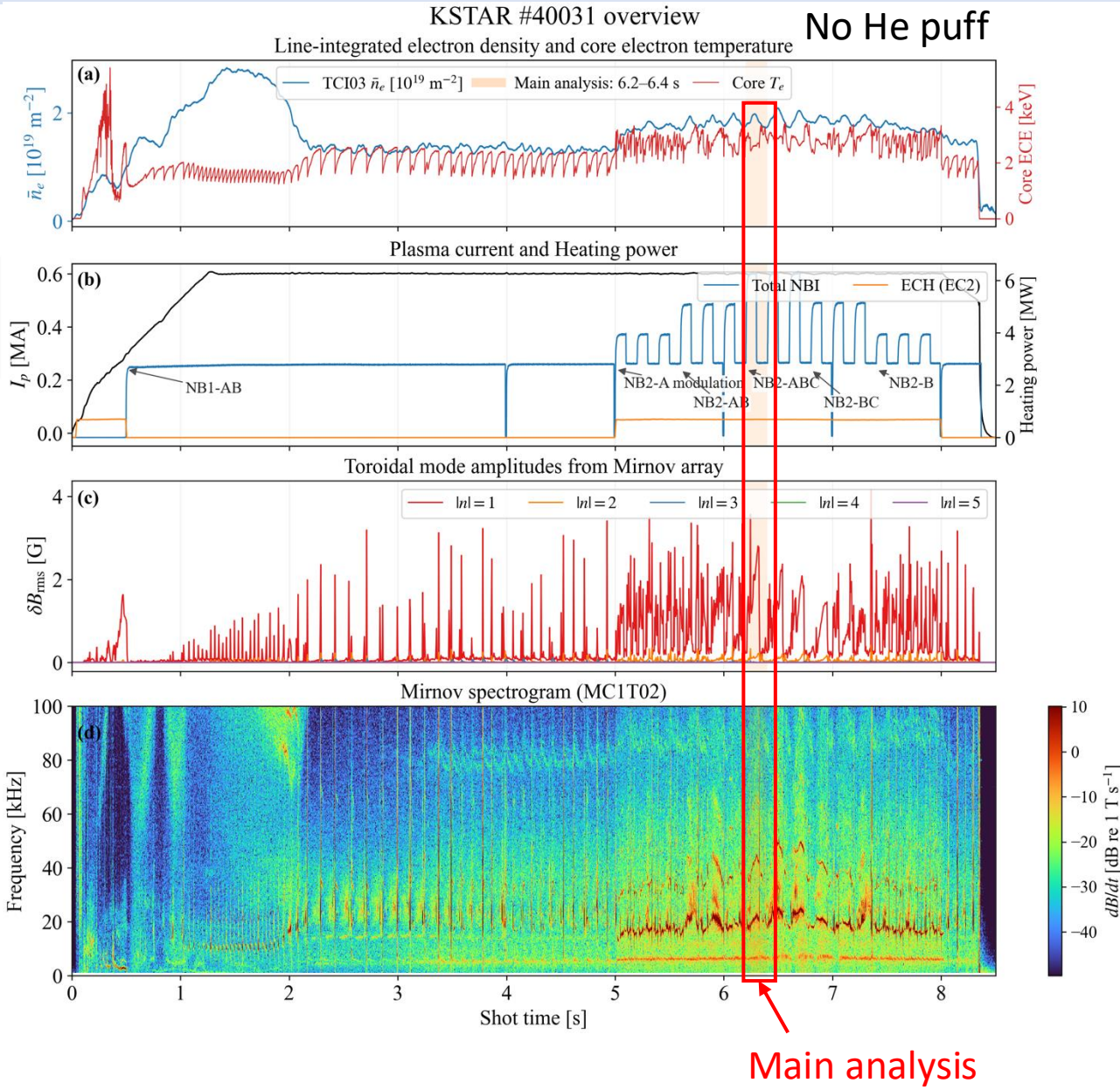


Experimental condition

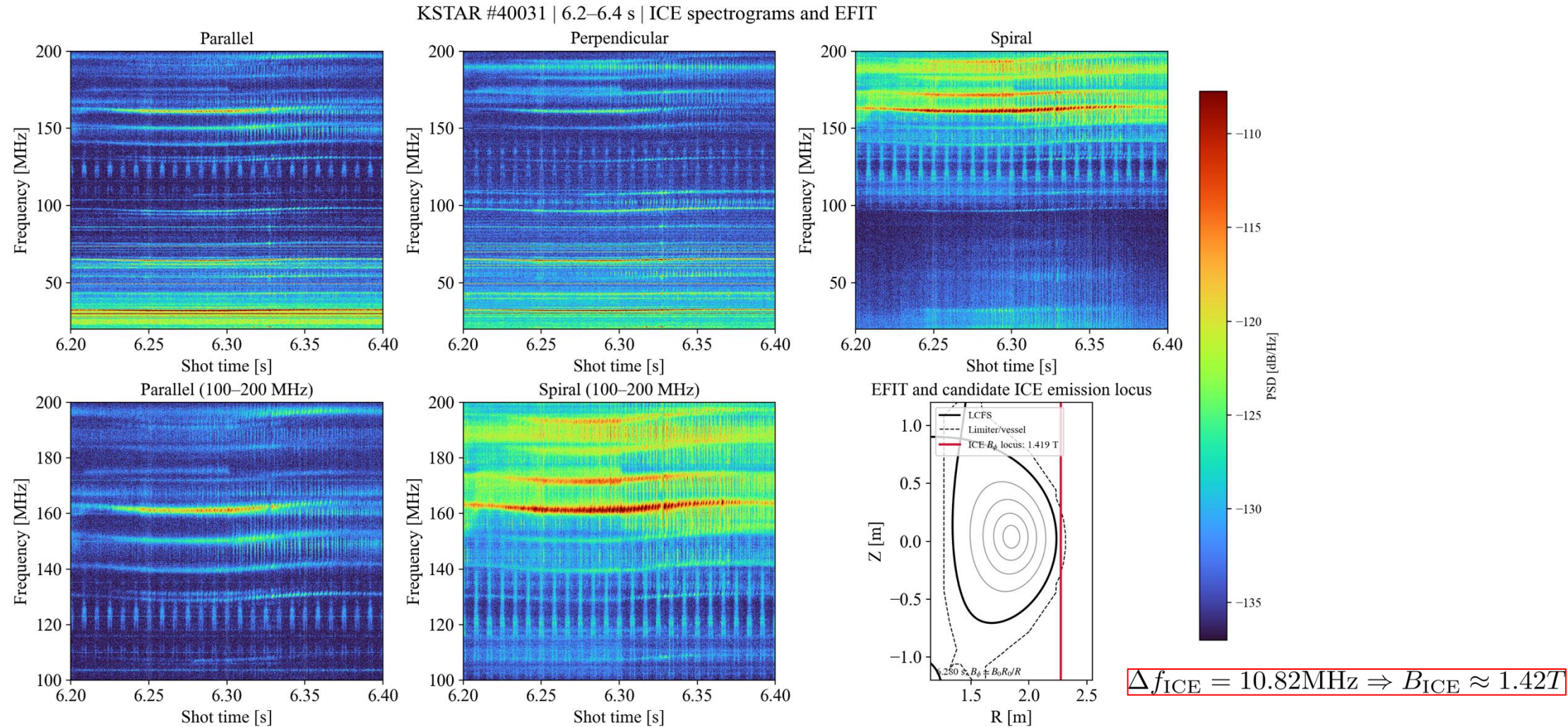
- $B_T = 1.8T$ at 1.8m
- NB1 energy [A,B]=[80keV, 80keV]
- NB2 energy [A,B,C]=[70keV or 60keV]
- Upper Single Null
- 100/100ms NB ON/OFF modulation

Control parameter

- # of ion sources
- He gas-puff level
- NB2 beam energy

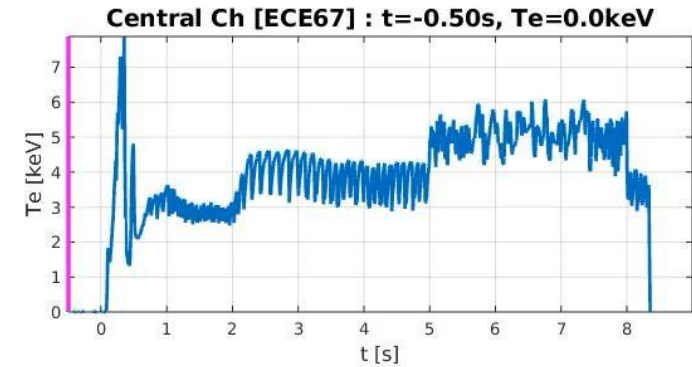
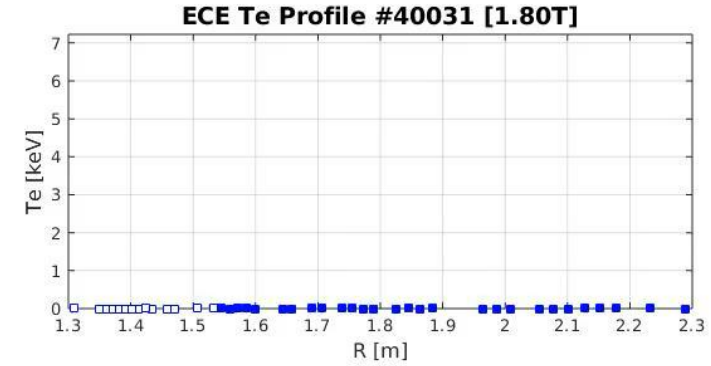
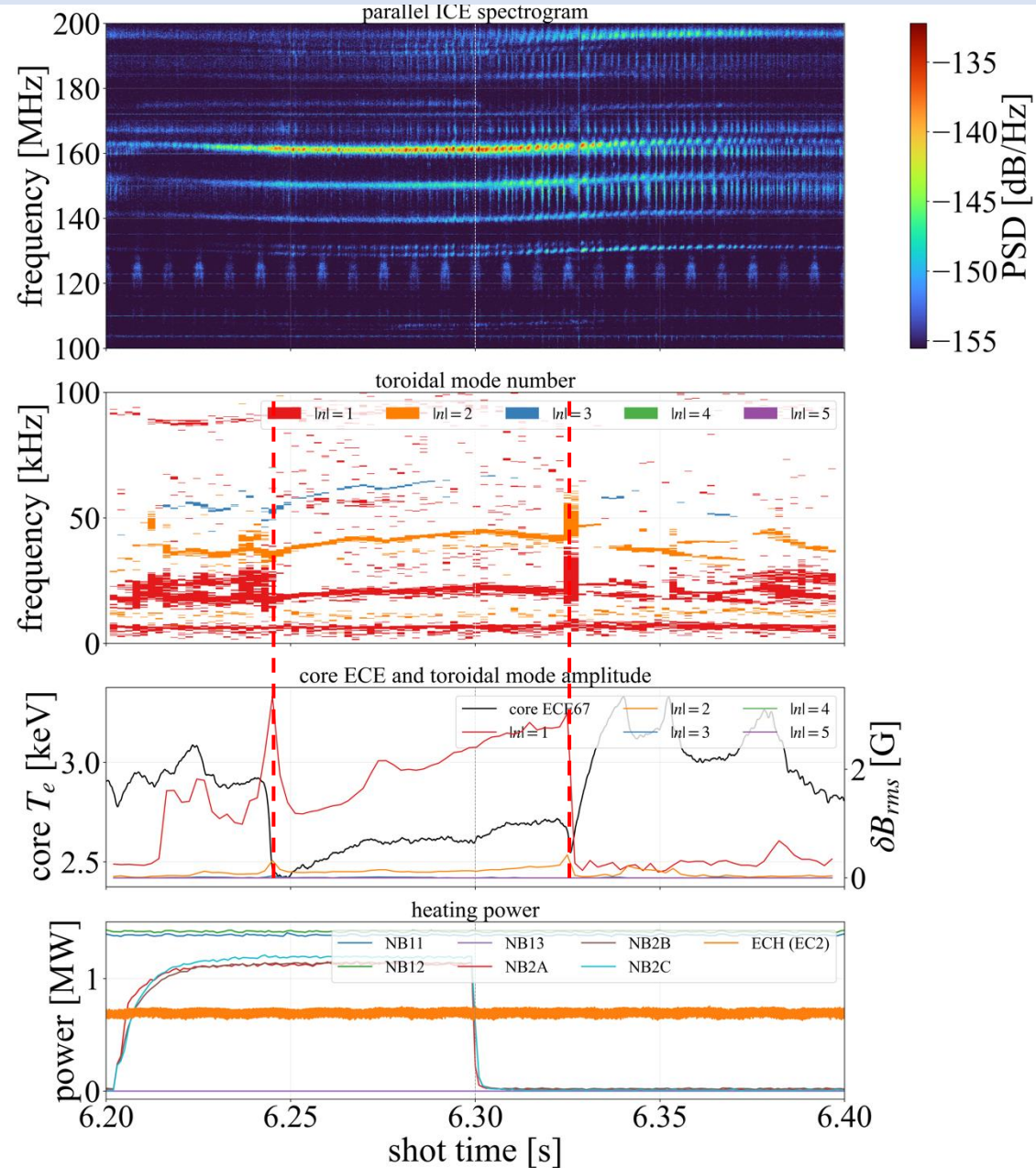


ICE observation in KSTAR with the In-vessel B-dot probe



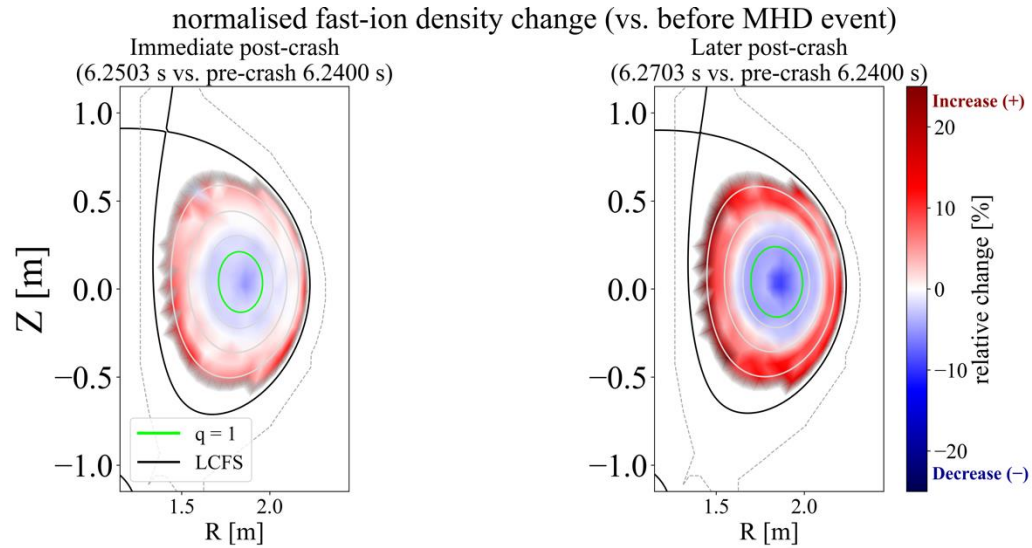
- Harmonic structures are simultaneously observed by the **in-vessel B-dot probe** and the **external spiral antenna**.
- The harmonic spacing, $\Delta f_{ICE} = \mathbf{10.82 \text{ MHz}}$, corresponds to a candidate source region near the LCFS.

ICE response associated with n=1 MHD activity / core-ECE events

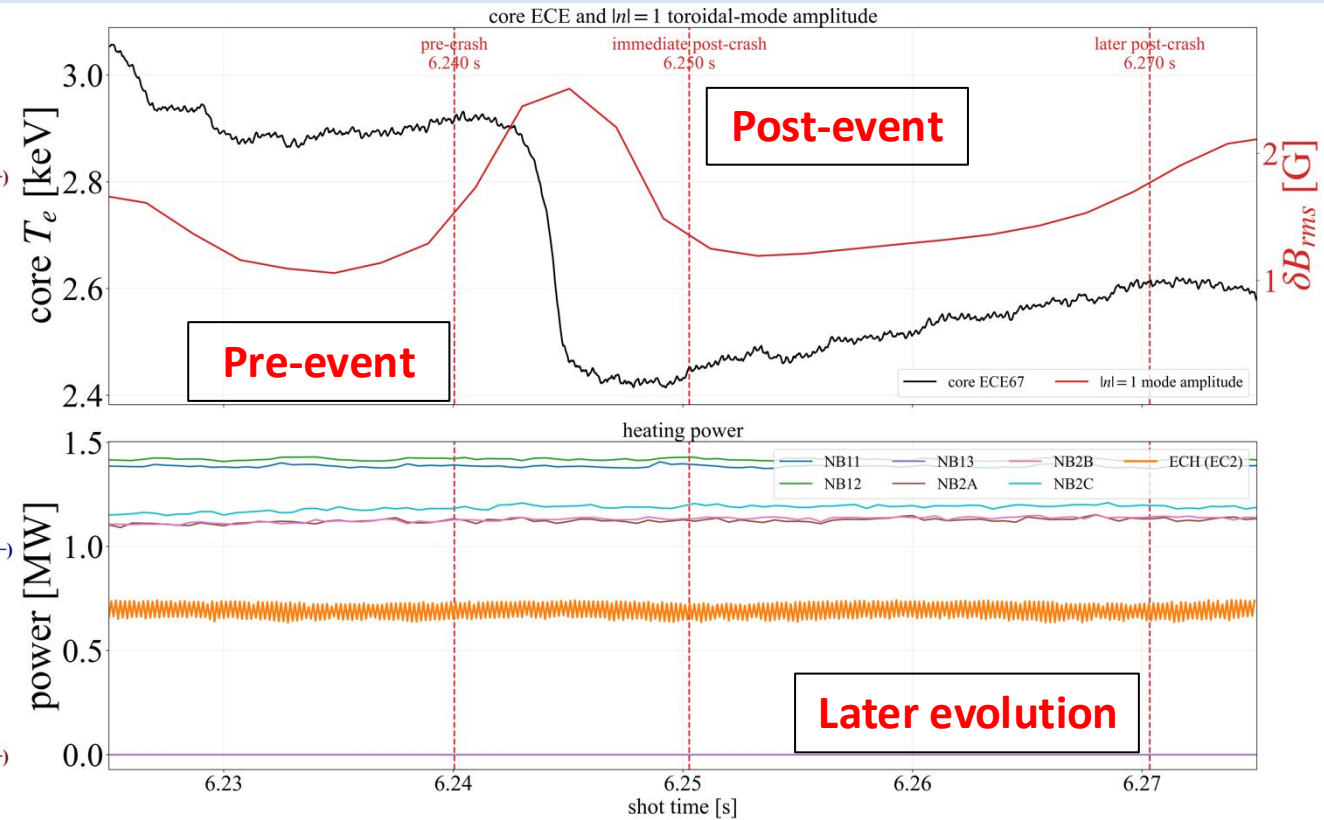
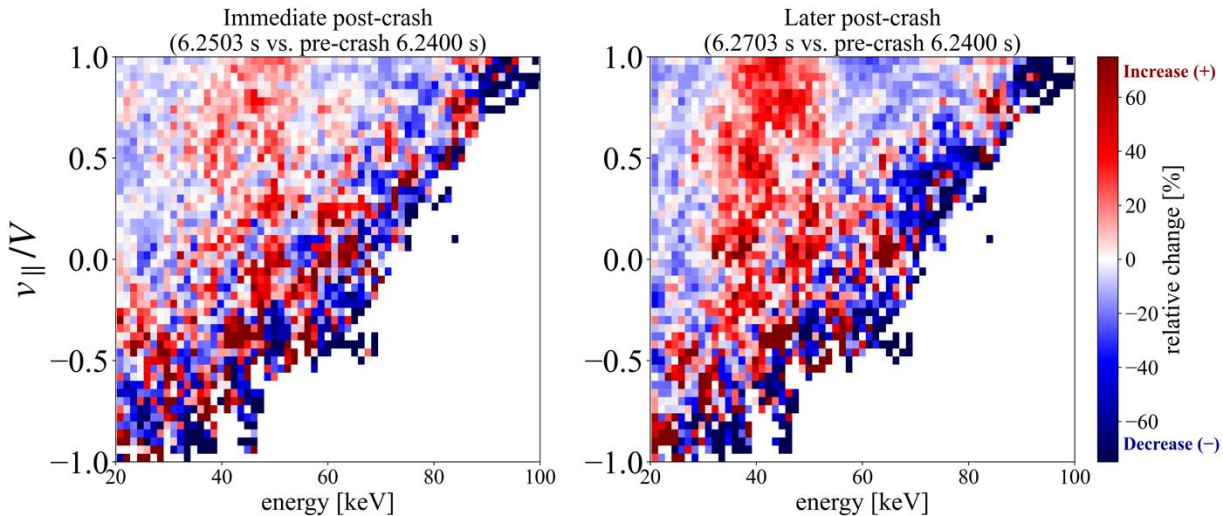


- Strong **n=1 MHD** activity + rapid Core-ECE drops.
 - Enhanced / **bursty ICE harmonics**
- Motivation : **fast-ion redistribution**

TRANSP inferred fast ion redistribution across the n=1 MHD event



normalised q=1-local phase-space change (vs. before MHD event)

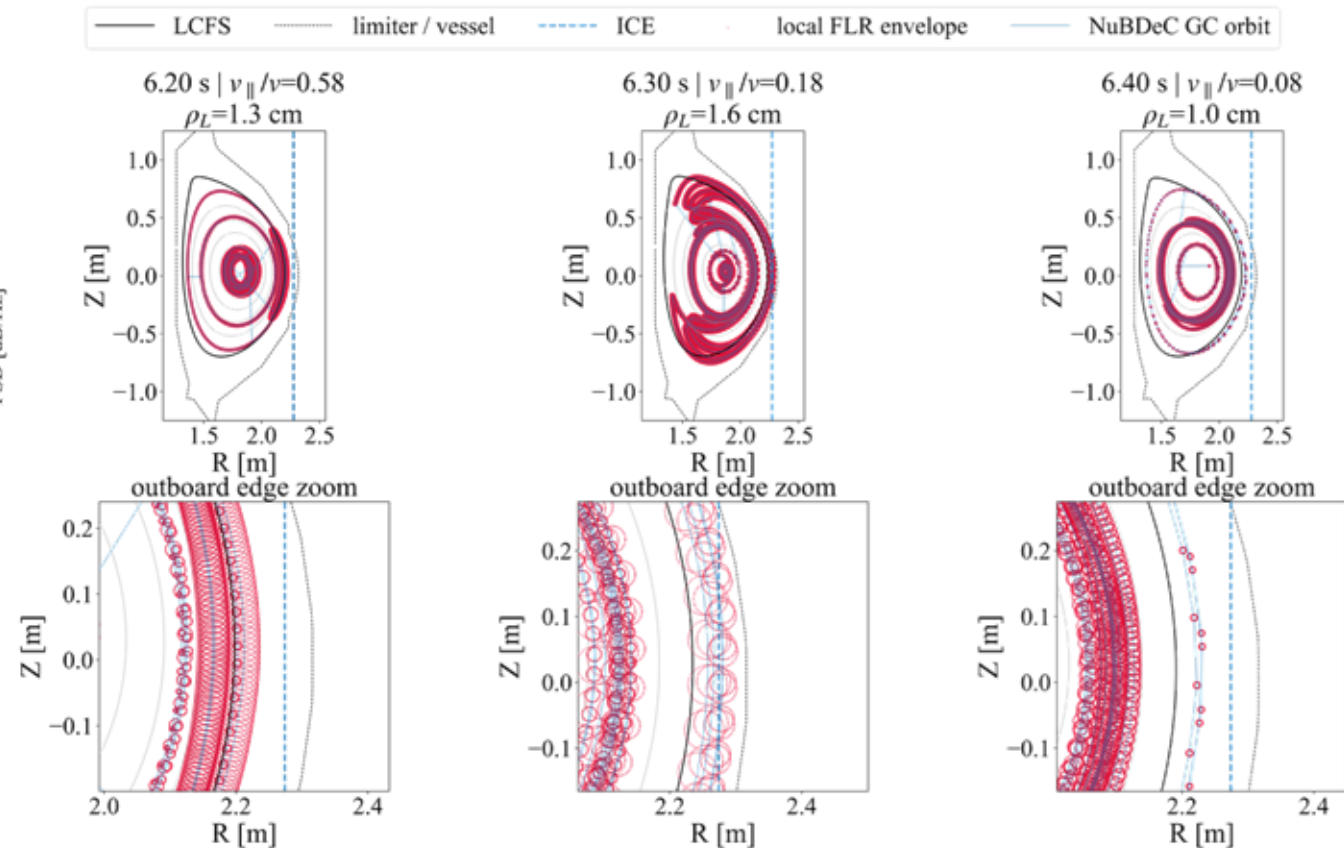
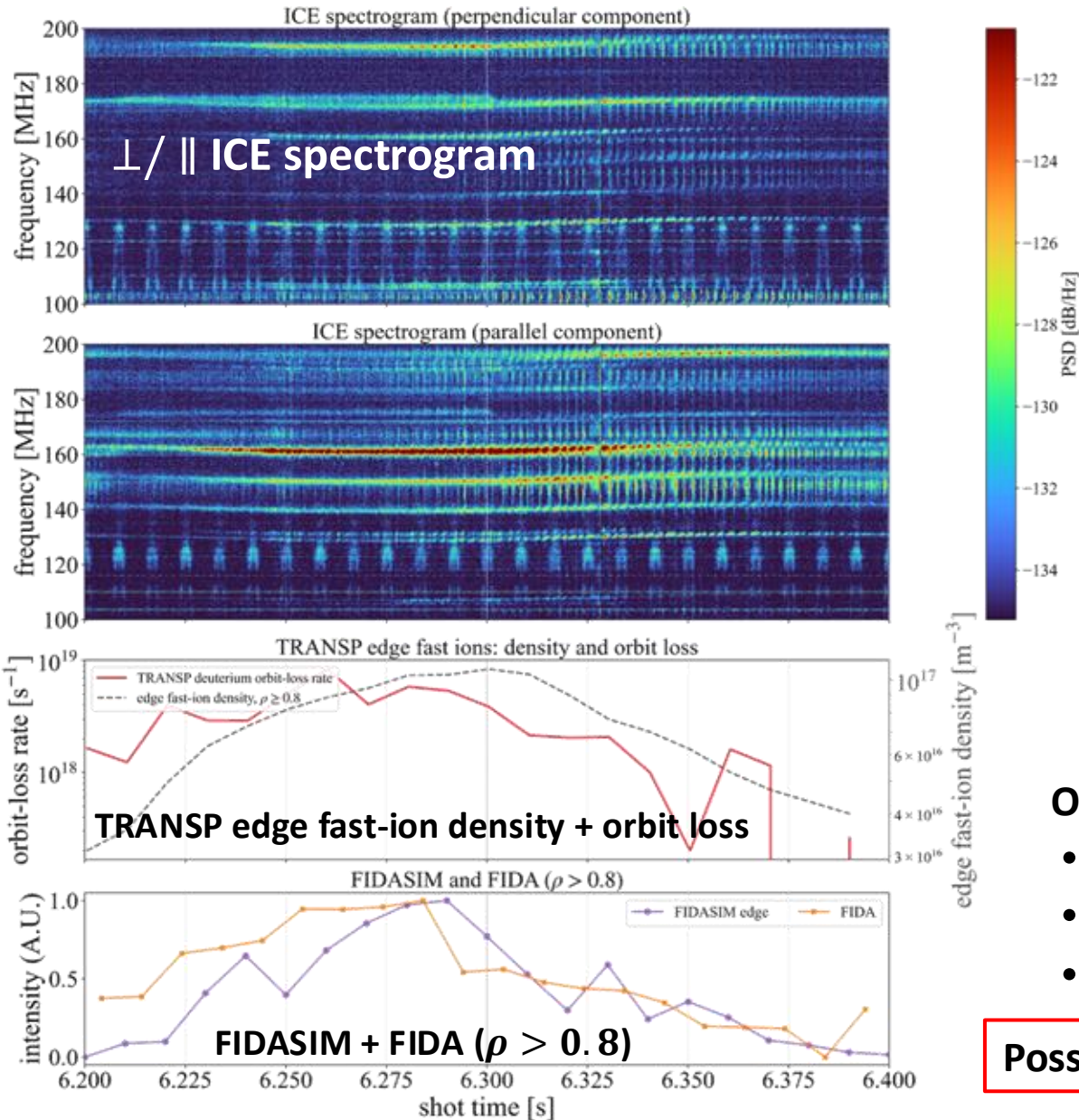


- Fast-ion density redistribution
- Energy-pitch phase-space redistribution
- Heating power $\sim$ unchanged

→ Consistent with MHD-induced fast-ion redistribution

Cross-comparison of ICE with edge fast-ion and orbit modeling

NuBDeC : orbit topology near the plasma edge

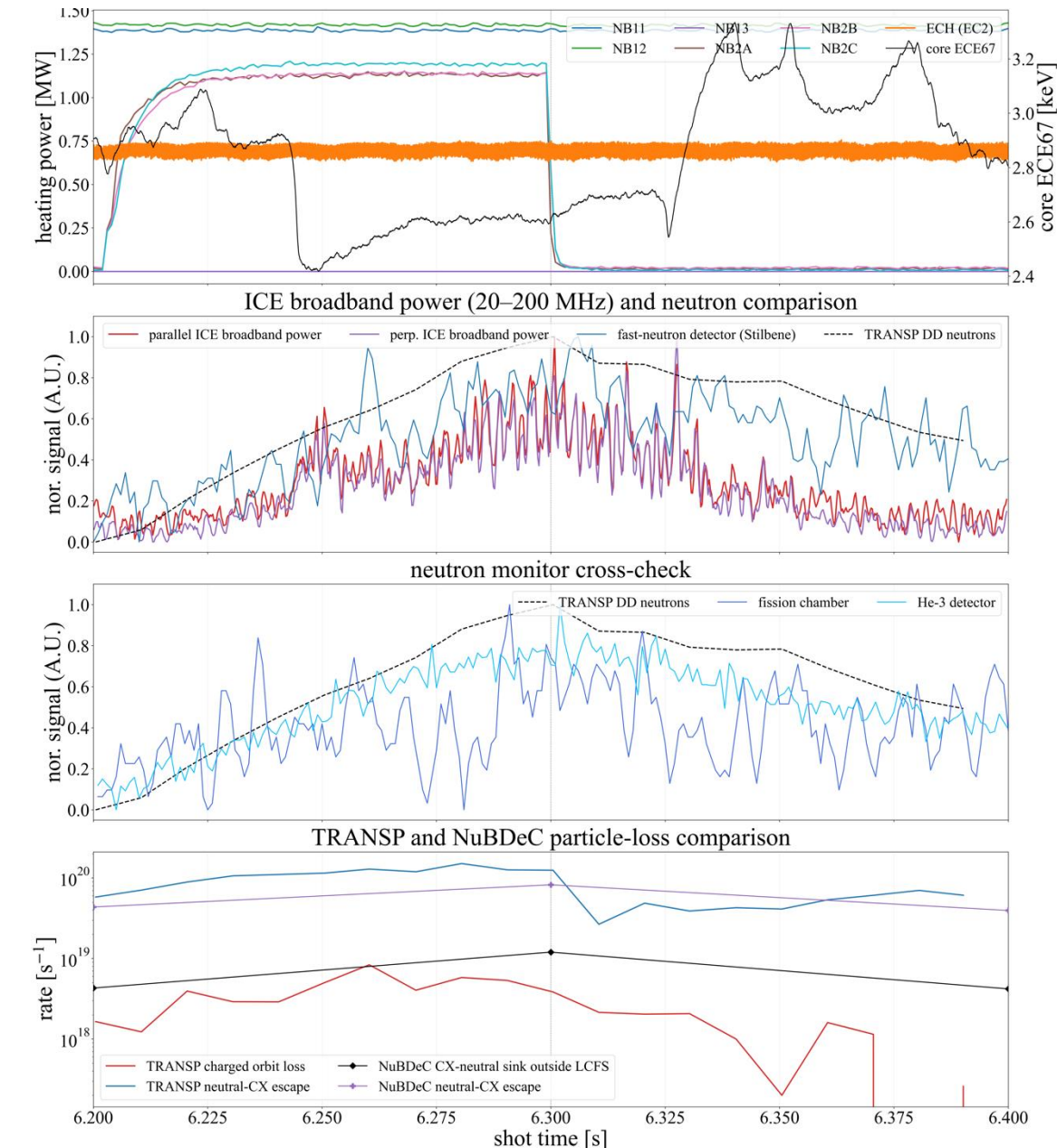


Orbit evolution: confined $\rightarrow$ edge-reaching $\rightarrow$ marginal / loss-related

- ICE enhancement
- Edge fast-ion response in TRANSP / FIDA
- NuBDeC orbit trajectories approaching the plasma edge

Possible contribution from marginally confined / loss-related fast ions

Temporal comparison of ICE and fast-ion loss-related quantities



Observations

- ICE broadband power ↔ neutron signal
→ confined fast-ion response / cross-check
- TRANSP / NuBDeC orbit-loss estimates
- Neutral-CX escape / edge-crossing channels
→ complementary constraints on loss-related populations

Interpretation

MHD-induced redistribution



Edge / marginally confined ions



ICE excitation



Possible fast-ion loss

ICE excitation ↔ ? loss-related population

IV. ICE-based energetic-ion inference and comparison with other diagnostics

Ion Cyclotron Emission analysis

1. Spatial phase → wavenumber

$$\Delta\phi_{ij} = \arg[S_{ij}(f, t)]$$

$$\Delta\phi_{ij} = \mathbf{k} \cdot (\mathbf{r}_i - \mathbf{r}_j) \quad (\text{mode } 2\pi) \quad \text{Same polarization channel}$$

$$\Delta\phi = k_{\parallel} \Delta r_{\parallel} + k_{\perp} \Delta r_{\perp}$$

Cross-phase + coherence → accepted k samples

2. Harmonic spacing + Doppler resonance → energetic-ion information

$$\Delta f_{\text{ICE}} \rightarrow B_{\text{ICE}} \rightarrow B_{\text{ICE}} \simeq \frac{2\pi m_D \Delta f_{\text{ICE}}}{e}$$

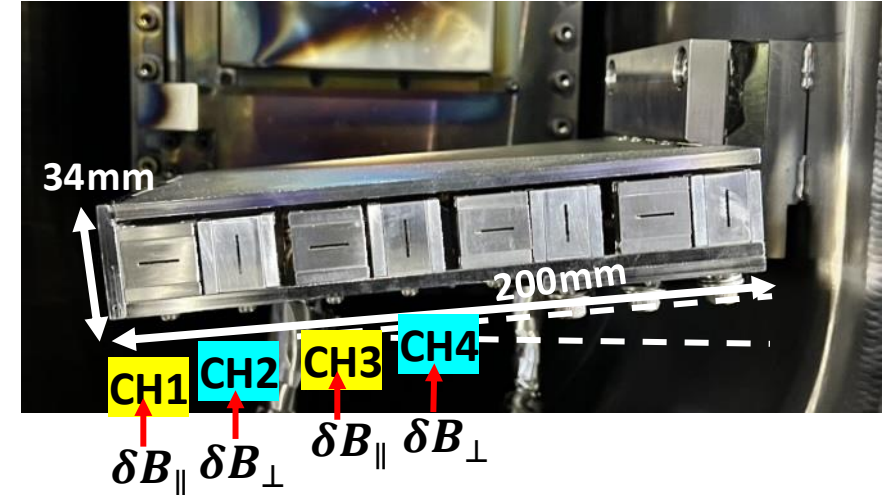
$$\omega - k_{\parallel} v_{\parallel} = l \Omega_{ci}$$

$$v_{\parallel} = \frac{\omega - l \Omega_{ci}}{k_{\parallel}} \quad E_{\parallel} = \frac{1}{2} m_D v_{\parallel}^2$$

$$f_{\text{ICE}} \rightarrow B_{\text{ICE}} : f_{\text{ICE}} + k_{\parallel} + B_{\text{ICE}} \rightarrow v_{\parallel} \rightarrow E_{\parallel}$$

 (inferred quantities)

 (measured by RF diagnostics)



3. Wave dispersion → density proxy

Assuming fast/compressional-wave dispersion

$$\omega \simeq k v_A$$

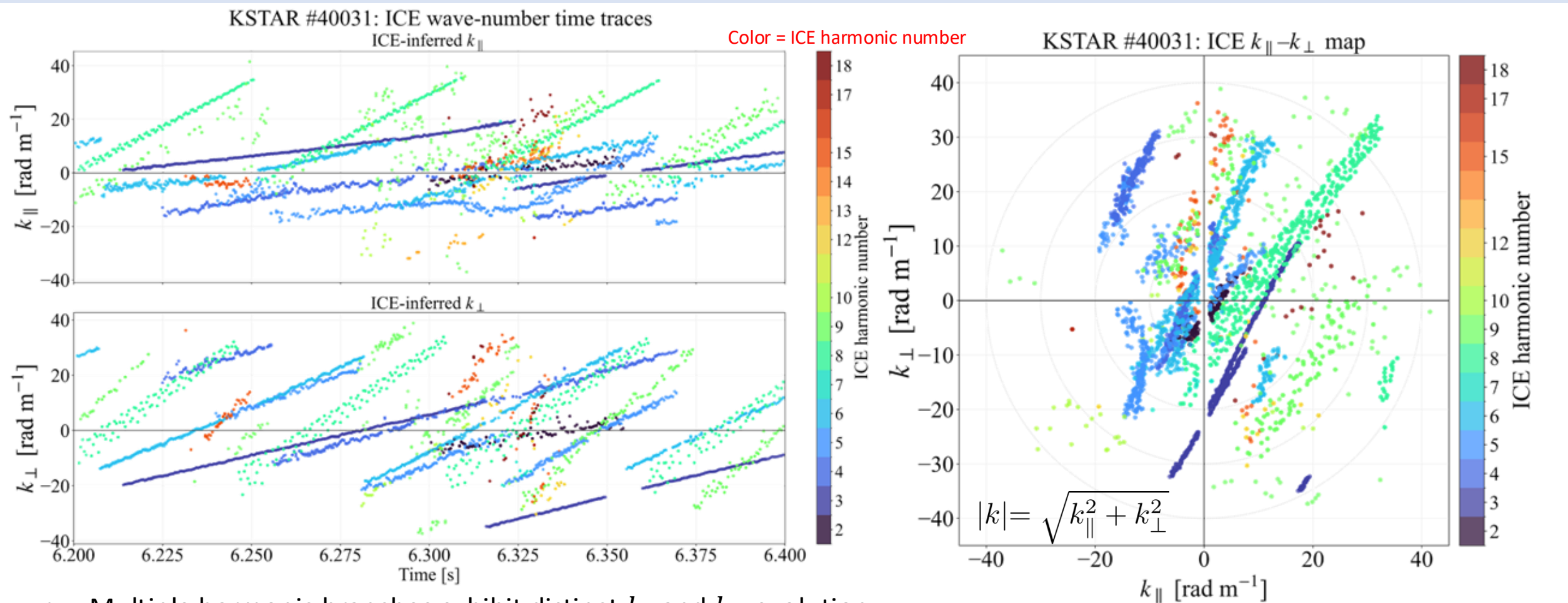
$$k = \sqrt{k_{\parallel}^2 + k_{\perp}^2}$$

$$v_A = \frac{B}{\sqrt{\mu_0 \rho_m}}$$

$$n_i^{\text{proxy}} \simeq \frac{B_{\text{ICE}}^2 (k_{\parallel}^2 + k_{\perp}^2)}{\mu_0 m_D \omega^2}$$

Model-dependent density proxy – not a direct density measurement

Wavenumber components from inter-channel phase differences



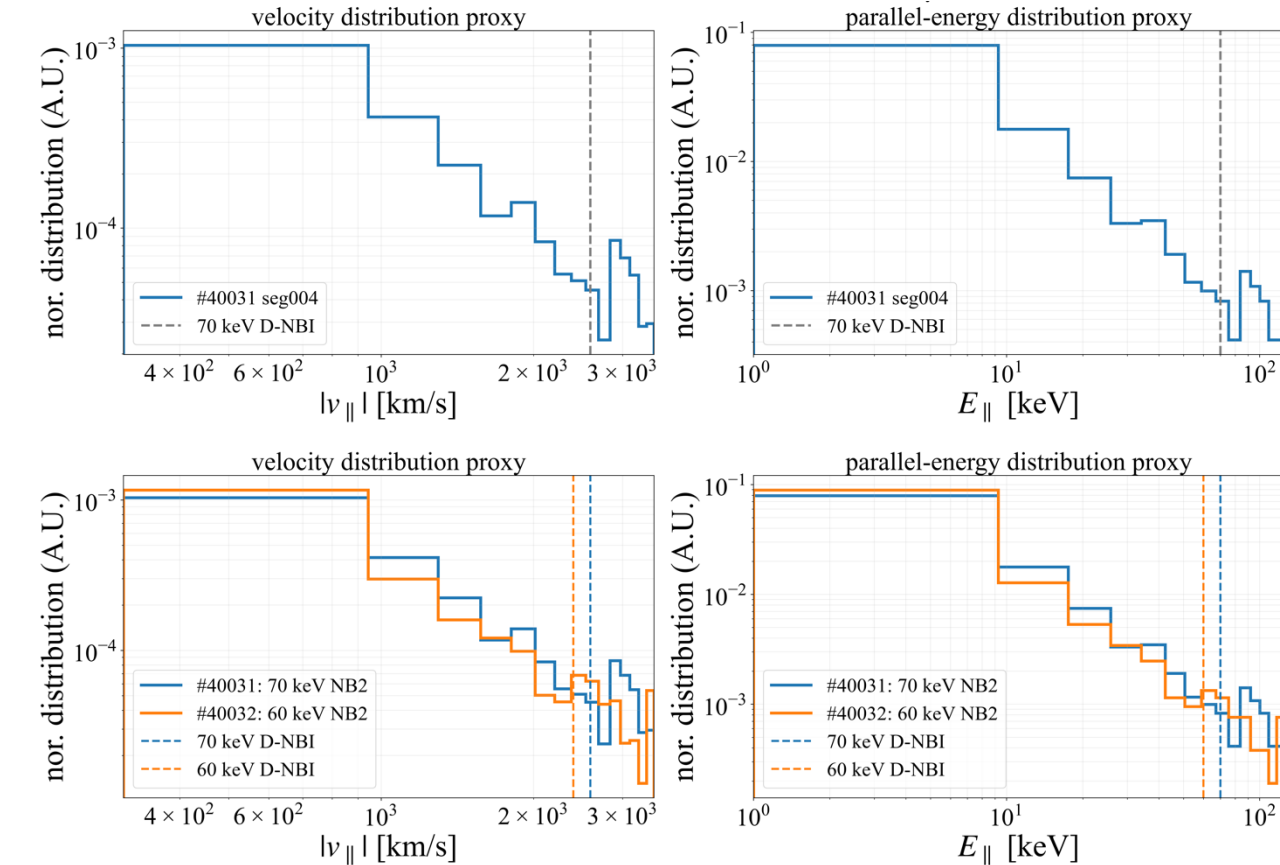
- Multiple harmonic branches exhibit distinct $k_{\parallel}$ and $k_{\perp}$ evolution
- Sign of k : propagation direction under the adopted coordinate convention

$C_{\text{crit}} = 1 - 0.05^{1/(L-1)} : L = 27 - 28, C_{\text{crit}} \approx 0.11$

accepted samples : $C > 0.3$
 $\Rightarrow$ statistically significant coherence

Alias-free range: $|k|_{\text{max}} = \frac{\pi}{d}$
d = distance inter channel (50,100,150 mm)

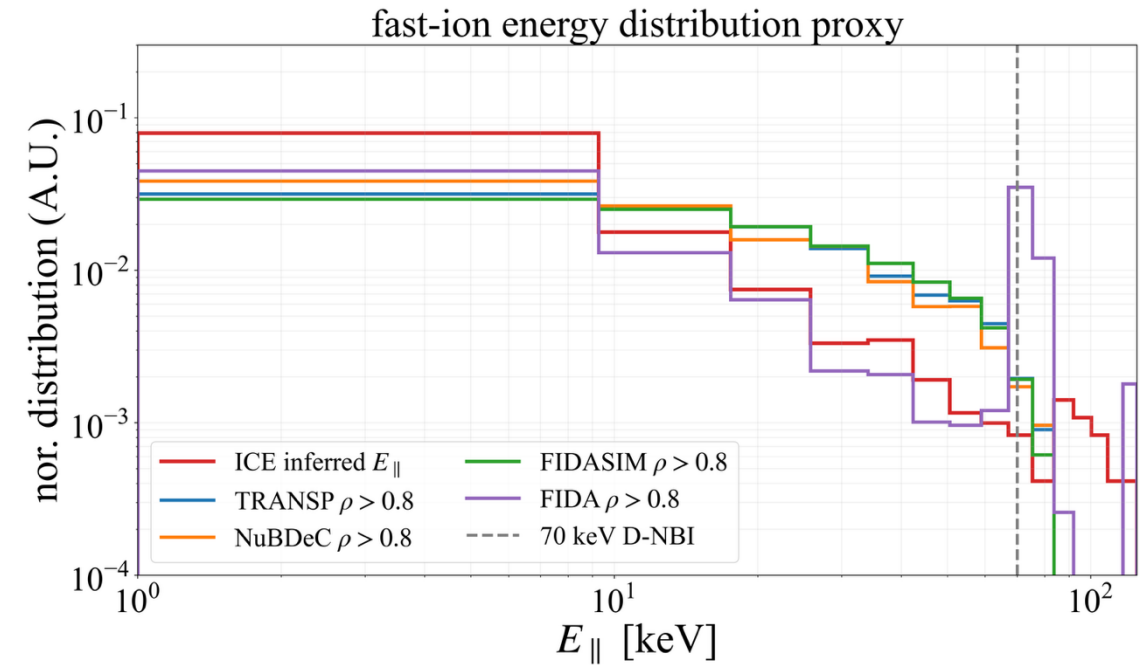
Comparison of ICE-inferred $E_{\parallel}$ proxy with fast-ion diagnostics and modeling



NBI-energy dependence(70,60keV) of ICE-inferred population

- Different phase-space sensitivities $\rightarrow$ distributions need not be identical (ICE vs modeling)

Qualitative comparison – different diagnostic sensitivities



$$\boxed{\omega} - \boxed{k_{\parallel} v_{\parallel}} = \boxed{l \Omega_{ci}}$$

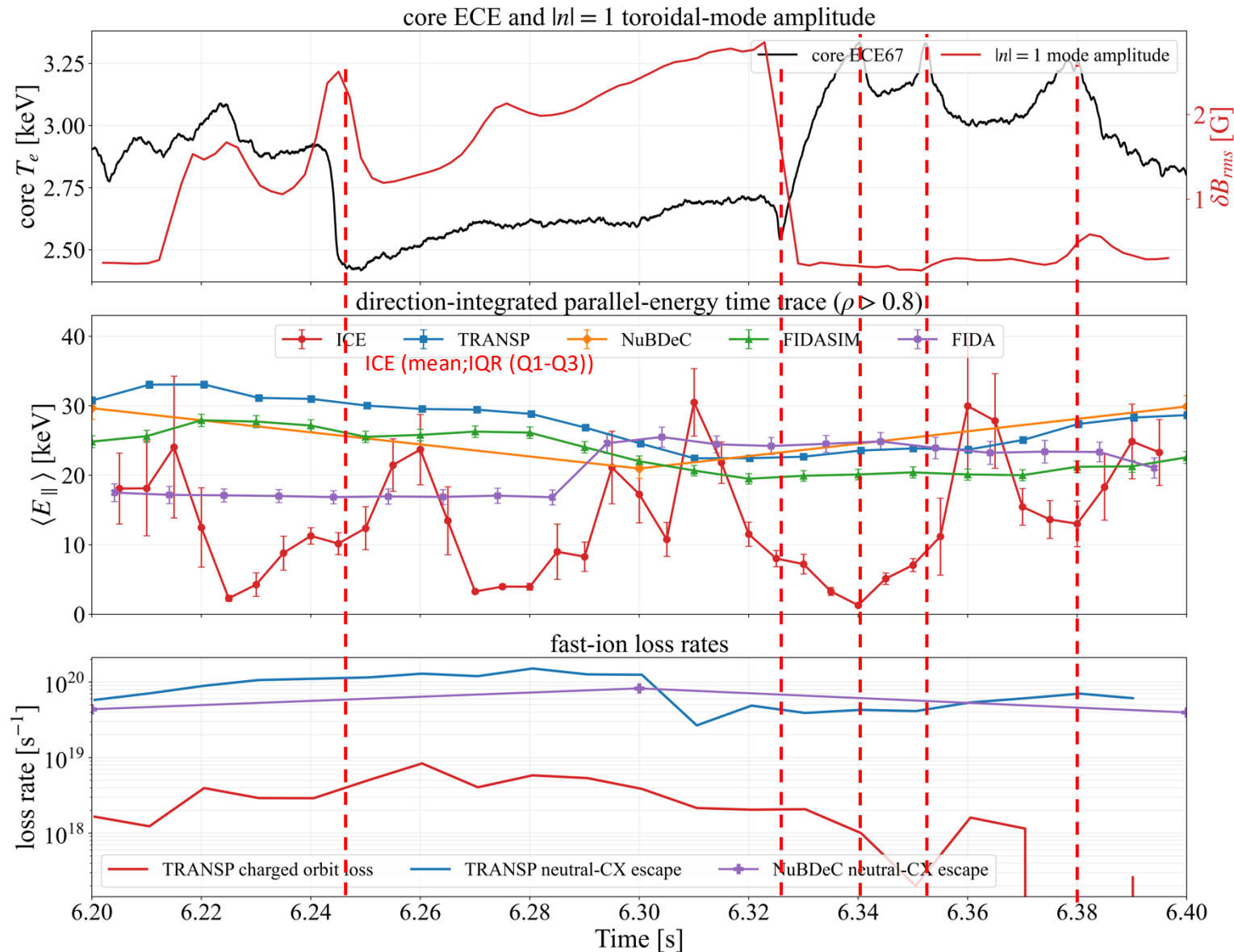


$$\boxed{v_{\parallel}} = \frac{\omega - l \Omega_{ci}}{k_{\parallel}} \quad \boxed{E_{\parallel}} = \frac{1}{2} m_D \boxed{v_{\parallel}^2}$$

 (inferred quantities)

 (measured by RF diagnostics)

Temporal evolution of ICE inferred $E_{\parallel}$ and fast-ion quantities



Observation

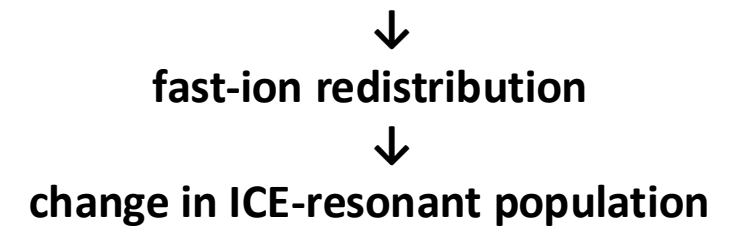
- Event-scale $E_{\parallel}$ variations around several $n=1$ / core-ECE events

Modeling limitation

- No additional anomalous fast-ion diffusion beyond the prescribed sawtooth-mixing model

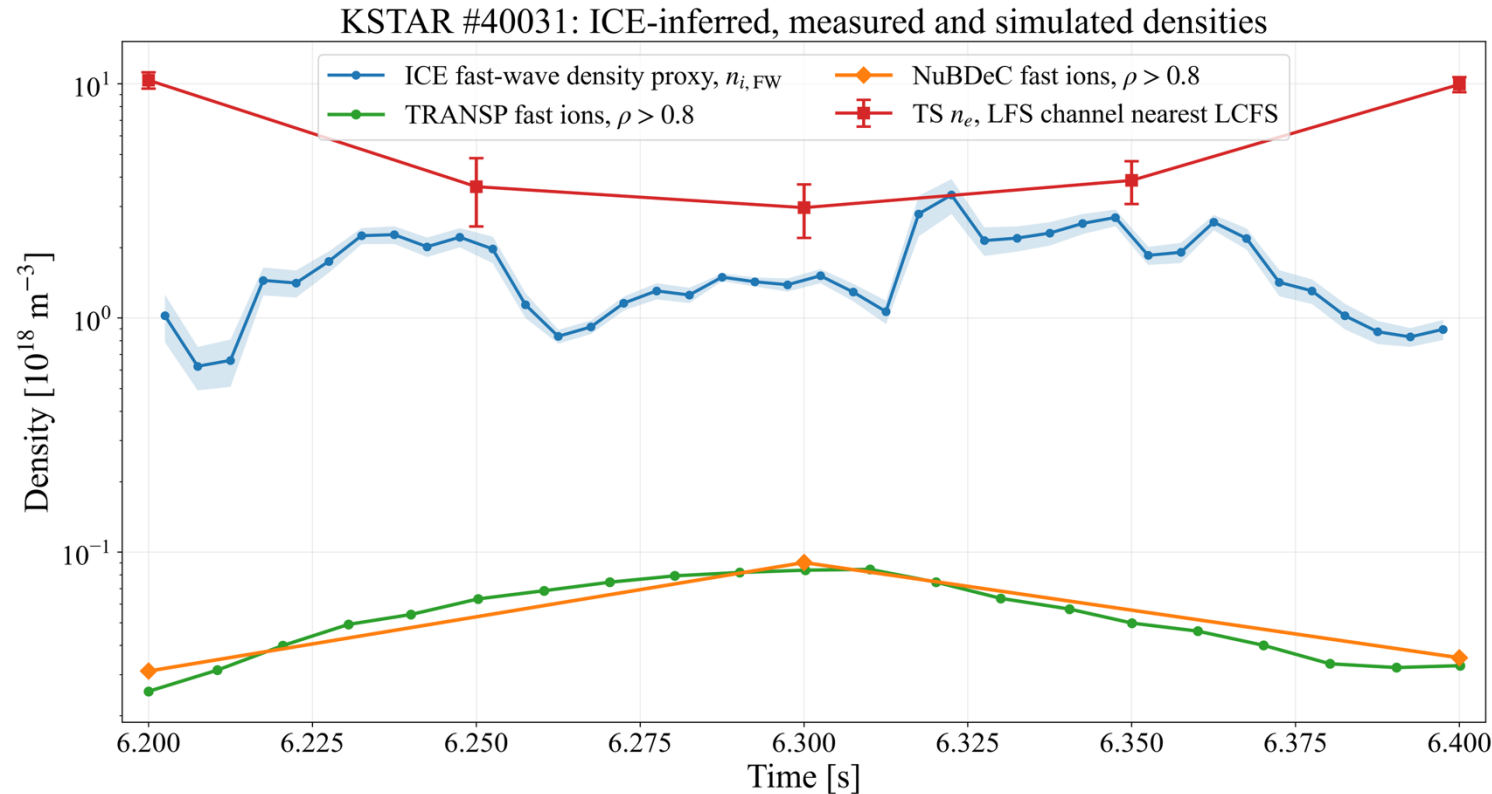
Interpretation

MHD event



Core-ECE events - - -

Model-dependent density proxy from ICE dispersion



Assumptions

- Fast/compressional-wave dispersion
- B_{ICE} from harmonic spacing $\omega \simeq kv_A$
- k from inter-channel phase

Physical meaning

- n_i^{proxy} : **bulk-ion** density proxy
- Not a fast-ion density

$$v_A = \frac{B}{\sqrt{\mu_0 \rho_m}} \rightarrow n_i^{proxy} \simeq \frac{B_{ICE}^2 (k_{\parallel}^2 + k_{\perp}^2)}{\mu_0 m_D \omega^2}$$

Result

- ICE proxy : $O(10^{18} \text{ m}^{-3})$
- Comparable order of magnitude to edge TS n_e
- Modeling fast-ion densities shown for context

 (inferred quantities)

 (measured by RF diagnostics)

Order of magnitude consistency only – not a direct density measurement

V. Summary & Outlook

- **Polarization-resolved harmonic ICE observed in KSTAR**
 $\Delta f_{ICE} \rightarrow B_{ICE} \rightarrow$ candidate edge source region
- **ICE responds to n=1 / core-ECE events**
→ consistent with fast-ion redistribution
→ possible contribution from confined / loss-related populations
- **Inter-channel phase enables k -resolved ICE analysis**
 $\Delta\phi \rightarrow k_{\parallel} \rightarrow v_{\parallel} \rightarrow E_{\parallel}$
- **ICE provides complementary EP / plasma information**
Energy proxy + model-dependent bulk-density proxy

- Robust k inference & uncertainty analysis
- Sawtooth-mixing / event-resolved validation
- Cross-validation with FIDA-TRANSP-NuBDeC
- Toward quantitative phase-space diagnosis with ICE
- Simultaneous ICE-FILD validation
(FILD unavailable during this exp.)

ICE observation → wave characterization → energetic-ion phase-space information

Future experimental analysis

2025.Dec.17
L-mode

2026.Mar.13
H-mode

Shot #	Shot status	NB2 energy	PVD He
40031	Successful	70	x
40032	Successful	60	x
40039	Successful	70	0.5V
40040	Successful (ECCD Fail)	70	1.5V
40041	Successful	70	2.5V
42027	Successful	70	x
42028	Successful	70	0.5V
42029	Successful	70	1.5V
42030	Successful	70	2.5V
42031	Disrupted @ 4.17s after He gas	70	3.5V
42032	Disrupted @ 4.02s after He gas	70	3.0V
42033	Disrupted at 5.34s	60	x
42034	Successful	60	0.5V
42035	Successful	60	1.5V

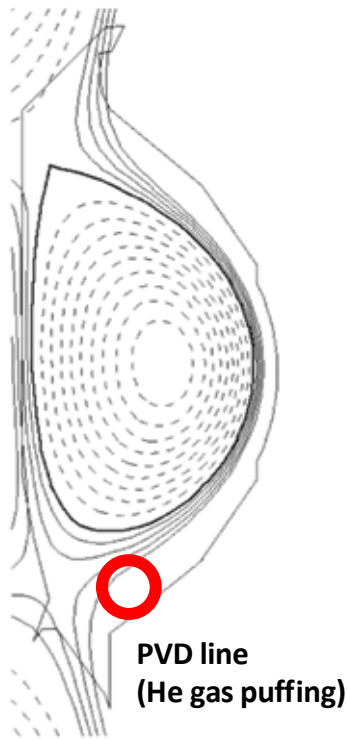
1. NBI-energy dependence

60keV ↔ 70keV

2. He gas-puff dependence

PVD valve = 0 → 2.5 V

3. L-mode → H-mode extension



Thank you