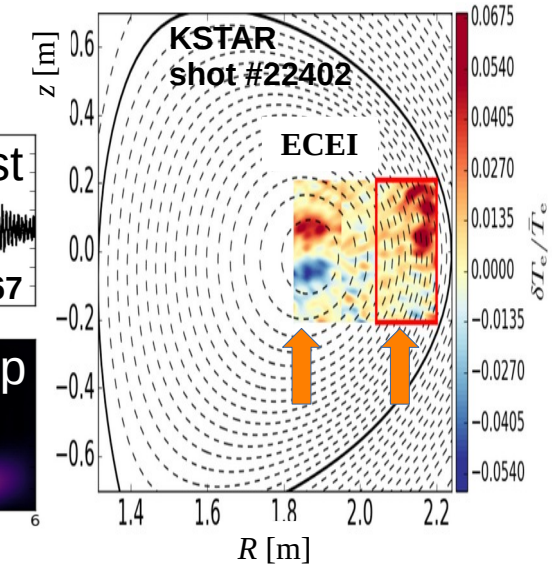
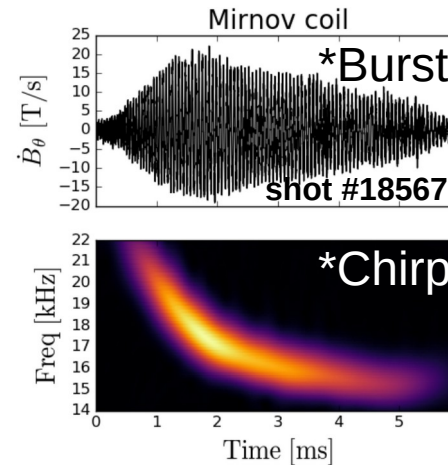


Study of low-frequency core-edge coupling in KSTAR: Double-peaked fishbone* observations & numerical analyses



Andreas Bierwage
QST/Japan

Wonjun Lee, Young-chul Ghim
KAIST/Korea



References & Acknowledgments

Non-monotonic radial structures of fluctuating temperatures and densities associated with fishbone activities in KSTAR

Cite as: Phys. Plasmas **30**, 022502 (2023); doi: 10.1063/5.0134354

Submitted: 10 November 2022 · Accepted: 28 January 2023 ·

Published Online: 21 February 2023



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Study of Low-Frequency Core-Edge Coupling in a Tokamak: I. Experimental Observation in KSTAR

Wonjun LEE^{1,2)}, Andreas BIERWAGE³⁾, Seungmin BONG¹⁾, Jaewook KIM⁴⁾, K.D. LEE⁴⁾, J.G. BAK⁴⁾, G.J. CHOI¹⁾, C. SUNG¹⁾, Y.-c. GHIM^{1*)}

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Submitting to *Fundamental Plasma Physics*.

Preprints: <https://doi.org/10.48550/arXiv.2603.24525>
<https://doi.org/10.48550/arXiv.2603.24463>

- **ECEI data:** M.J. Choi, Jaehyun Lee, M.H. Kim (KFE)
- **MEGA code:** Yasushi Todo
<https://doi.org/10.5281/zenodo.17170100>
- **Discussions:** Valentin Igochine (IPP Garching), Kimin Kim (KFE), Kouji Shinohara (U Tokyo), Timur Zh. Esirkepov and Shuhei Sumida (QST)
- **Grants:** NRF of Korea
- **HPC:** JFRS-1, Plasma Simulator, HPE SGI8600

Study of Low-Frequency Core-Edge Coupling in a Tokamak: II. Spatial Channeling & Focusing In Antenna-Driven MHD

Andreas BIERWAGE^{1,2,*)}, Wonjun LEE^{3,4)}, Young-chul GHIM³⁾, Panith ADULSIRISWAD¹⁾, Nobuyuki AIBA²⁾, Seungmin BONG³⁾, Gyungjin CHOI³⁾, Matteo FALESSI^{5,6)}, Philipp W. LAUBER⁷⁾, Masatoshi YAGI¹⁾

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³⁾Department of Nuclear and Quantum Engineering, Korea Advanced Institute of Science and Technology (KAIST), Daejeon 34141, South Korea

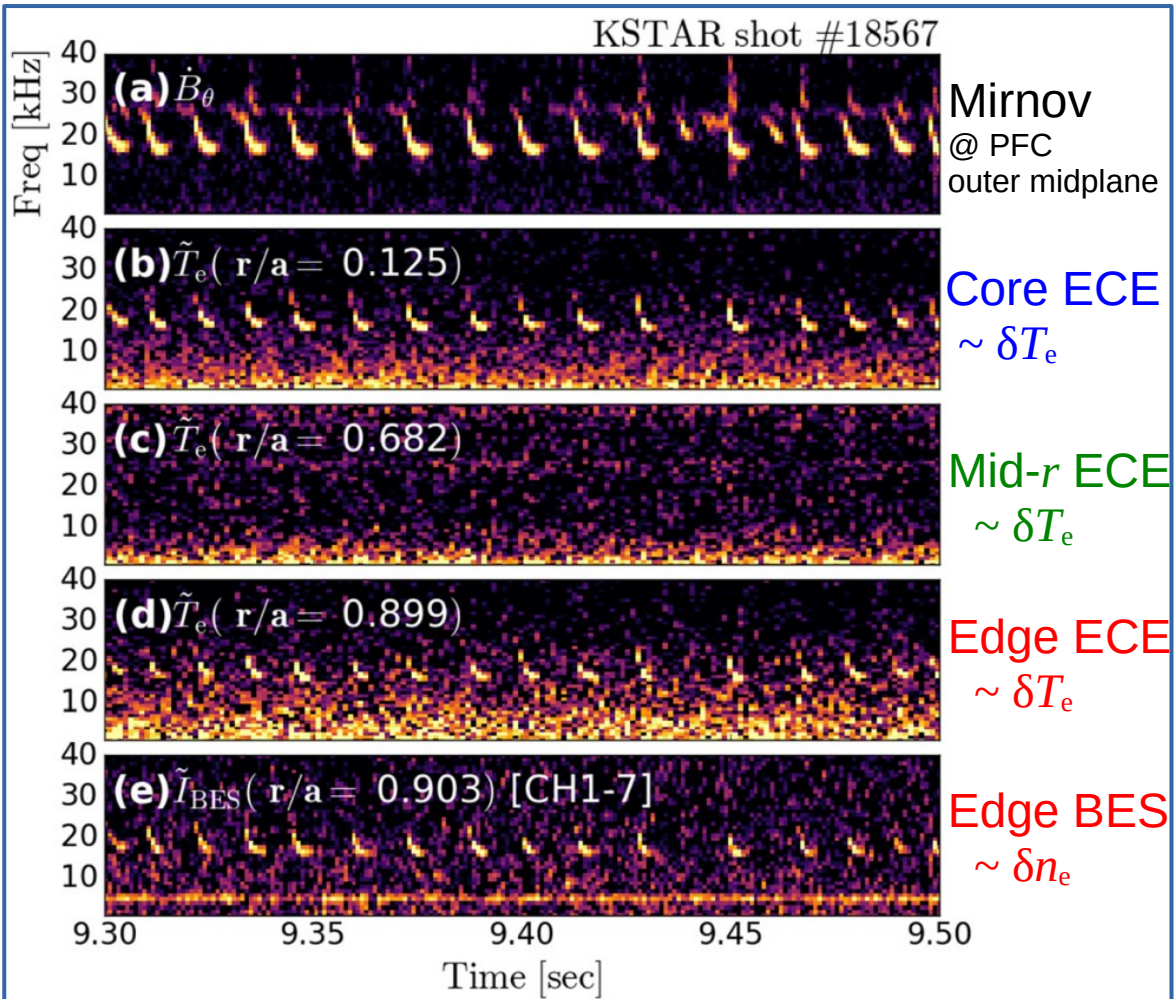
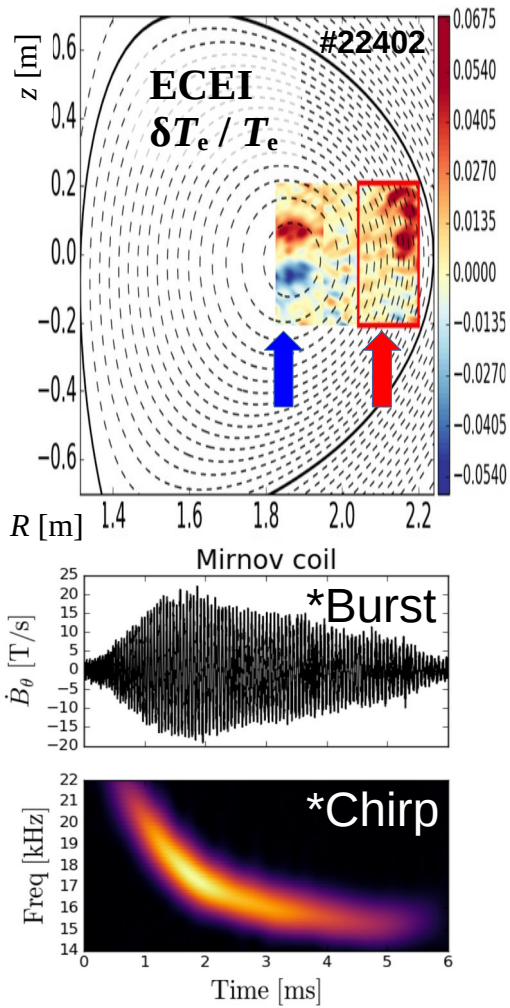
⁴⁾Max-Planck-Institut für Plasmaphysik, Wendelsteinstrasse 1, D-17491 Greifswald, Germany

⁵⁾Center for Nonlinear Plasma Science and C.R. ENEA Frascati, Via E. Fermi 45, 00044 Frascati, Italy

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⁷⁾Max-Planck-Institut für Plasmaphysik, Boltzmannstrasse 2, D-85748 Garching, Germany

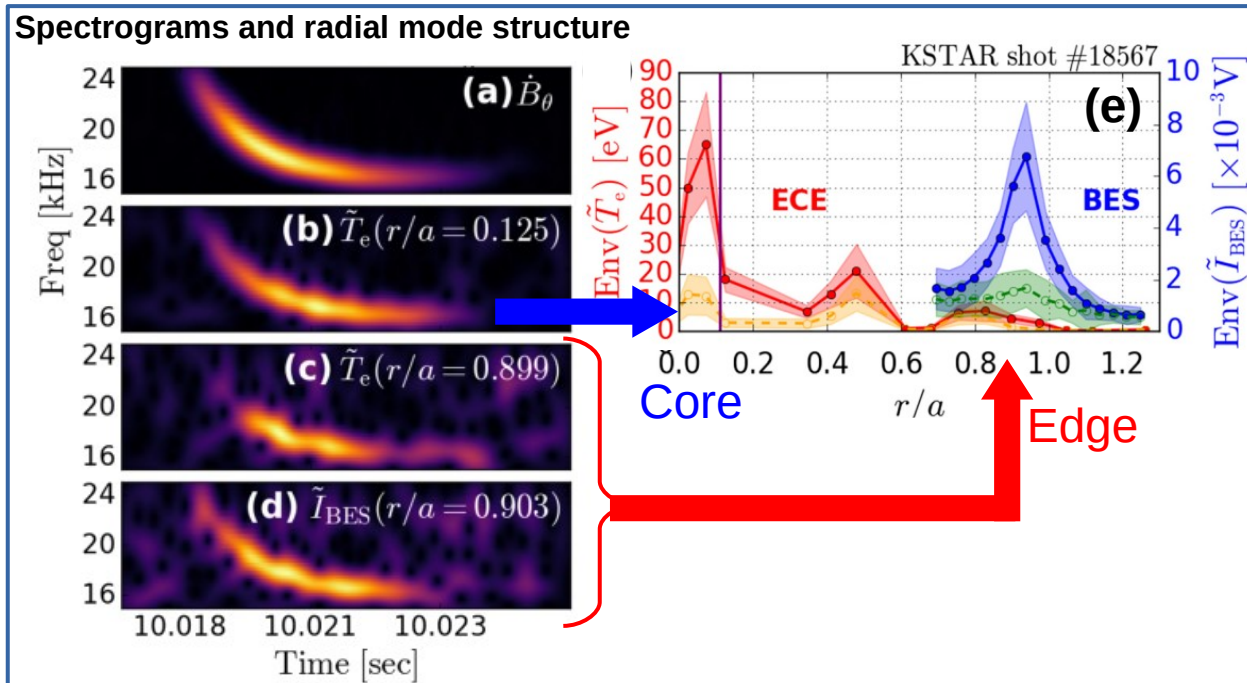
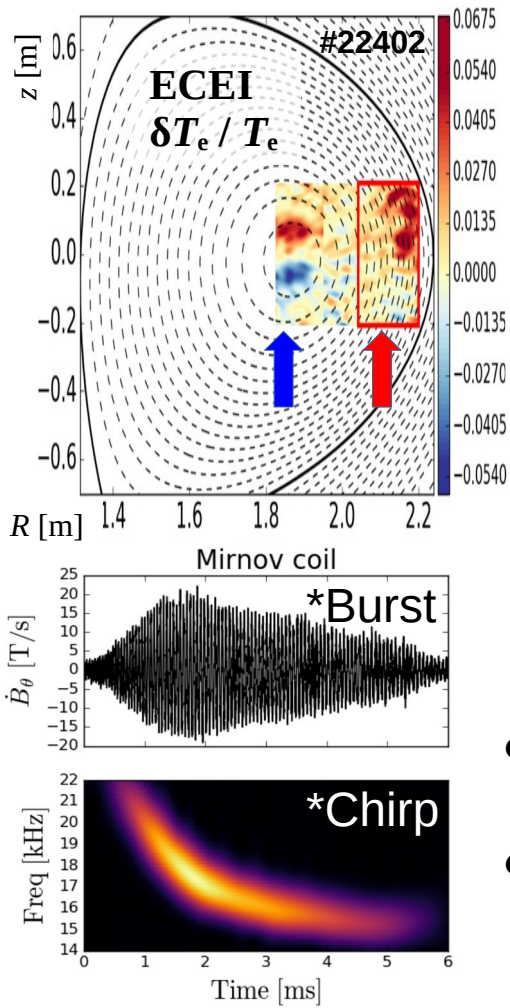
Motivation: First observation of double-peaked fishbone-like* low-frequency modes in KSTAR plasmas with differential rotation



Wonjun Lee *et al.*,
Phys. Plasmas **30**,
 022502 (2023)
 doi: 10.1063/5.0134354

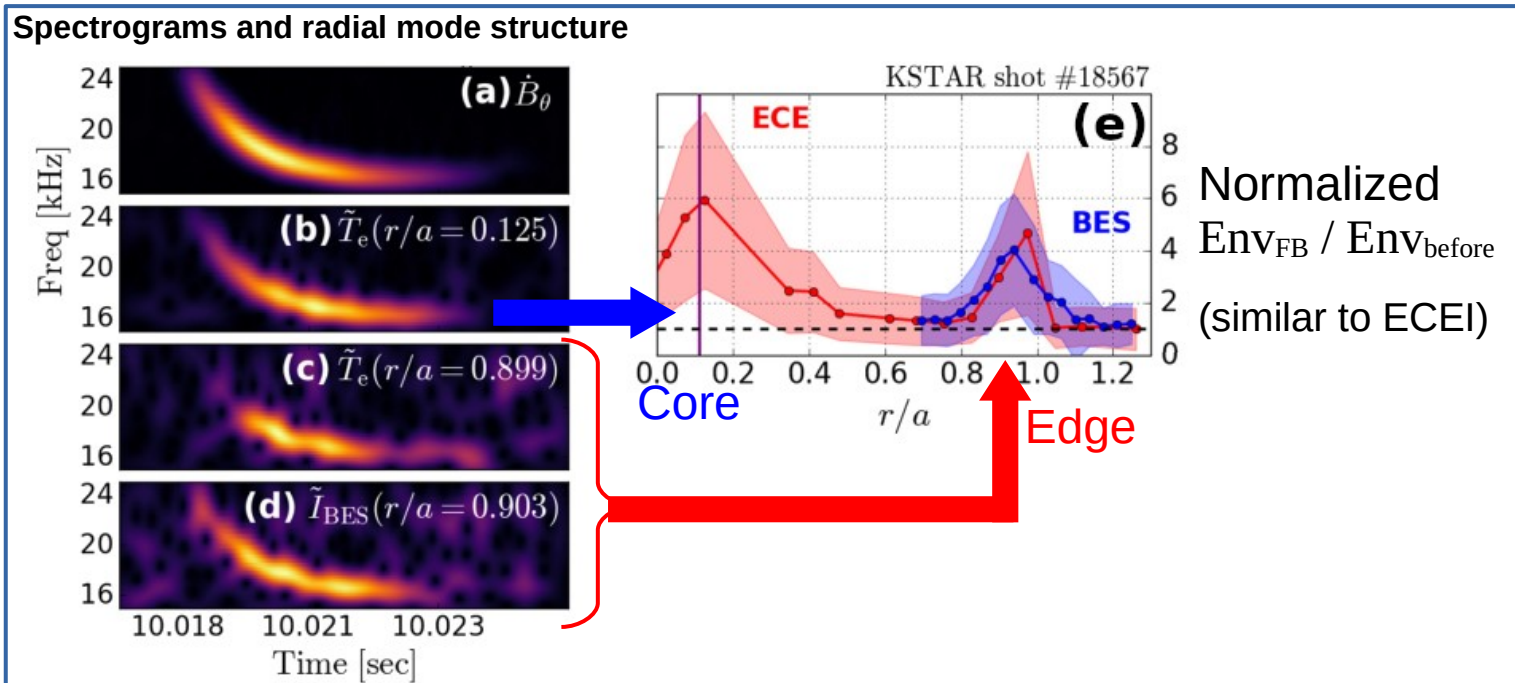
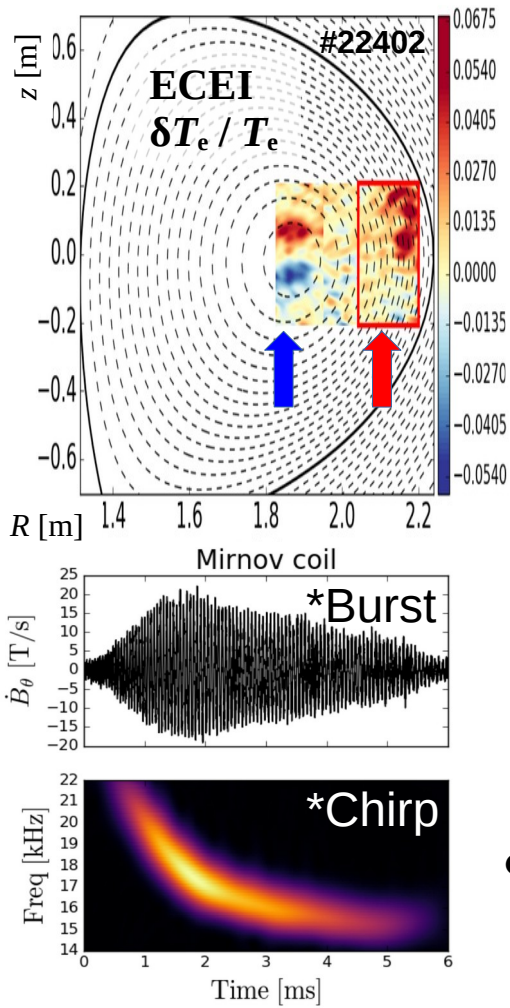
- Quasi-periodic electromagnetic bursts in NB-driven plasmas.
- Activity in both core & edge; but only noise in between.
- Chirping at same lab-frame freq., despite sheared rotation.

Motivation: First observation of double-peaked fishbone-like* low-frequency modes in KSTAR plasmas with differential rotation



- Dominant mode numbers: $n = 1$ (likely), $m_{\text{core}} = 1$ (ECEI), $m_{\text{edge}} \sim 3 \dots 4$ (est.)
- Important note about edge peak:
Much smaller than core peak, though may occupy larger volume.

Motivation: First observation of double-peaked fishbone-like* low-frequency modes in KSTAR plasmas with differential rotation



- Important note about edge peak:
Appears enlarged in most plots "normalized" by background ($T_e^{\text{edge}} \ll T_e^{\text{core}}$).

Outline

Study of low-frequency core-edge coupling in KSTAR: Double-peaked fishbone observations & numerical analyses

I Statistical analysis of experimental data

- ▶ Classification based on FB strength ↔ Role of ELM control coil (ECC) config.
- ▶ Spatio-temporal structure, phasing between core and edge components

II Possible explanations / contributing mechanisms

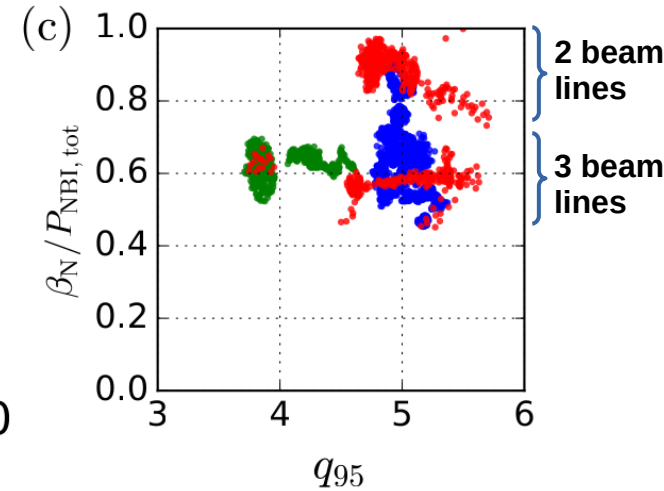
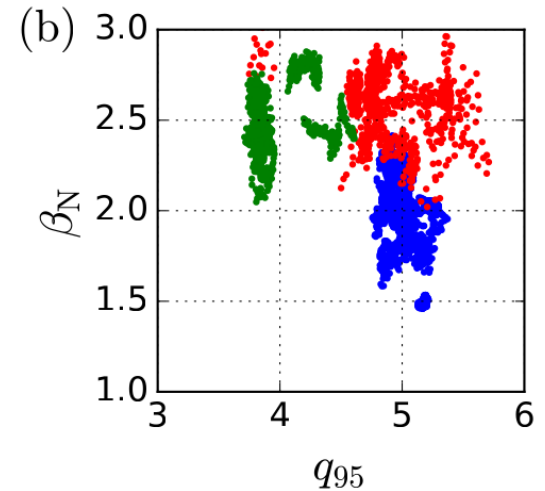
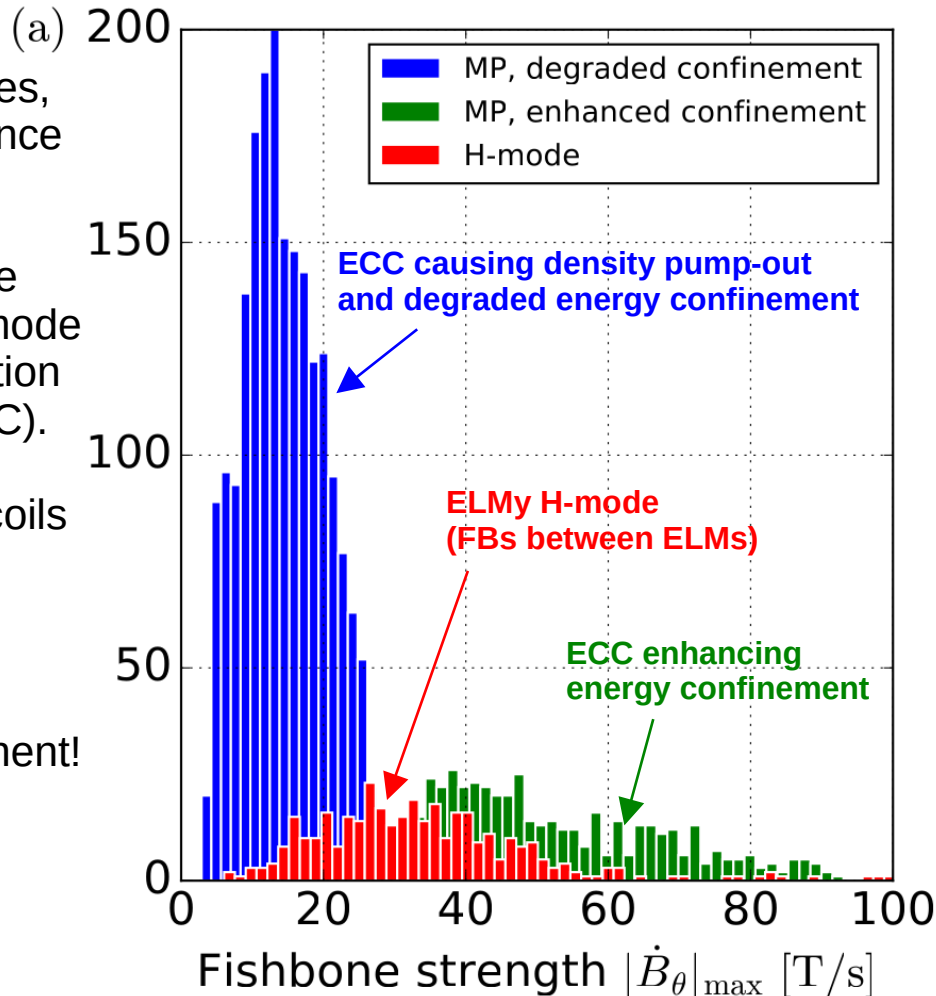
III Numerical study of radial coupling via MHD waves

IV Summary & outlook

Histograms of double-peaked FB strength

Includes ~3,000 fishbone events from 40 KSTAR discharges

- Seen primarily in H-modes, both in presence & absence of ELMs.
- FB strength and structure varies with quality of H-mode determined by configuration of ELM control coils (ECC).
- Remember that Mirnov coils are located on PFCs.
 - Closer to (and presumably more sensitive to) the FB's outer component!

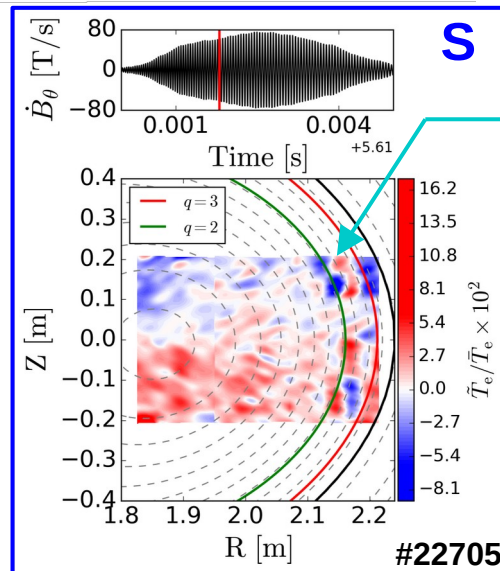
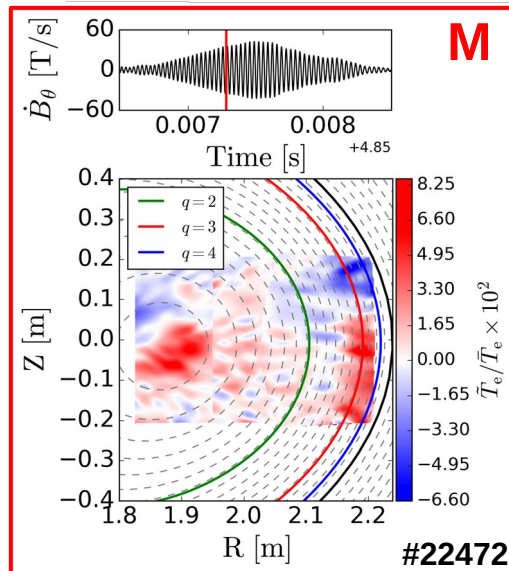
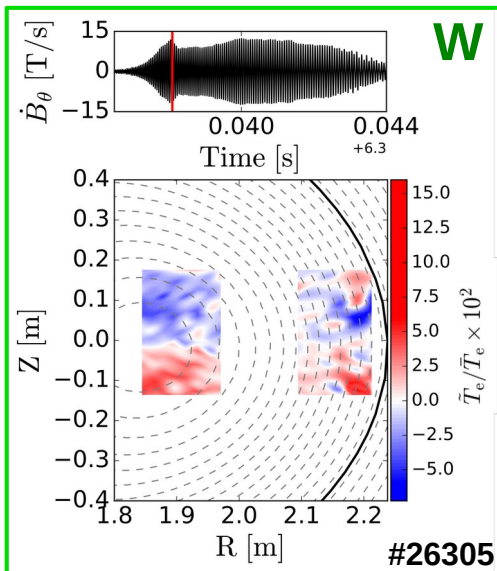
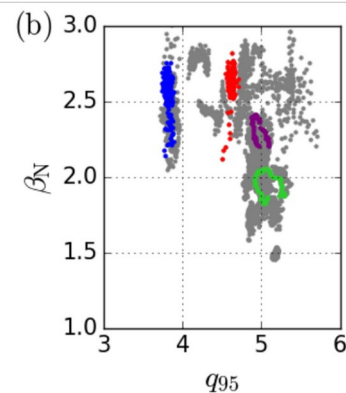
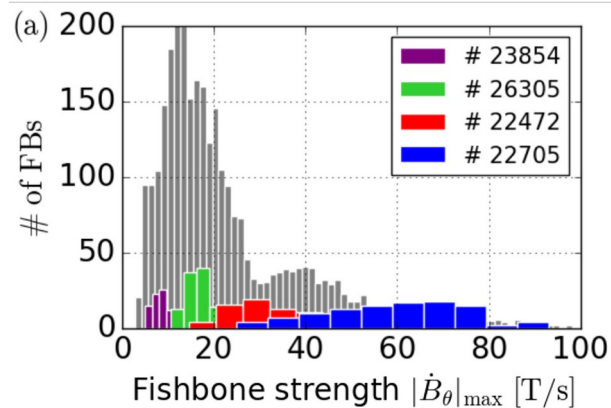


Classification for detailed analysis

Very weak, **Weak**, **Moderate**, **Strong**

Recall:
ECEI signal is divided
by local background,
 $\sim \delta T_e / T_e$,
enhancing edge signal.

Examples:

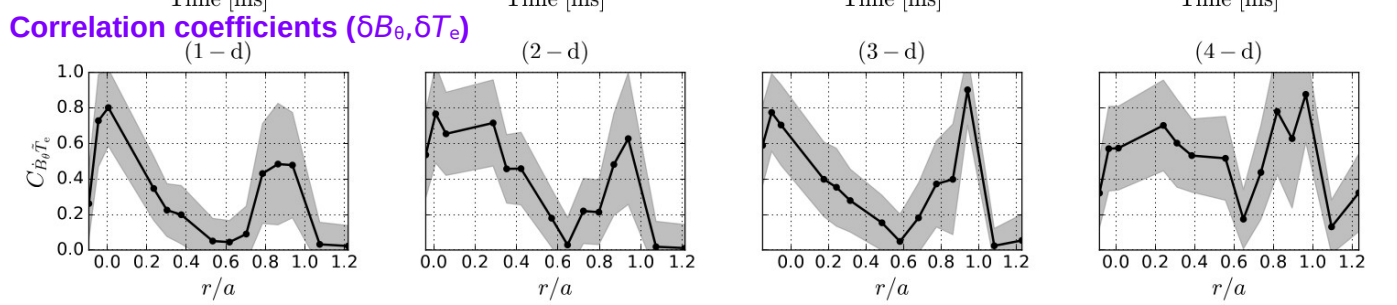
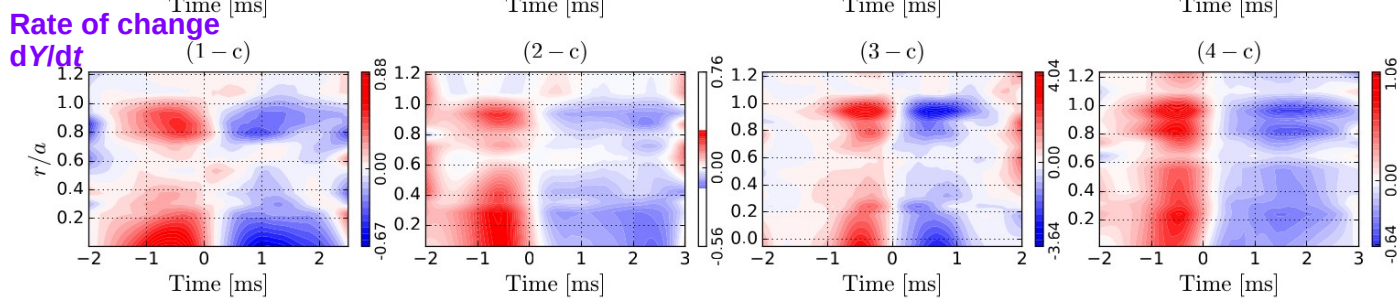
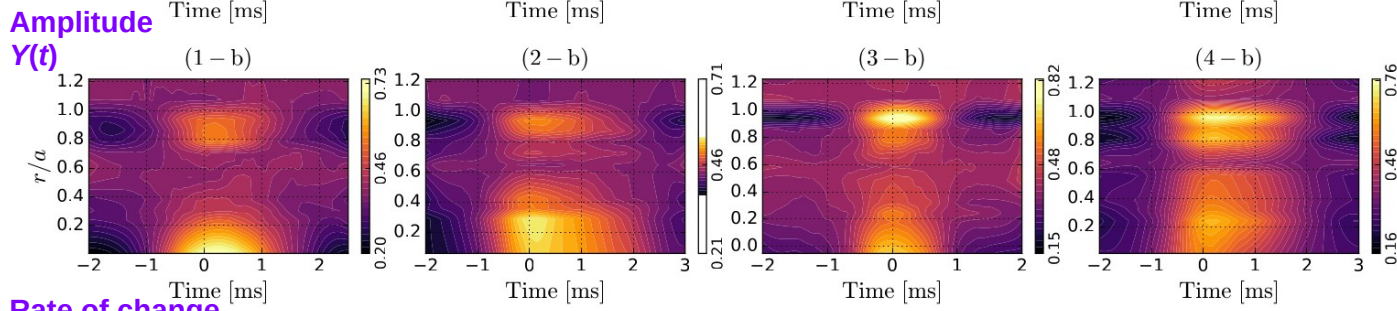
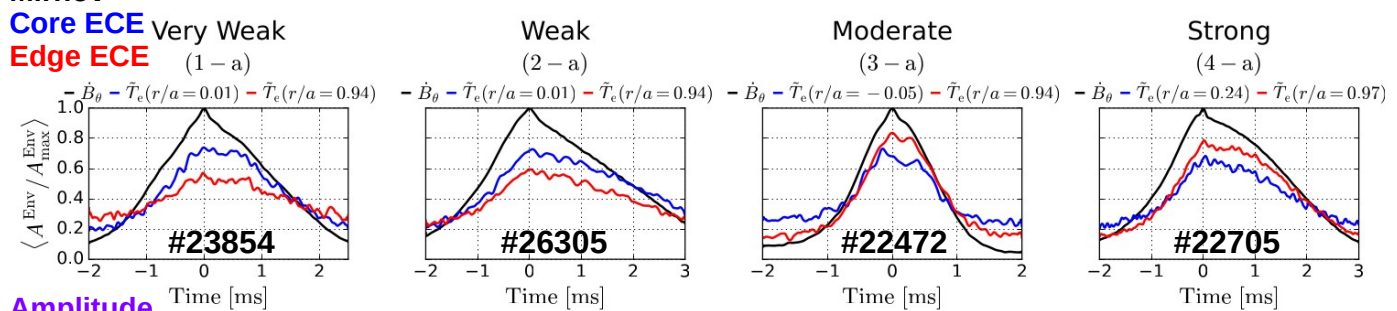


Note:
Signatures of
tearing parity are
seen occasionally.

For somewhat similar
observations in DIII-D, see:

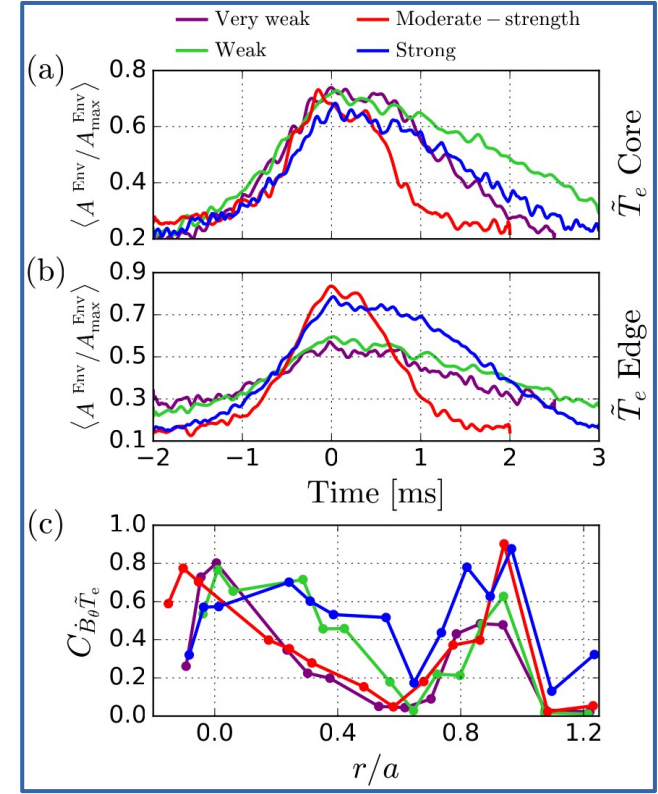
X. Du+ PRL 127 (2021) 025001
“Multiscale chirping modes driven
by thermal ions in a plasma with
reactor-relevant ion temperature”
10.1103/PhysRevLett.127.025001

Mironov Reduced H-mode (MP induced density pump-out)
 ELMy H-mode (no MP)
 Enhanced H-mode (optimized MP)

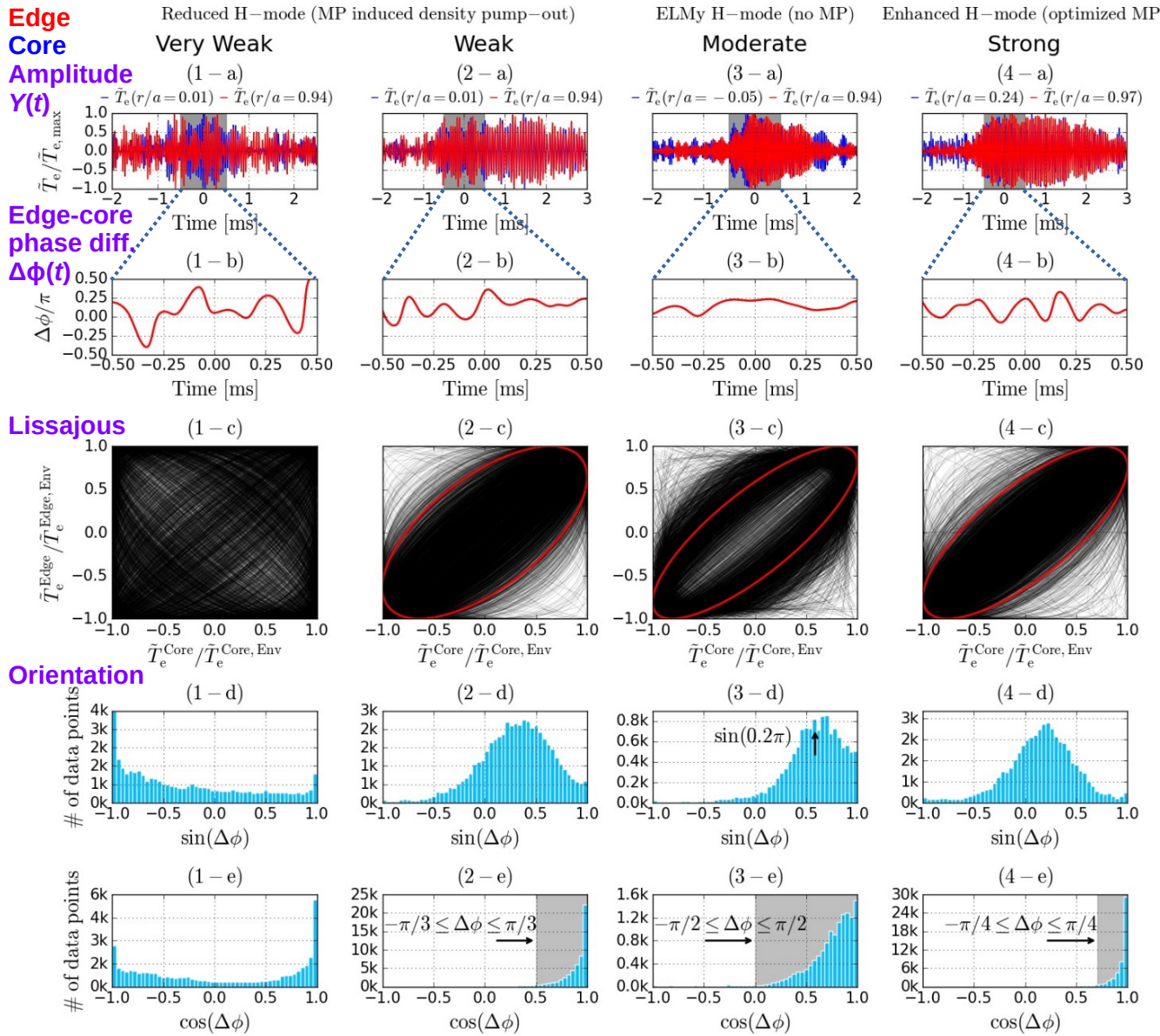


Spatio-temporal structure

(conditional averages over dozens of FBs)

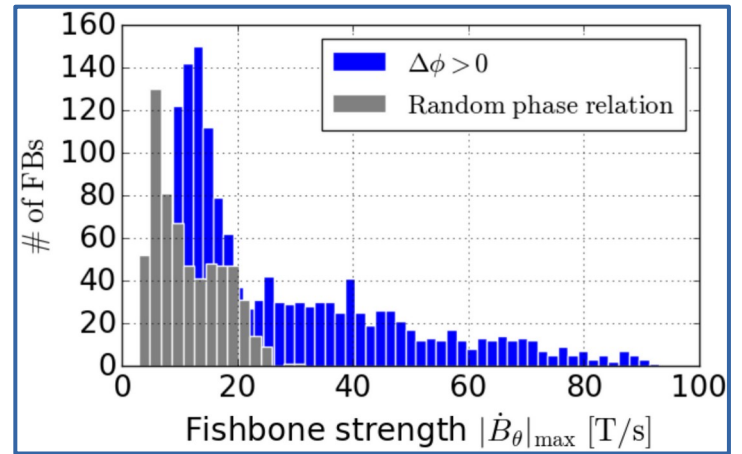


● Pronounced minimum observed consistently at mid-radius.



Phase analysis

(conditional averages over dozens of FBs)



- These results show that fishbone's core component trails behind edge component in outer midplane.
 - **Outer component may be primary** and **inner secondary / parasitic** ... if their coupling mechanism is localized near outer midplane.
- Difficult to prove conclusively, but can do numerical feasibility tests.**

Outline

Study of low-frequency core-edge coupling in KSTAR: Double-peaked fishbone observations & numerical analyses

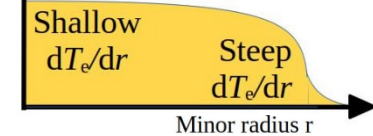
I Statistical analysis of experimental data

II Possible explanations / contributing mechanisms

1. Background profile effect

$$\frac{\tilde{T}_e}{T_e} \sim \delta\xi \frac{dT_e/dr}{T_e}$$

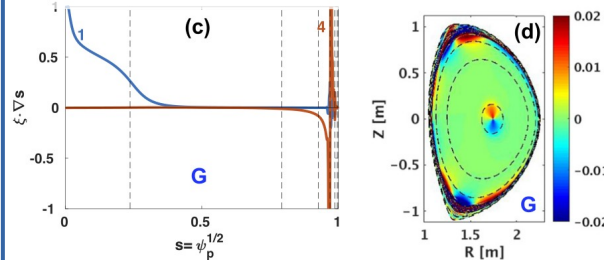
H-mode-like



But found also in a few L-mode plasmas. → Lee+ 2026, arxiv.

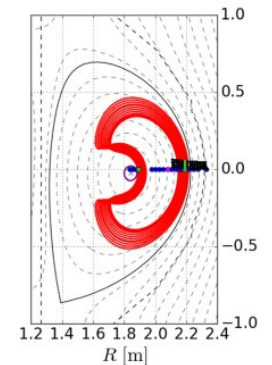
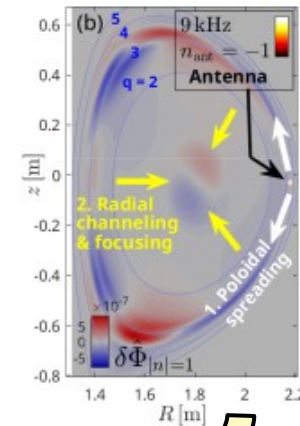
2. Double-peaked eigenmode

Example from DIII-D study (MARS-K):



Liu, Xie & Du *Nucl. Fusion* **62**, 086050 (2022)
<https://doi.org/10.1088/1741-4326/ac7b9a>

Pair of modes, coupled by ...
3. MHD waves 4. Wide orbits



Proposed by Lee et al.
Phys. Plasmas **30**, 022502 (2023)
<https://doi.org/10.1063/5.0134354>
→ Numerical study underway.

III Numerical study of radial coupling via MHD waves

IV Summary & outlook

MHD antenna study
→ Bierwage+ 2026, arxiv.

Outline

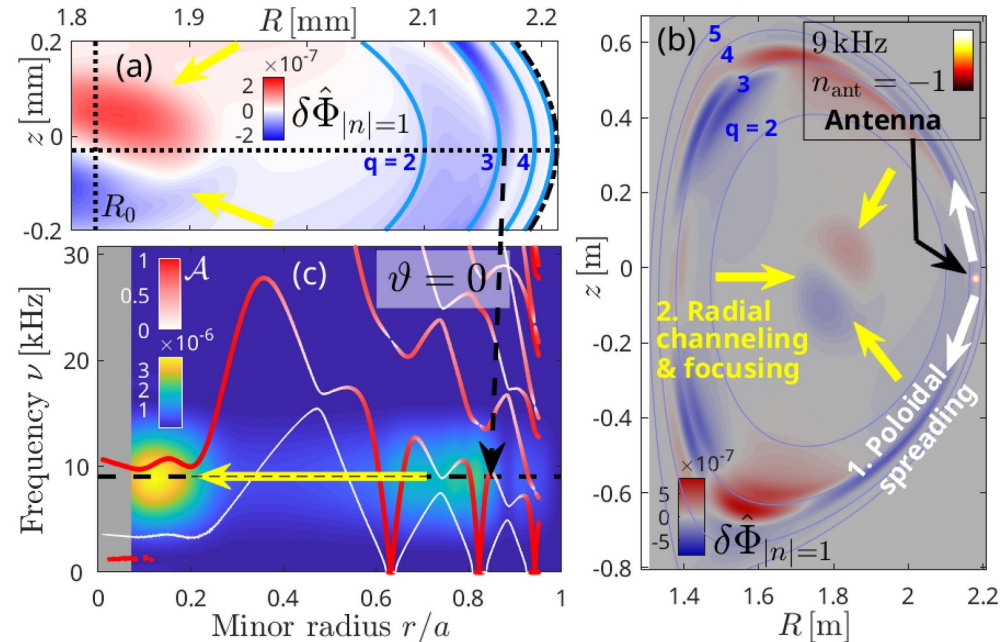
Study of low-frequency core-edge coupling in KSTAR: Double-peaked fishbone observations & numerical analyses

- I Statistical analysis of experimental data
- II Possible explanations / contributing mechanisms

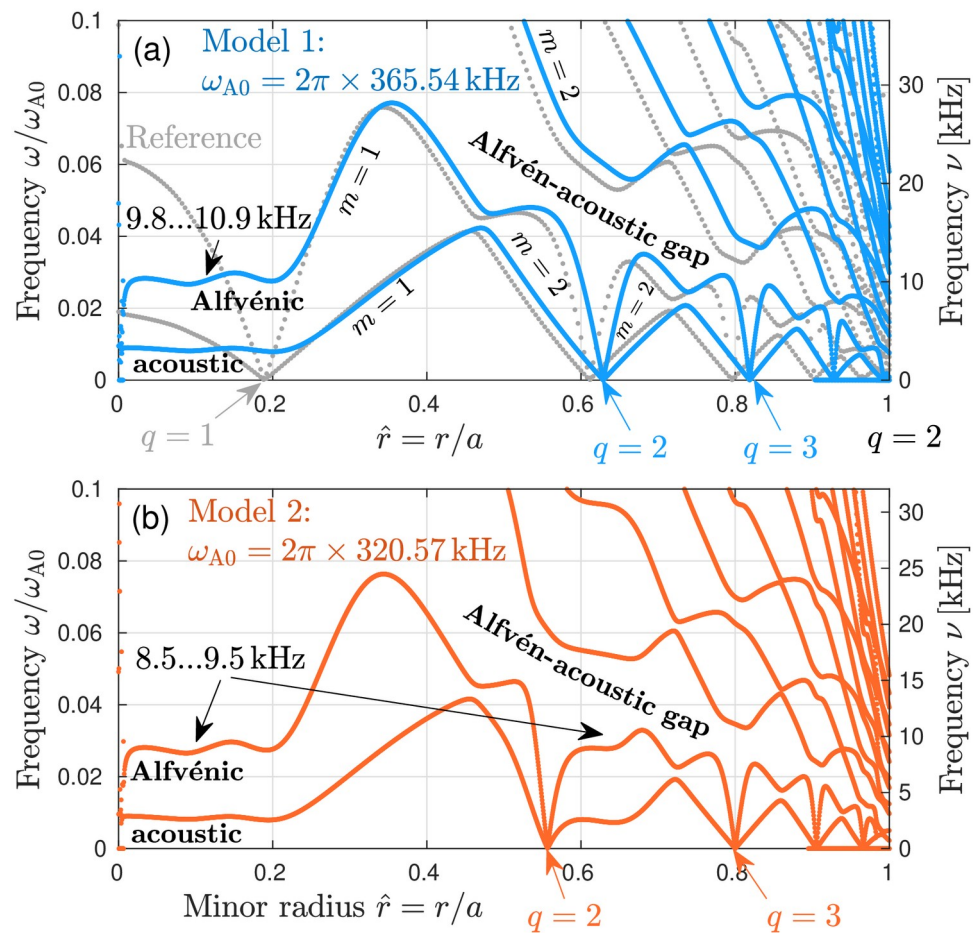
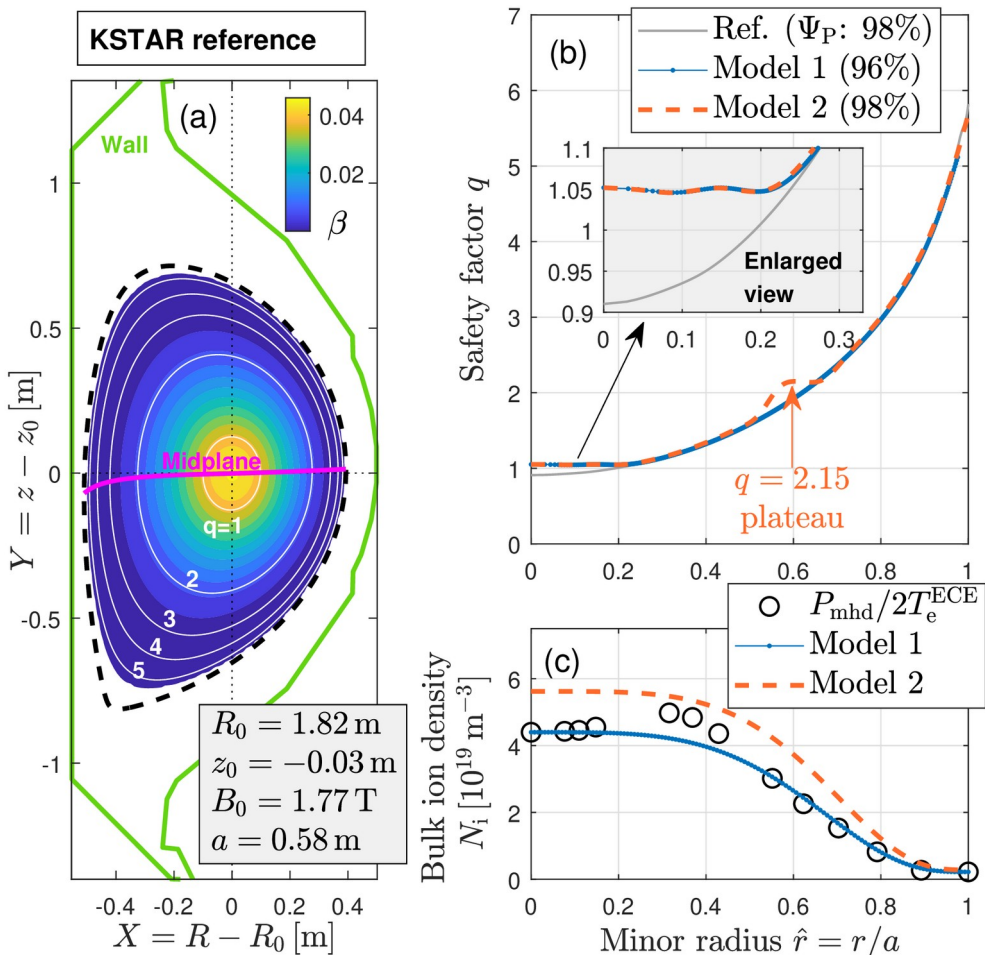
III Numerical study of radial coupling via MHD waves

- ▶ Antenna-drive visco-resistive MHD
- ▶ Spatio channeling & focusing

IV Summary & outlook



Simulation model KSTAR plasma



Simulation model

MEGA code (excluding EPs $\mathbf{j}_{h,eff}$)

Visco-resistive full MHD:

$$\partial\rho_b/\partial t = -\nabla \cdot (\rho_b \mathbf{u}) + \chi \nabla^2 \rho_b + S_\rho$$

$$\rho_b \partial \mathbf{u} / \partial t = -\rho_b \mathbf{u} \cdot \nabla \mathbf{u} - \nabla p_b + (\mathbf{j} - \cancel{\mathbf{j}_{h,eff}}) \times \mathbf{B} + \mathbf{S}_u \quad (3)$$

$$-\left[\nabla \times (\nu \rho_b \nabla \times \mathbf{u}) + \frac{4}{3} \nabla (\nu \rho_b \nabla \cdot \mathbf{u}) \right], \quad (4)$$

$$\partial \mathbf{B} / \partial t = -\nabla \times \mathbf{E}, \quad (5)$$

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{j} + \mathbf{S}_E, \quad (6)$$

$$\mu_0 \mathbf{j} = \nabla \times \mathbf{B}, \quad (7)$$

$$\partial p_b / \partial t = -\nabla \cdot (p_b \mathbf{u}) - (\Gamma - 1) p_b \nabla \cdot \mathbf{u} + \chi \nabla^2 p_b$$

$$+ \nu \rho_b (\Gamma - 1) \left[(\nabla \times \mathbf{u})^2 + \frac{4}{3} (\nabla \cdot \mathbf{u})^2 \right]$$

$$+ (\Gamma - 1) (\mathbf{j} - \cancel{\mathbf{j}_{h,eff}}) \cdot (\eta \mathbf{j} + \mathbf{S}_E) + S_p. \quad (8)$$

Source and diffusion terms:

$$S_\rho = -\chi \nabla^2 \rho_{b,eq}, \quad (9)$$

$$\mathbf{S}_u = \nabla p_{b,eq} - (\mathbf{j}_{eq} - \cancel{\mathbf{j}_{h,eq}}) \times \mathbf{B}_{eq}, \quad (10)$$

$$\mathbf{S}_E = -\eta \mathbf{j}_{eq}, \quad (11)$$

$$S_p = -\chi \nabla^2 p_{b,eq}, \quad (12)$$

Antenna:

$$\delta \mathbf{B}_{ant} = \varrho_{A0} B_0 \hat{A}_{ant} \nabla \times (\delta \hat{E}_{ant}(R, z, \zeta, t) \hat{\mathbf{e}}_\zeta), \quad (10a)$$

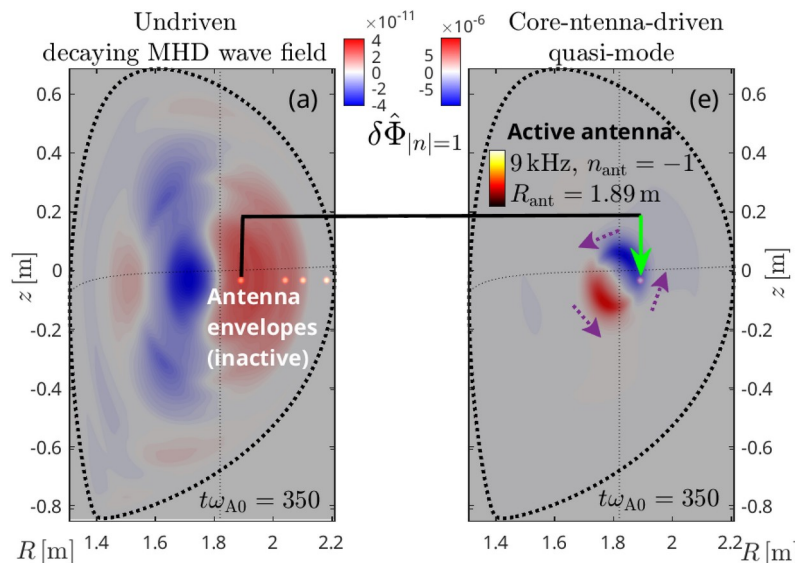
$$\delta \hat{E}_{ant} = \cos(n_{ant} \zeta - \omega_{ant} t) \times \begin{cases} \cos^3(\chi) & : \chi < \frac{\pi}{2}, \\ 0 & : \text{else,} \end{cases} \quad (10b)$$

$$\chi \equiv \frac{\pi}{2} \sqrt{(R - R_{ant})^2 + (z - z_{ant})^2} / w_{ant}^2, \quad (10c)$$

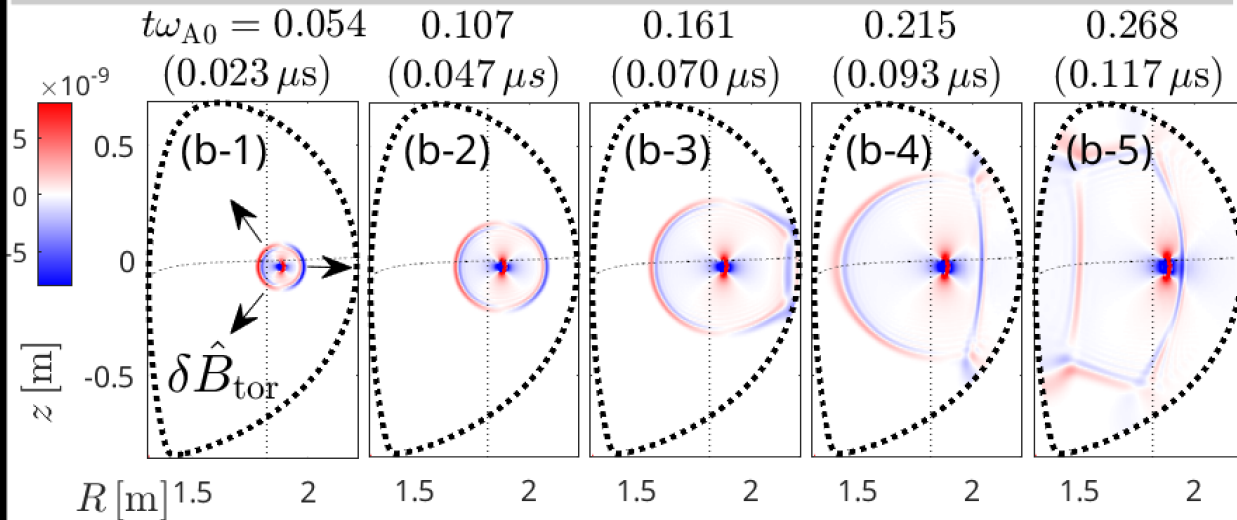
$$\rightarrow \mathbf{B}(t) = \mathbf{B}_{eq} + \delta \mathbf{B}(t) + \delta \mathbf{B}_{ant}(t)$$

Results

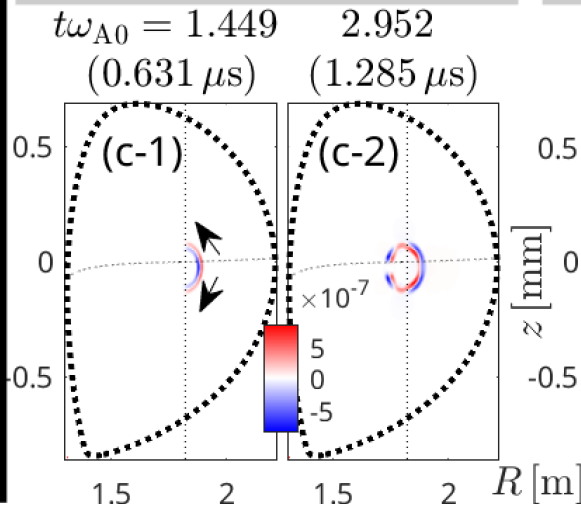
Early antenna response



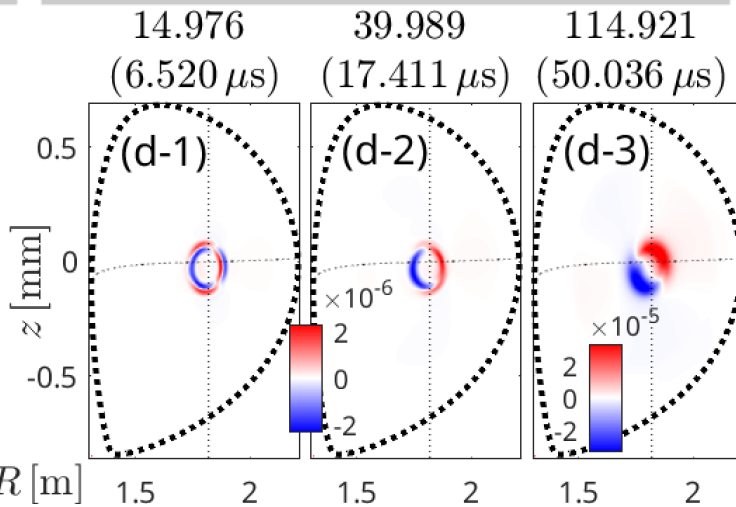
Stage 0: Fast magnetoacoustic waves (very low amplitude)



Stage 1: Poloidal spreading

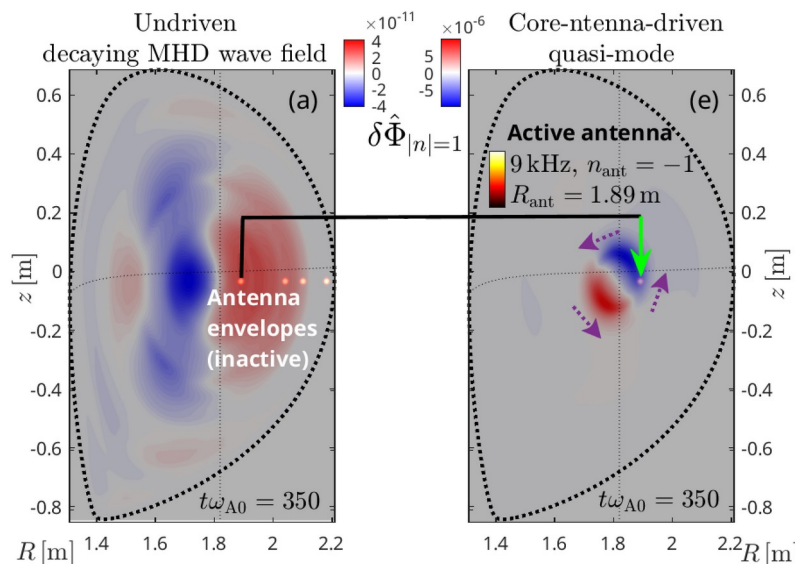


Stage 2: Low-freq. mode formation

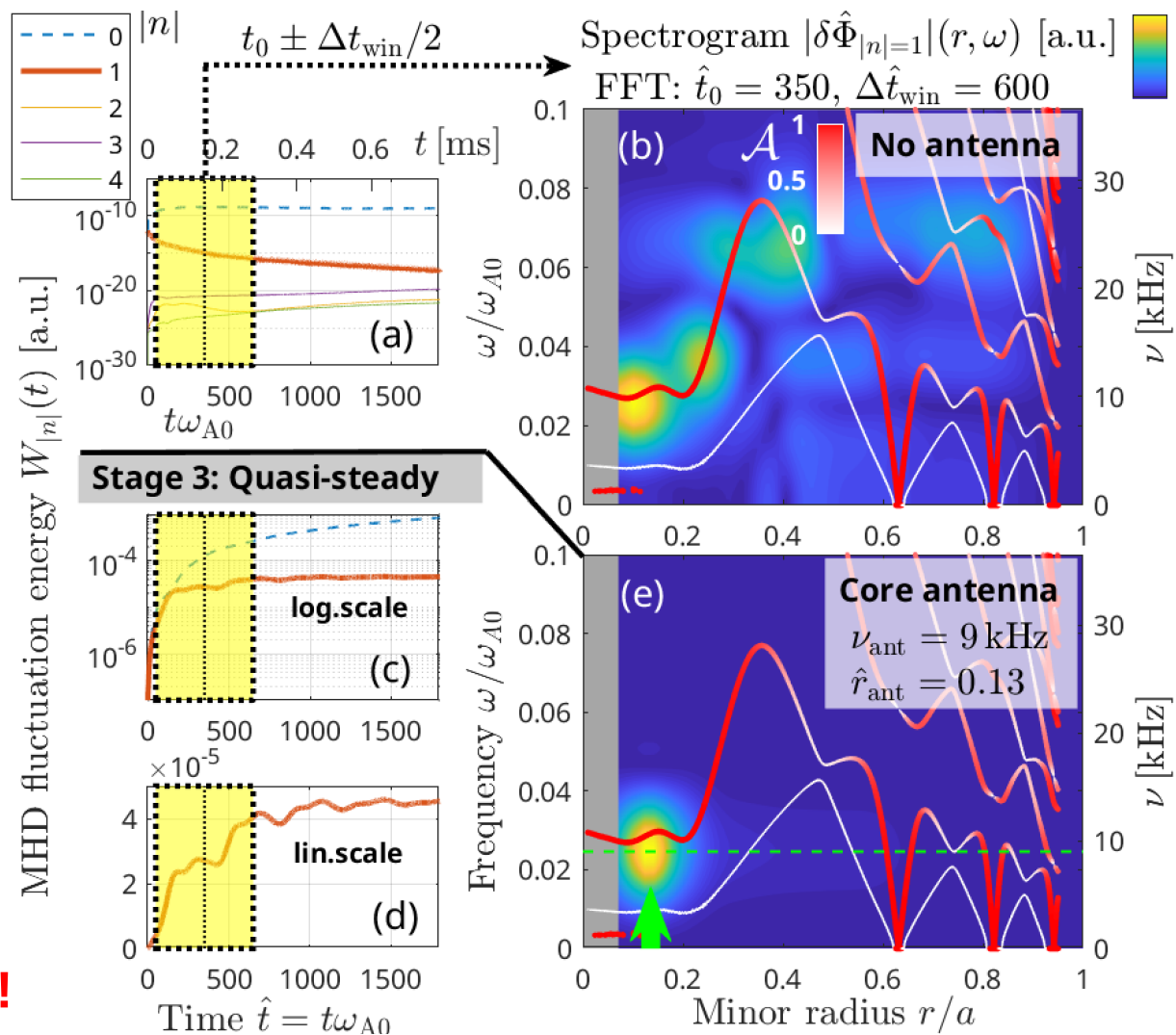


Results

Quasi-steady state



Driving inner core:
No edge-response
seen in present model !
(fixed-boundary
visco-resistive MHD)

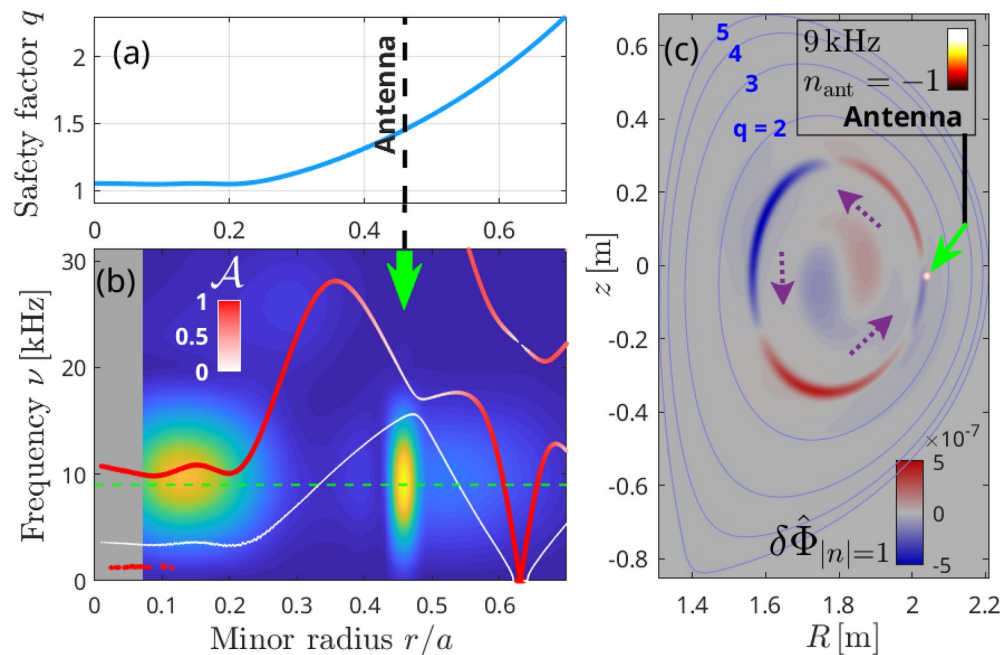


Continua & Alfvénicity computed by FALCON code. → Falessi *et al*,
Phys. Plasmas **26**, 082502 (2019), *J. Plasma Phys.* **86**, 845860501 (2020)

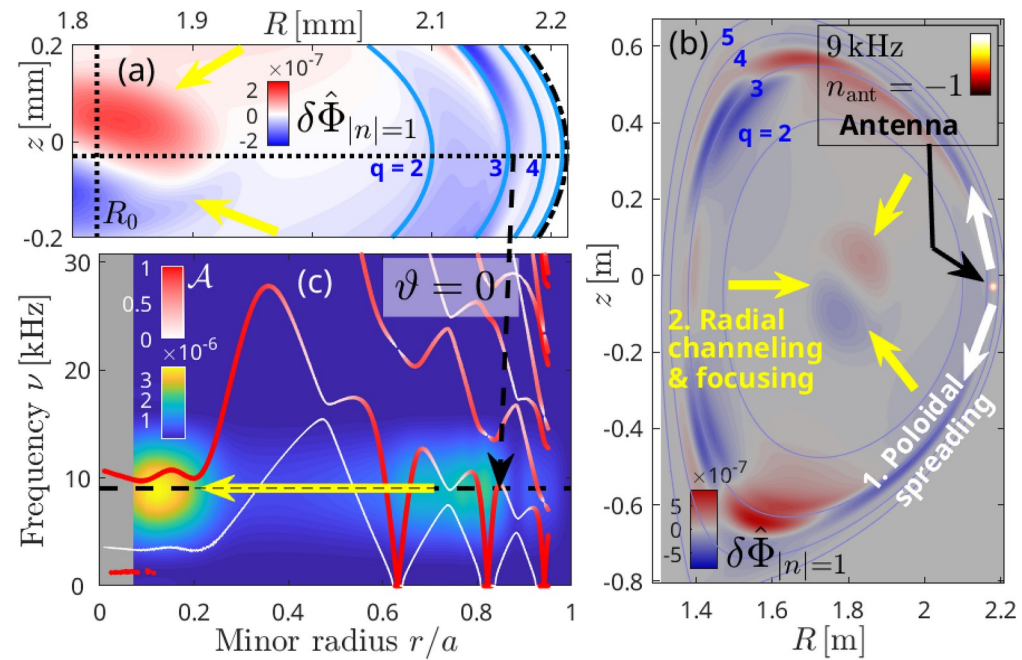
Simulation results

Demonstration of action-at-a-distance

Drive at mid-radius:



Drive near edge:



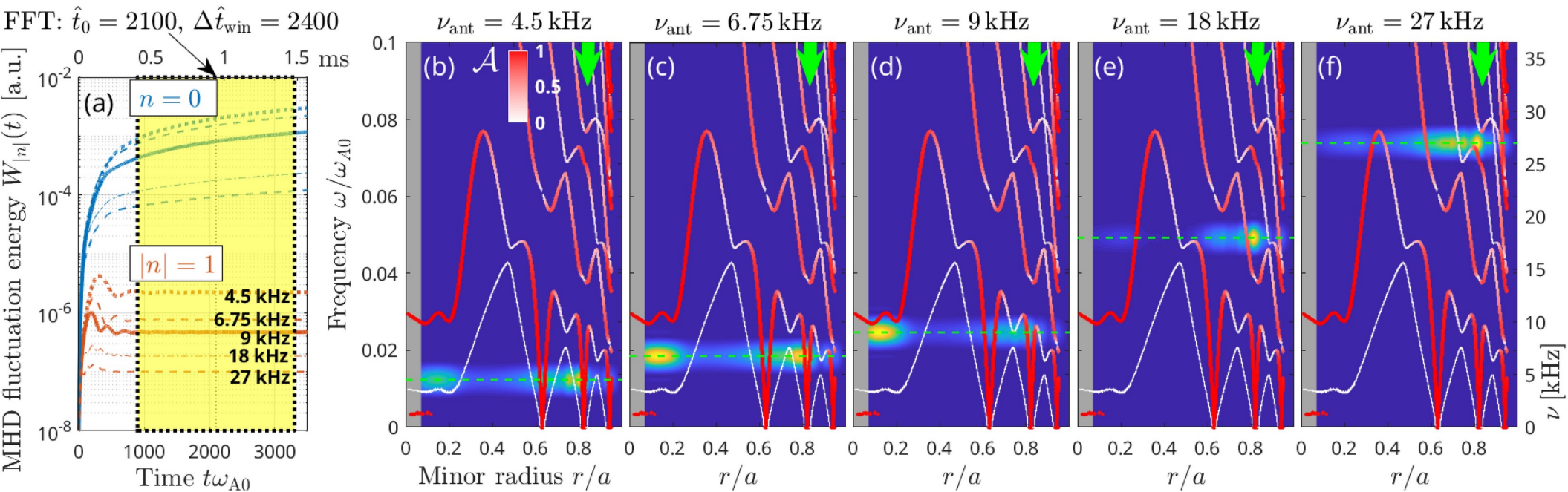
Experiment (ECEI):



Simulation results

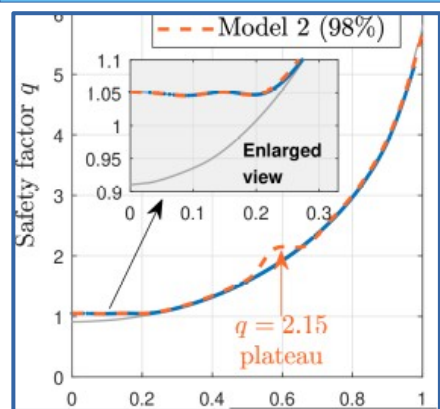
Demonstration of sub-resonant response → Can facilitate down-chirping

Drive near edge, frequency scan:

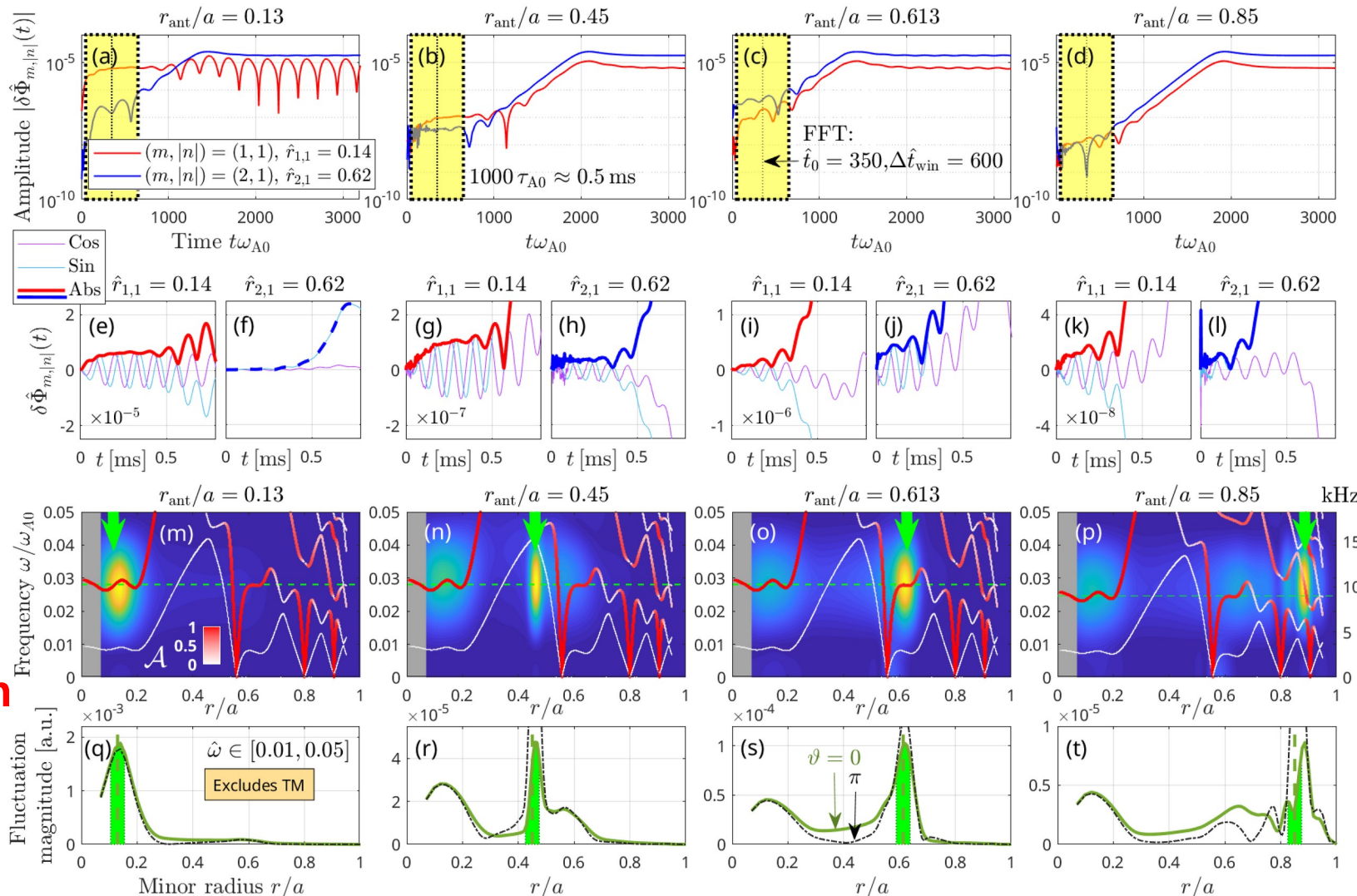


Simulation results

Demonstration of volumetric focusing effect



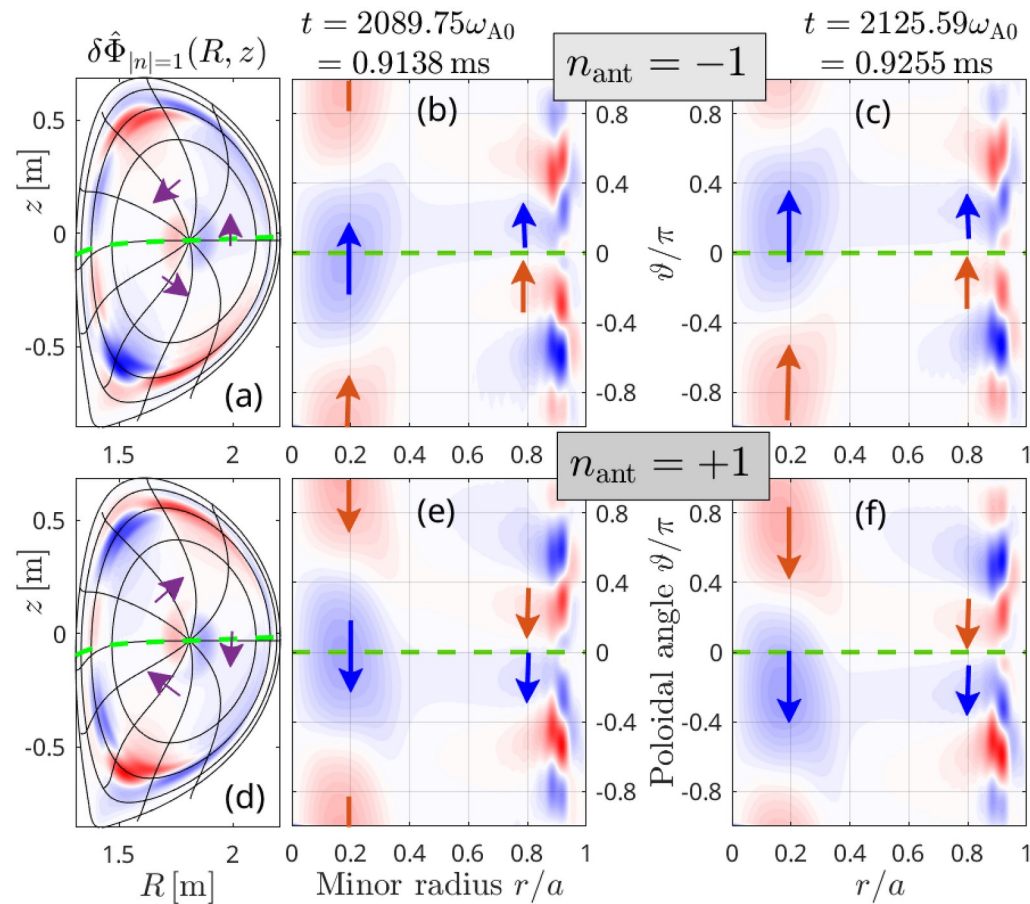
KSTAR "Model 2" (on- & off-axis continuum plateaus), scan r_{ant}



Inward drive more efficient than outward drive.

Discussion

Phasing between antenna near-field (“edge mode”) & quasi-mode in core



In sim., antenna is primary, core 1/1 mode is secondary/parasitic. → Exp, too?

Discussion

Plasma compressibility

Disable density & pressure fluctuations:

~~$$\partial \rho_b / \partial t = -\nabla \cdot (\rho_b \mathbf{u}) + \chi \nabla^2 \rho_b + S_\rho \rightarrow 0$$~~

~~$$\rho_b \partial \mathbf{u} / \partial t = -\rho_b \mathbf{u} \cdot \nabla \mathbf{u} - \nabla p_b + (\mathbf{j} - \mathbf{j}_{h,eff}) \times \mathbf{B} + S_u \quad (3)$$~~

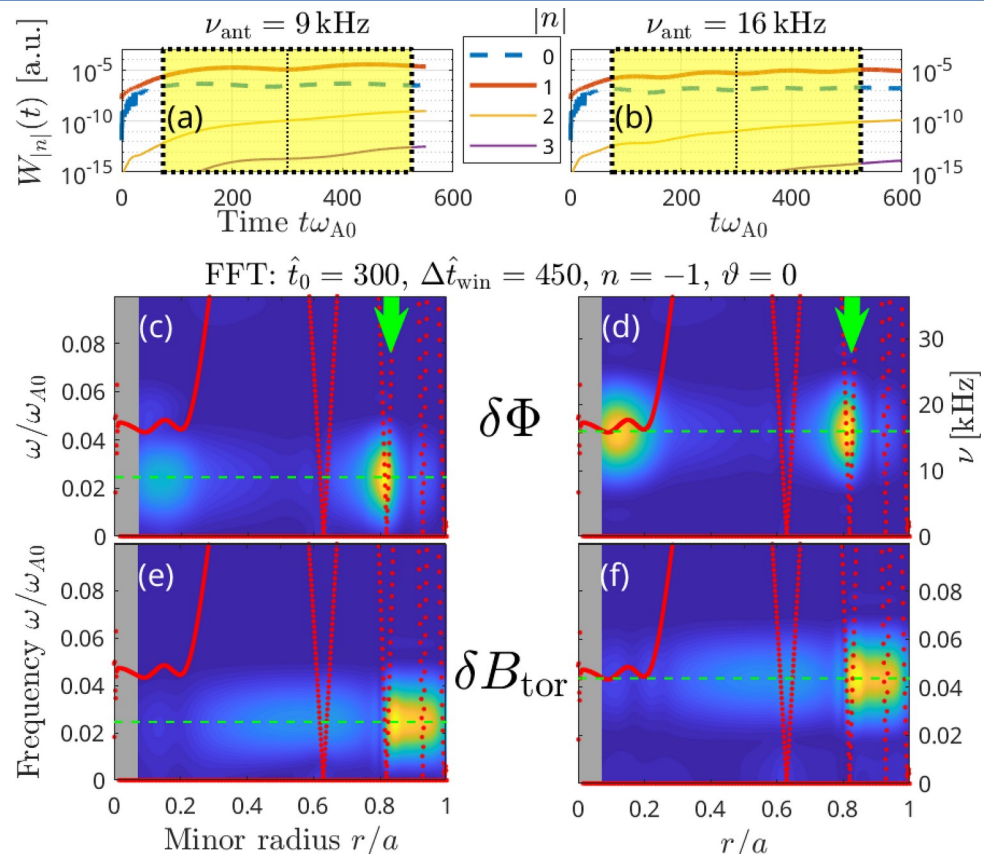
~~$$-\left[\nabla \times (\nu \rho_b \nabla \times \mathbf{u}) + \frac{4}{3} \nabla (\nu \rho_b \nabla \cdot \mathbf{u}) \right], \quad (4)$$~~

~~$$\partial \mathbf{B} / \partial t = -\nabla \times \mathbf{E}, \quad (5)$$~~

~~$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{j} + S_E, \quad (6)$$~~

~~$$\mu_0 \mathbf{j} = \nabla \times \mathbf{B}, \quad (7)$$~~

~~$$\begin{aligned} \partial p_b / \partial t = & -\nabla \cdot (p_b \mathbf{u}) - (\Gamma - 1) p_b \nabla \cdot \mathbf{u} + \chi \nabla^2 p_b \\ & + \nu \rho_b (\Gamma - 1) \left[(\nabla \times \mathbf{u})^2 + \frac{4}{3} (\nabla \cdot \mathbf{u})^2 \right] \rightarrow 0 \\ & + (\Gamma - 1) (\mathbf{j} - \mathbf{j}_{h,eff}) \cdot (\eta \mathbf{j} + S_E) + S_p. \end{aligned} \quad (8)$$~~



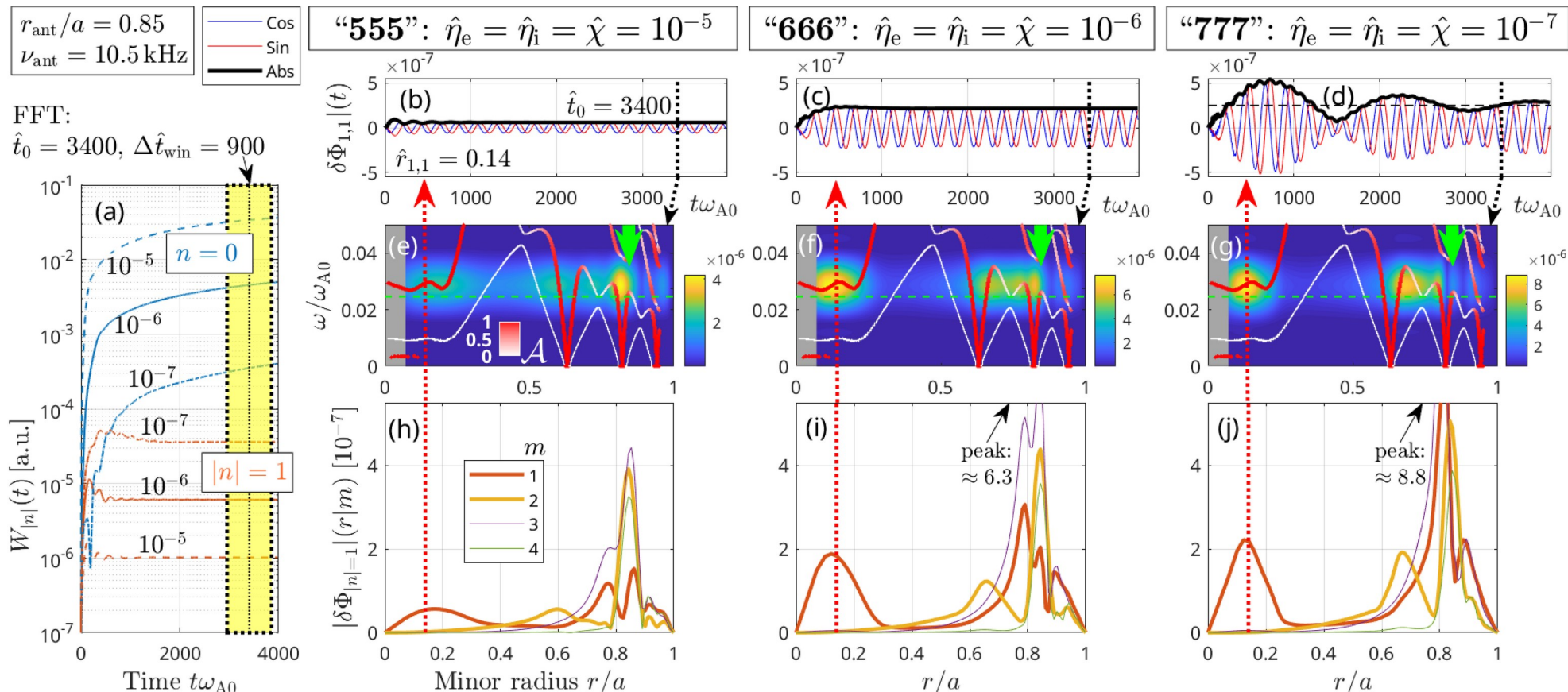
Plasma compressibility contributes, but not essential.

Low- β magnetoacoustic (fast) waves, geometric and non-ideal effects suffice.

Discussion

Plasma diffusivity: electric resistivity, ion viscosity, (thermal diffusion)

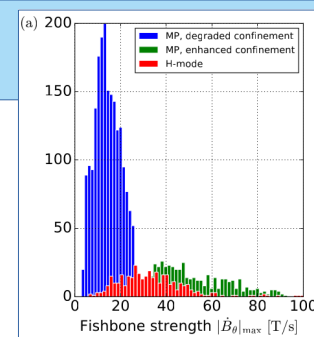
Example: Co-vary $S = \text{Re} = 10^5 \dots 10^7$ (i.e., $\text{Pr} = 1$)



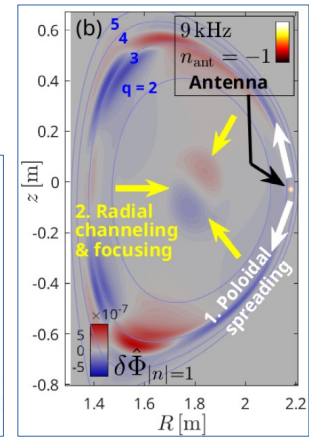
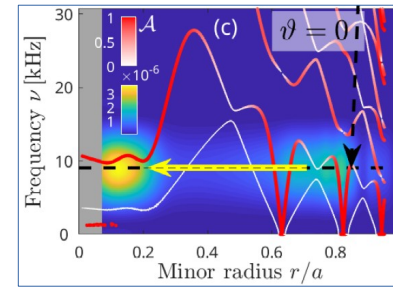
Results seem robust, but equilibration time becomes long for weak diffusion.

Summary

- Statistical analysis of many double-peaked fishbones in KSTAR
- Surveyed several possible contributing physical factors
- Found weak-evidence for edge-to-core drive (phasing near outer midplane in exp. & sim.)
- Confirmed action-at-a-distance & volumetric focusing effect (proof-of-principle via antenna-driven simulations)



For details, see
Lee+ 2026, [arxiv](#).
Bierwage+ 2026, [arxiv](#).
→ Fund. Plasma Phys.



Outlook

- Continue looking into compressible, non-ideal effects. Benchmark against kinetic models underway to verify low-frequency response (MEGA-KTI, LIGKA, ORB5 / EUTERPE, ...)
- Examine EP resonances and eigenmodes in differentially rotating plasmas with free boundary. (E_r matters at low ω ! Preparations: [Bierwage+ Comp. Phys. Comm. 317, 109823 \(2025\)](#))
- Need better understanding of processes in plasma with flat $q \sim 1$ near center ($r \rightarrow 0$). (degenerate nonequilibrium, sensitive to sources, sinks, nonideal effects, higher-order $\delta B_{\parallel}^{(i>0)}$)