ミクロ乱流間相互作用の研究

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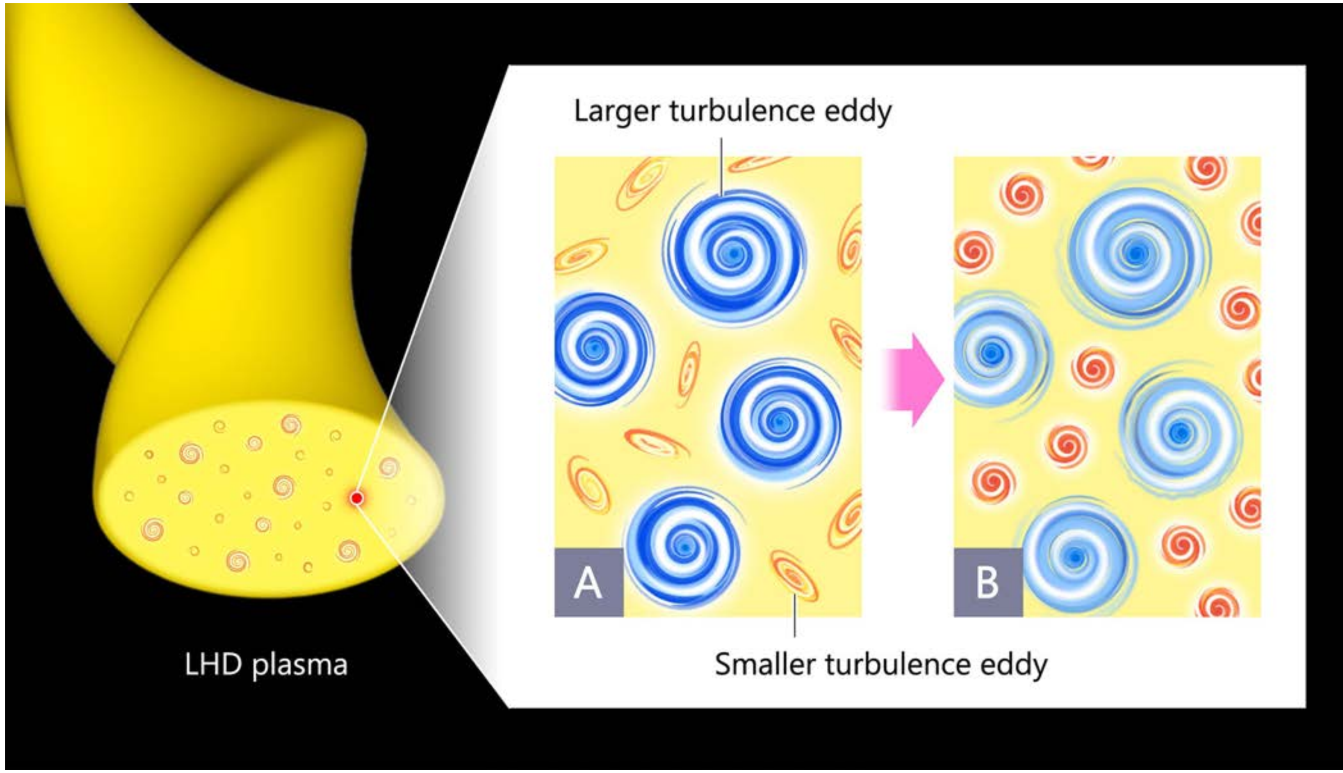

Acknowledgments

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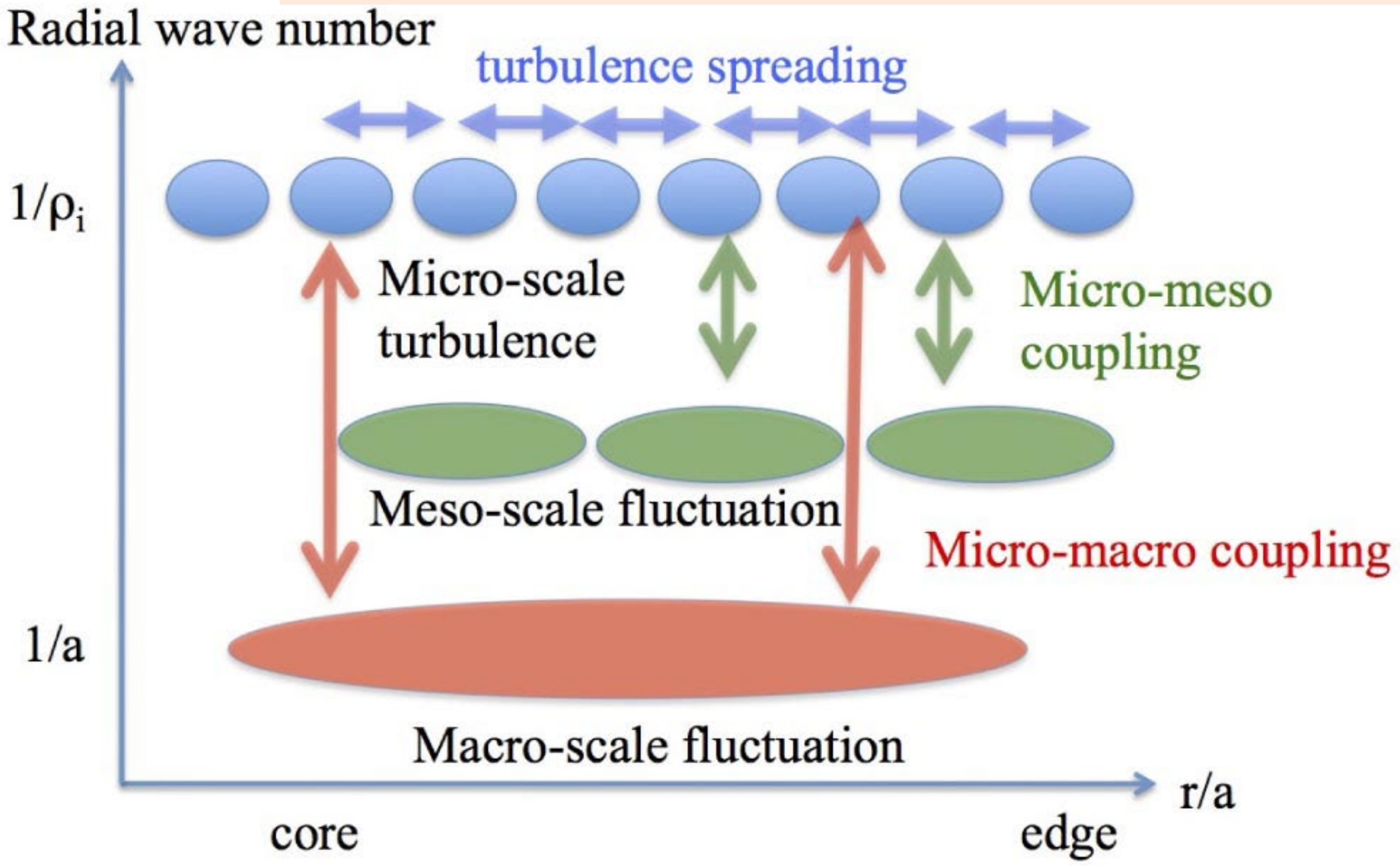
Violation of local closure in transport
→ multi-scale turbulence interaction

Elementary processes in multiple-scale turbulence



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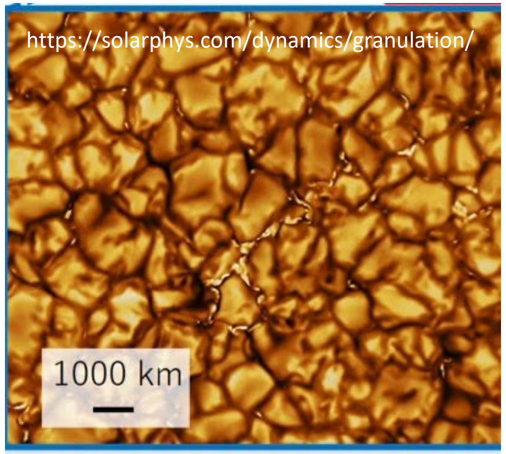
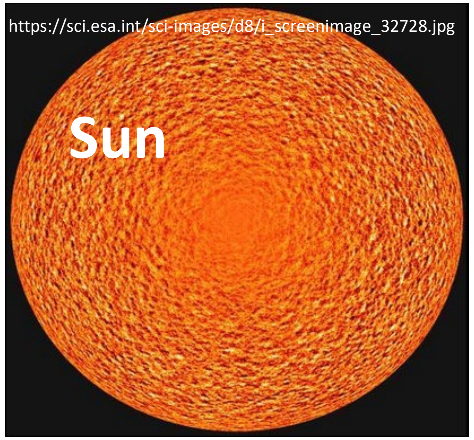
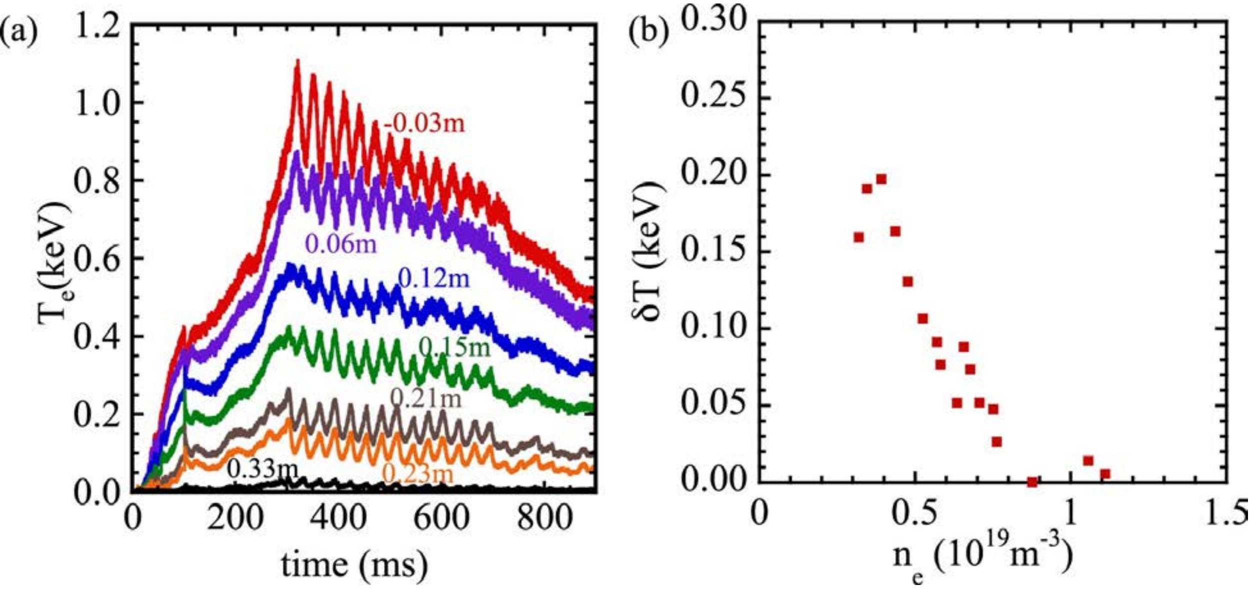




Appearance of violation of local closure by perturbations

HL-2A

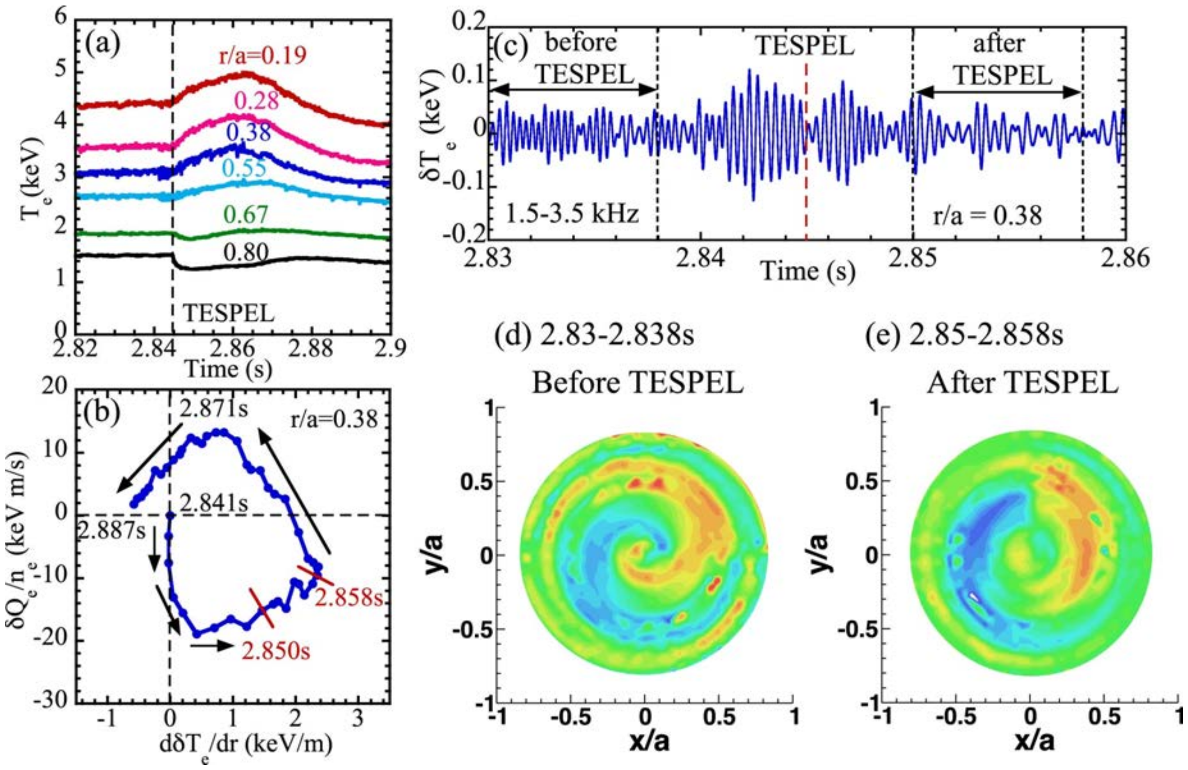
By multiple SMBI



(*a*) Time evolution of electron temperature in a discharge with multiple SMBI and (*b*) increase of central electron temperature after the SMBI as a function of electron density in HL-2A.

LHD

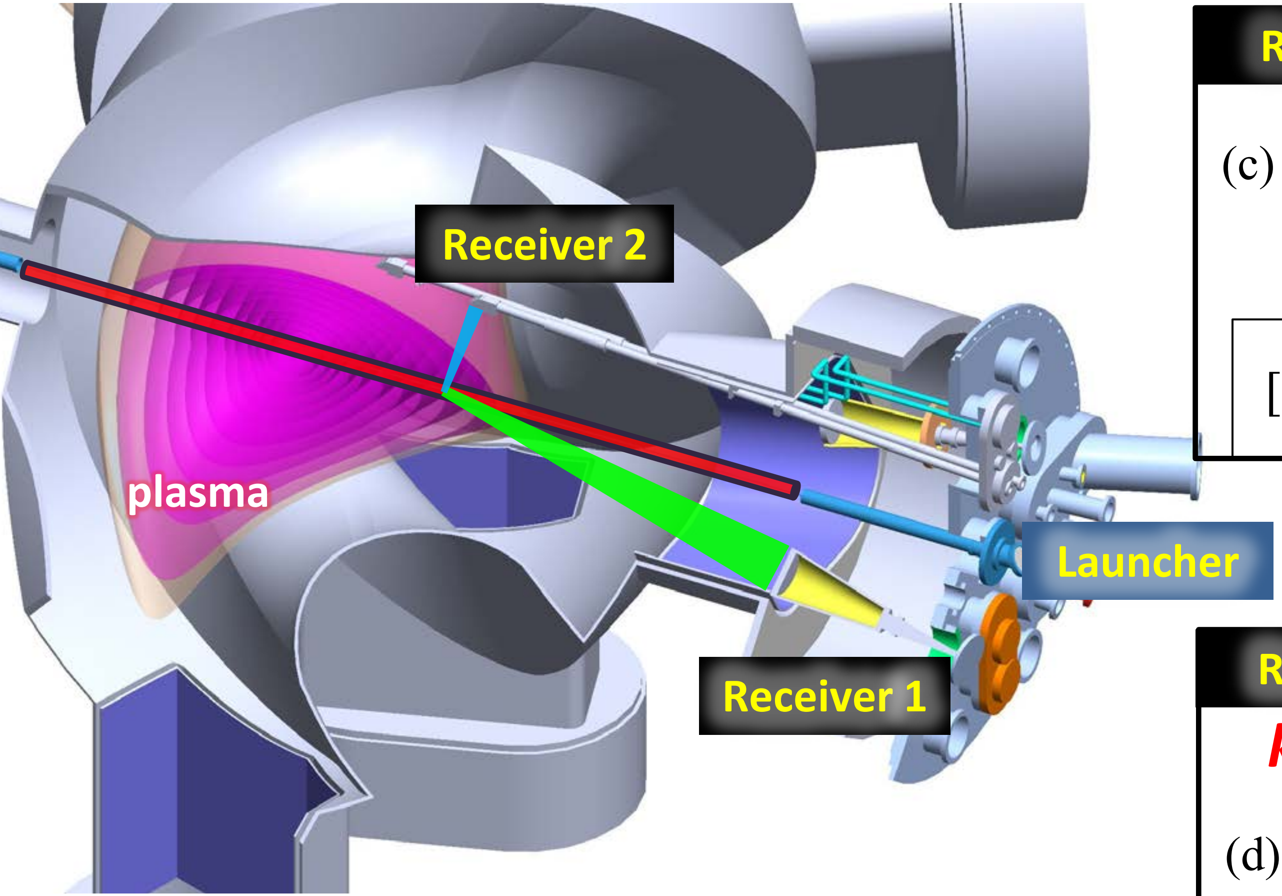
By TESPEL

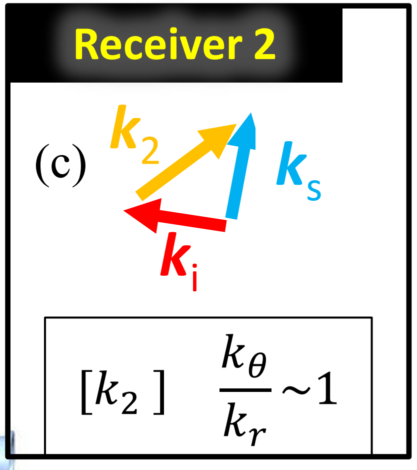


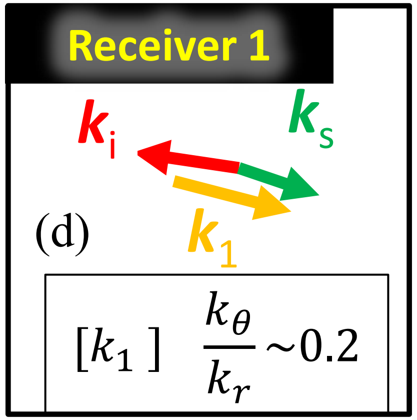
(*a*) Time evolution of electron temperature, (*b*) flux gradient relation between increment of heat flux normalized electron density and increment of temperature gradient at r_{eff}/a_{99} = 0.38, (*c*) envelope of temperature fluctuation at low-frequency band (1.5–3.5 kHz) at r_{eff}/a_{99} = 0.38 …urbulence structure on the poloidal cross- …after the TESPEL injection in LHD.

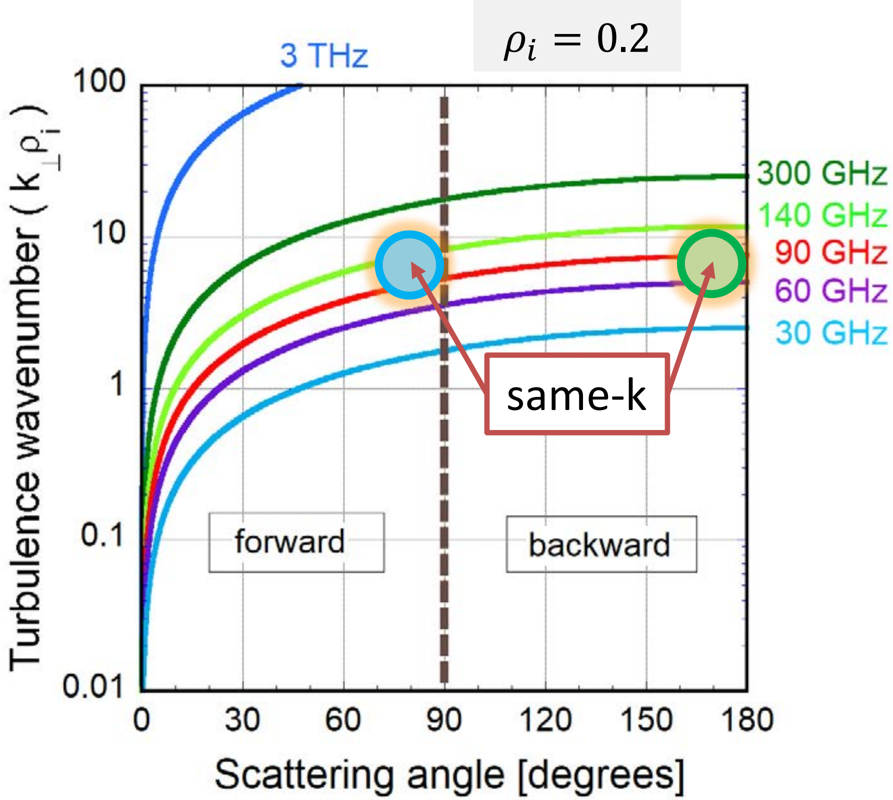
Dynamic transport experiments give us the exciting plasma phenomenon.

90 & 140GHz scattering system can access to *high*-k turb.







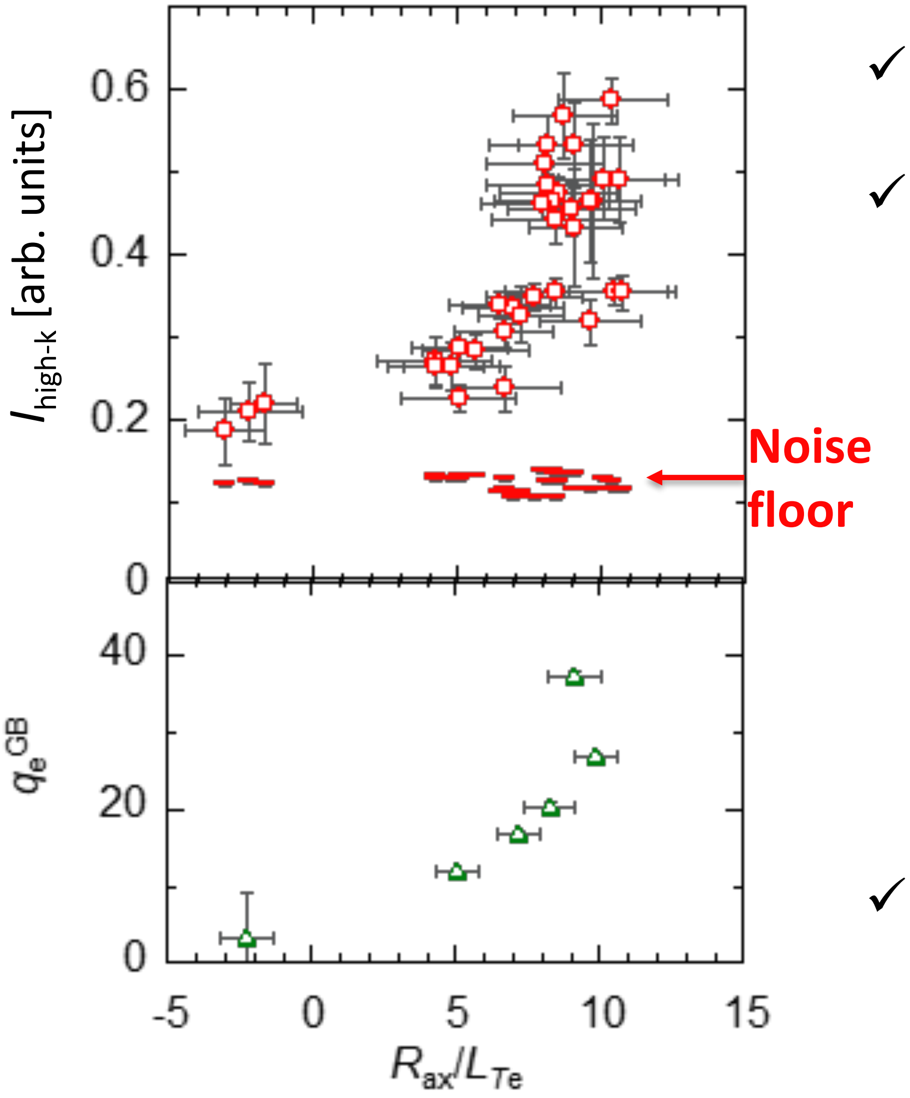


higher *k* measurement is available, including those with **anisotropy**.

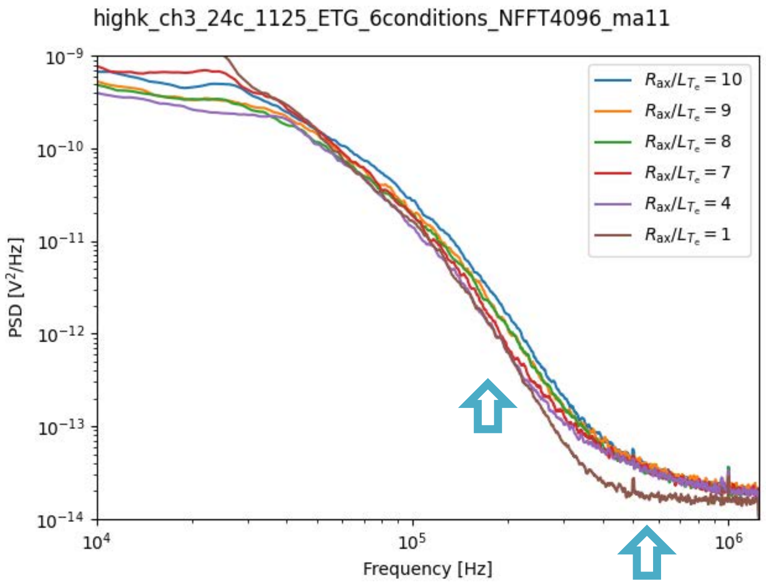
T. Tokuzawa+, J. Fusion Energy, 44:53 (2025).

- Two BS systems are routinely operated in LHD for measuring the electron-scale turbulence. Each system is sensitive to radial wavenumber k_r and poloidal wavenumber k_θ turbulences.

Discovery that turbulence on the electronic scale is strongly excited, and, at the same time, the heat flux increases.



- ✓ Electron-scale turbulence intensity increases steeply with increasing normalized electron-temperature gradient R_{ax}/L_{Te}.
- ✓ Electron-heat flux also increases steeply with increasing R_{ax}/L_{Te}.

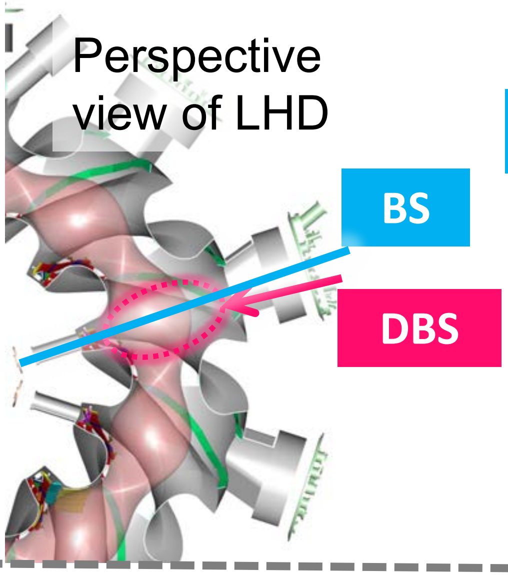


- ✓ Even at R_{ax}/L_{Te} ~ 0, electron-scale turbulence significantly exists.

➔ New mystery

T. Nasu+, Nucl. Fusion 64 096008 (2024).
T. Tokuzawa+, J. Fusion Energy, 44:53 (2025).

Simultaneous observation of micro-scale(low-k) and HF-scale (high-k) turbulence & of turbulence anisotropy

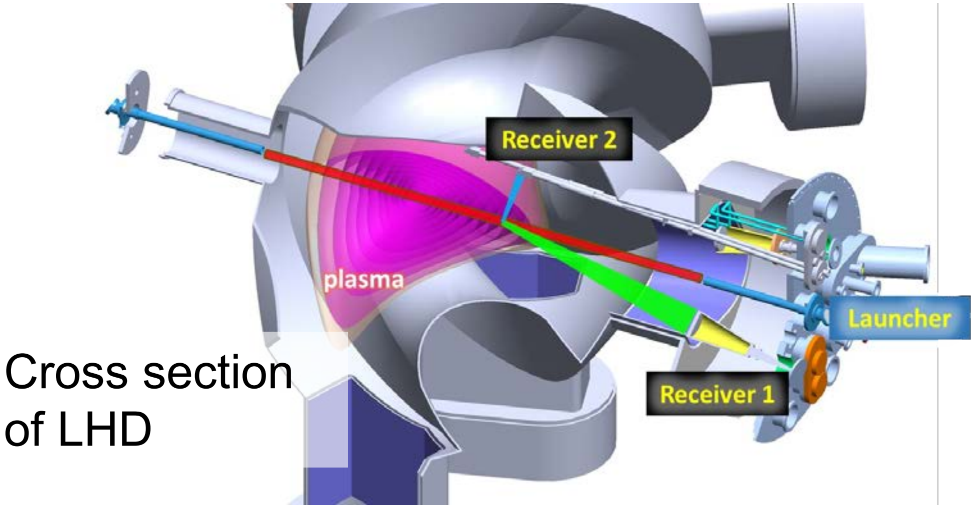


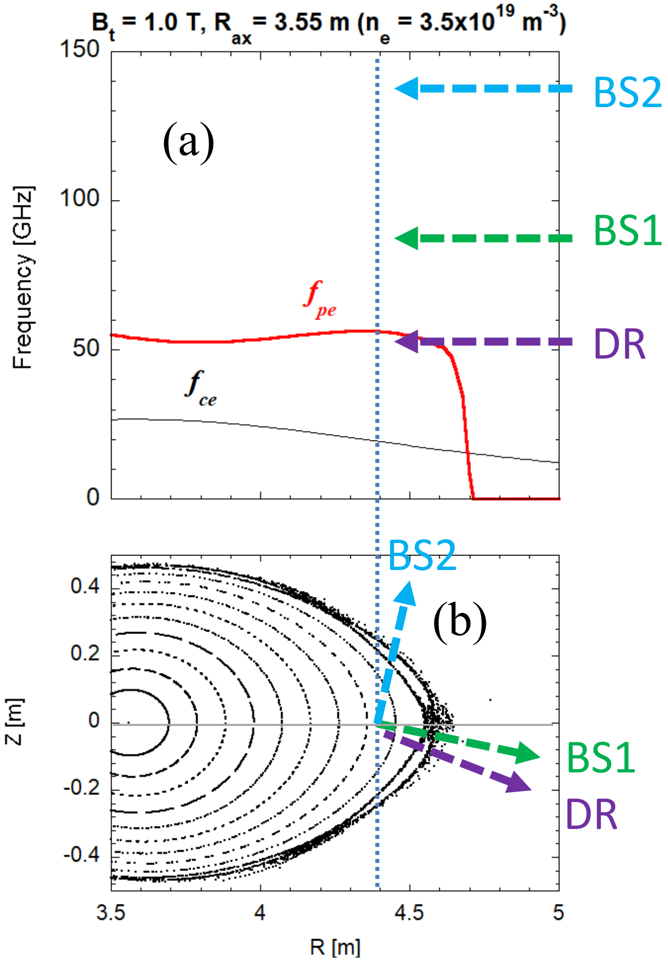
High-k ($k_{\perp}\rho_s$~10)

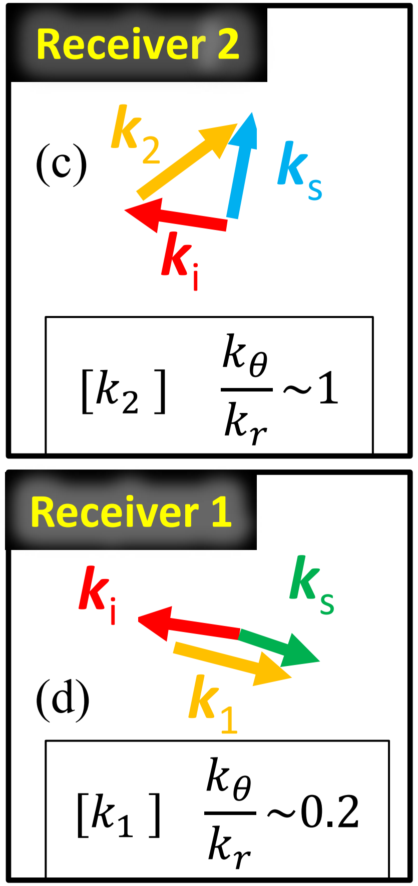
$k_{\perp} = 30\sim40\ \mathrm{cm}^{-1}$

Low –k ($k_{\perp}\rho_s$~10)

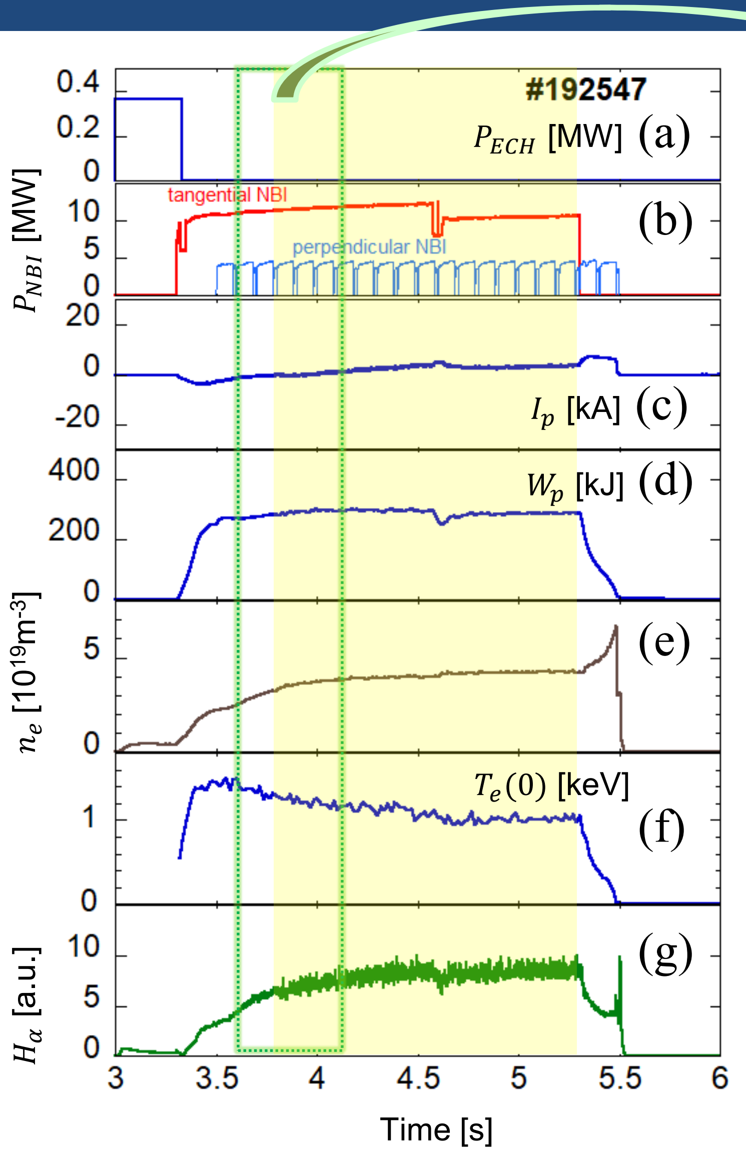
$k_{\perp} = 2\sim20\ \mathrm{cm}^{-1}$

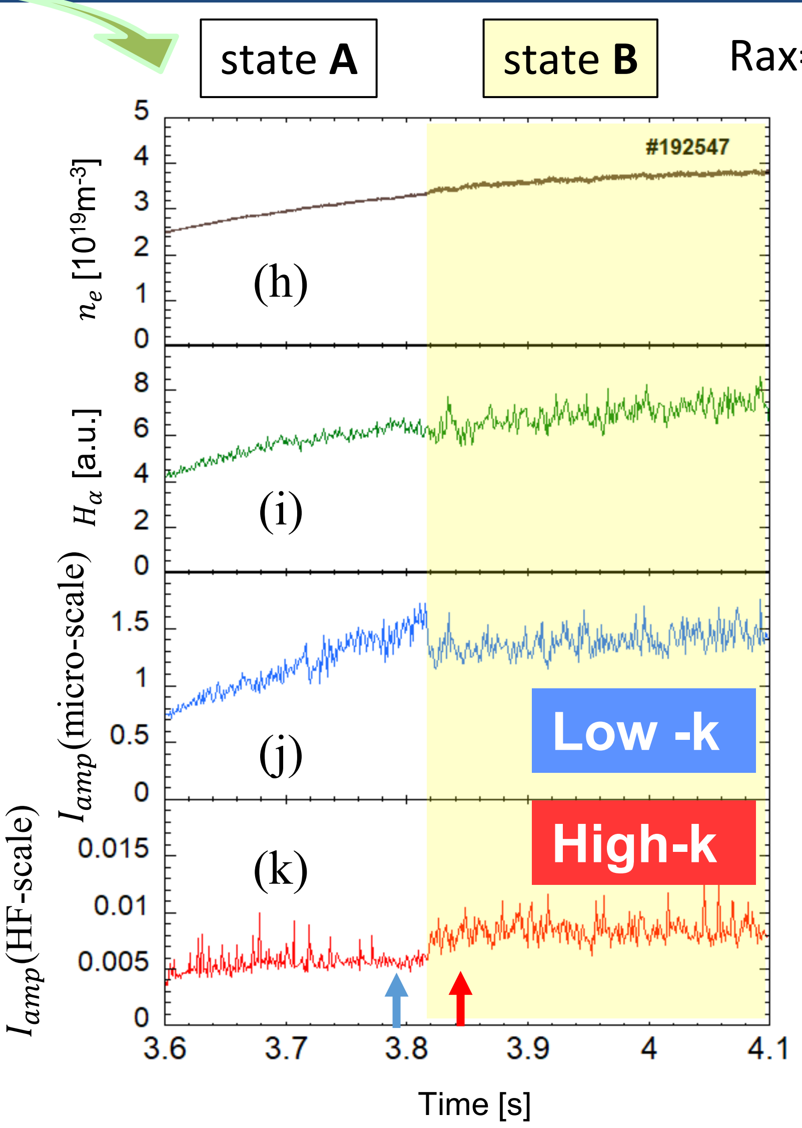






Temporal behavior of plasma parameters



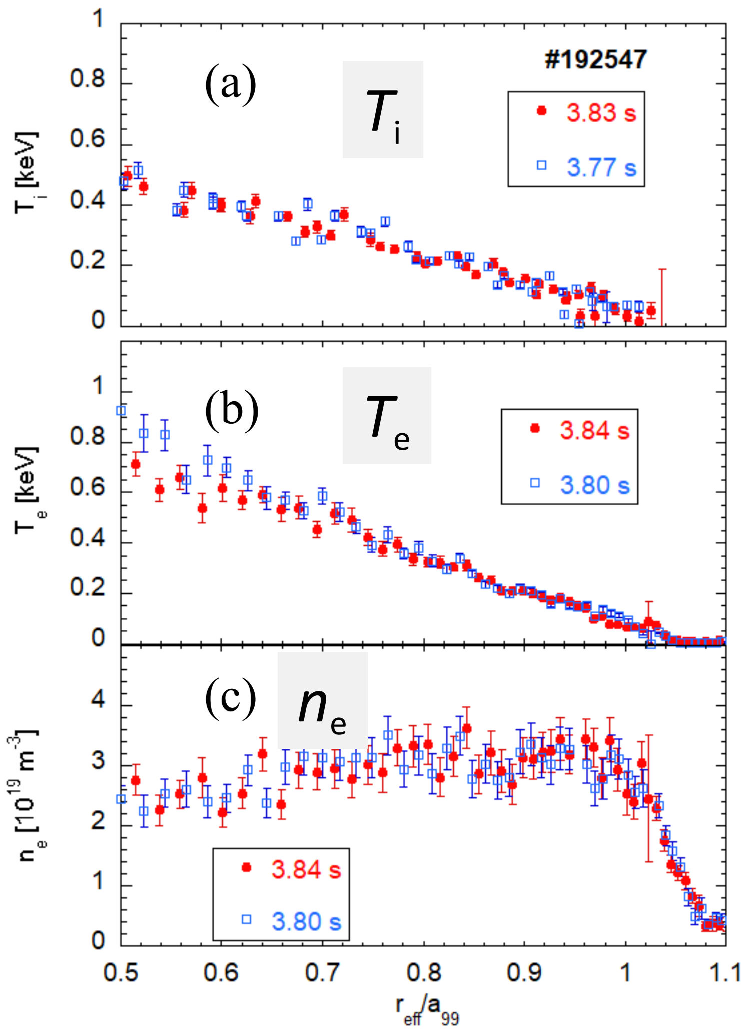


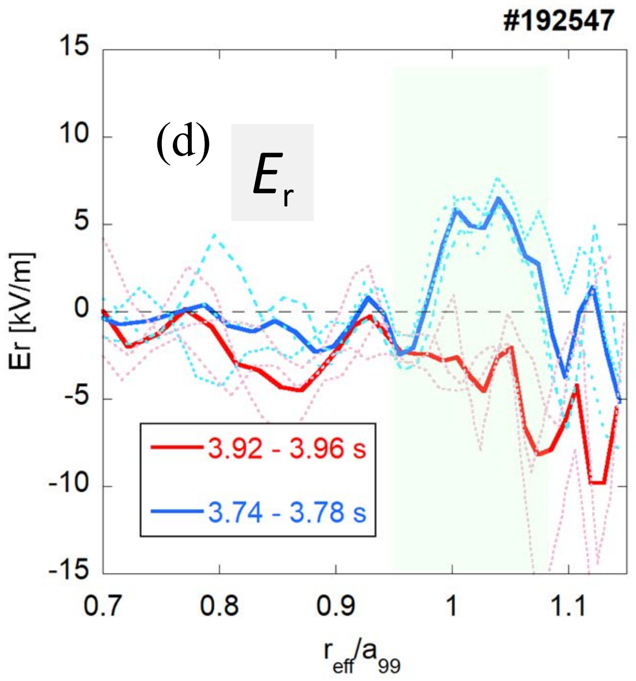
Rax=3.55m, Bt=1T

- Before and after the bifurcation, low-k turbulence rapidly decreases and high-k turbulence increases.
- The other (macro) parameters show slow time variation.

NO significant change of radial profiles of Ti, Te, ne, and Er at the observation location in two states

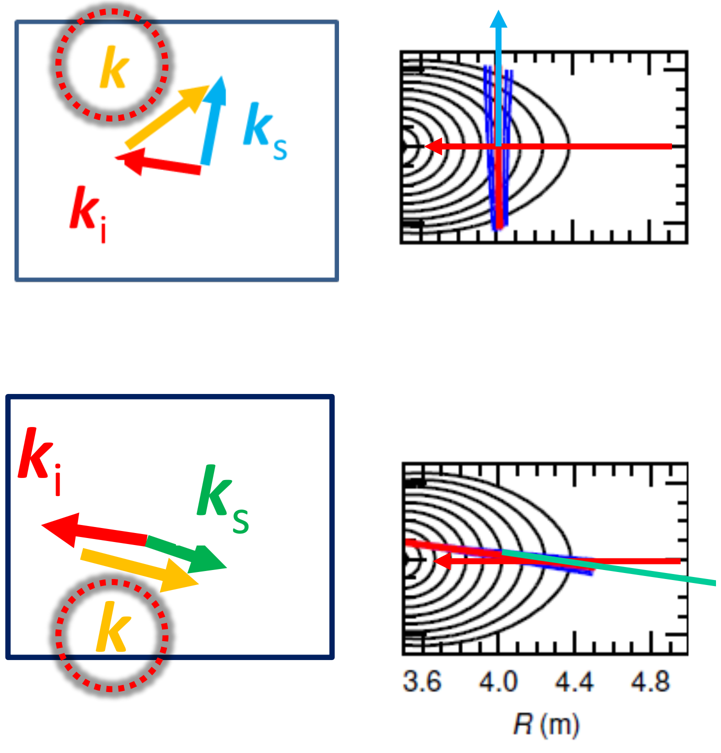
✓ There is no significant change in the macro parameter profiles before and after the bifurcation (with the exception of the peripheral Er).

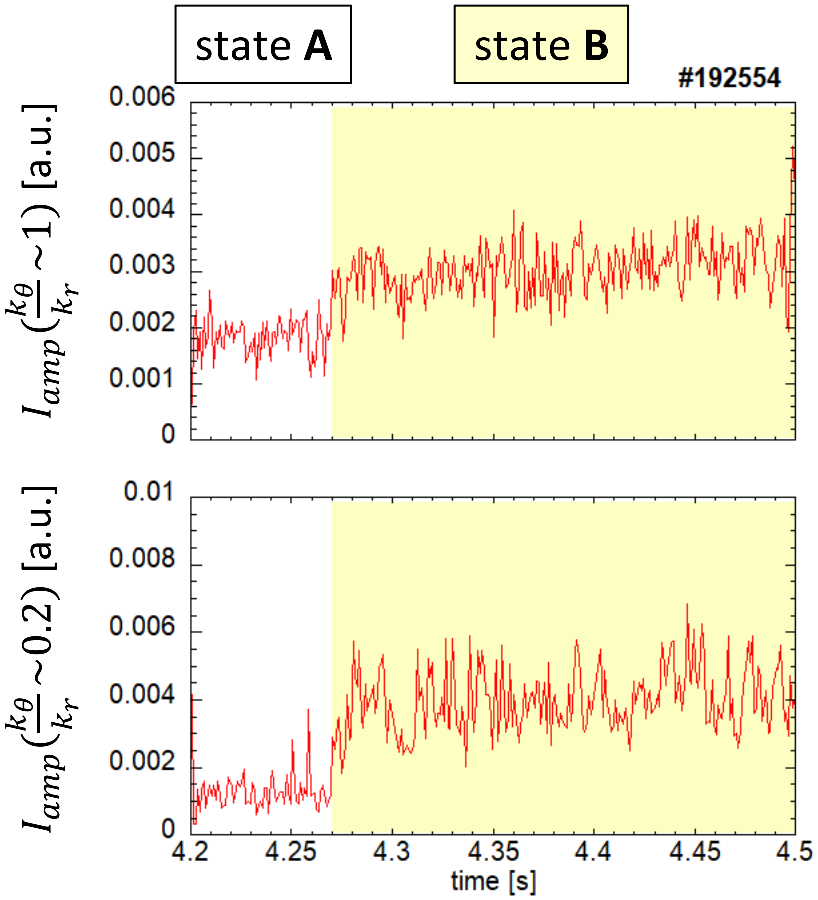


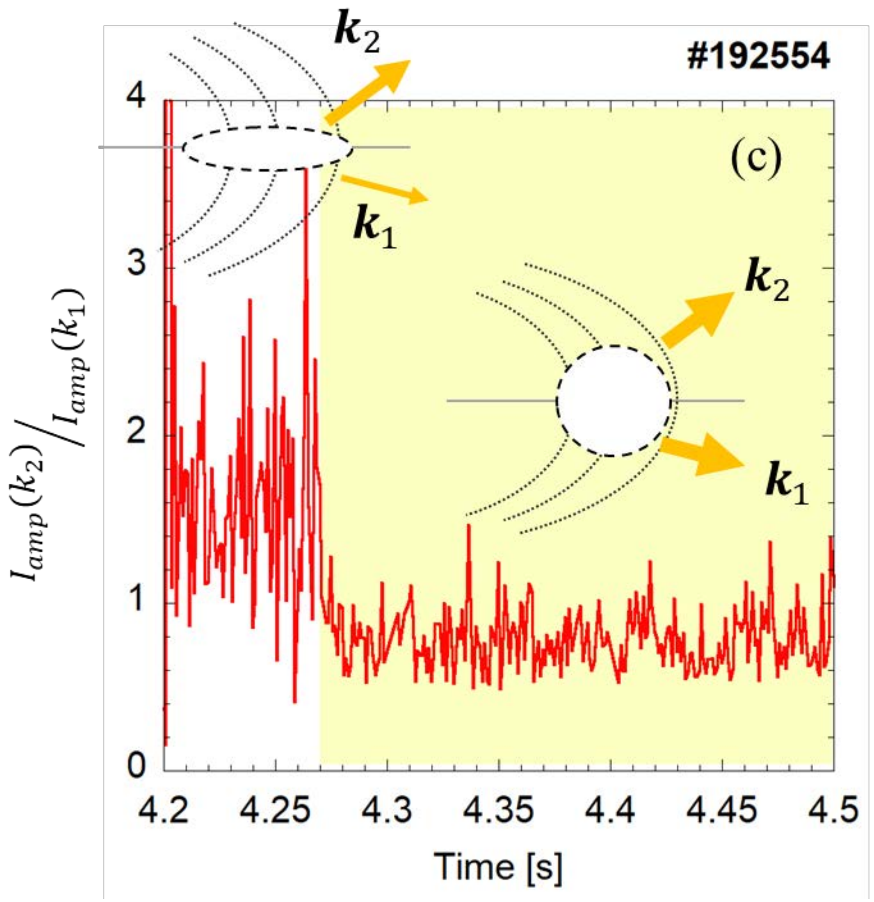


Observations of anisotropic changes may indicate as the evidence of vortex deforming.

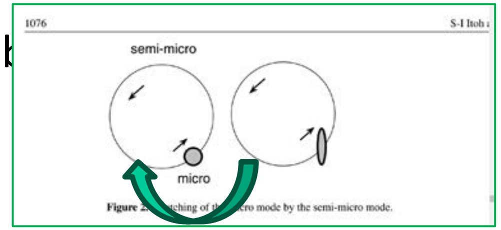
Anisotropy of *high*-k



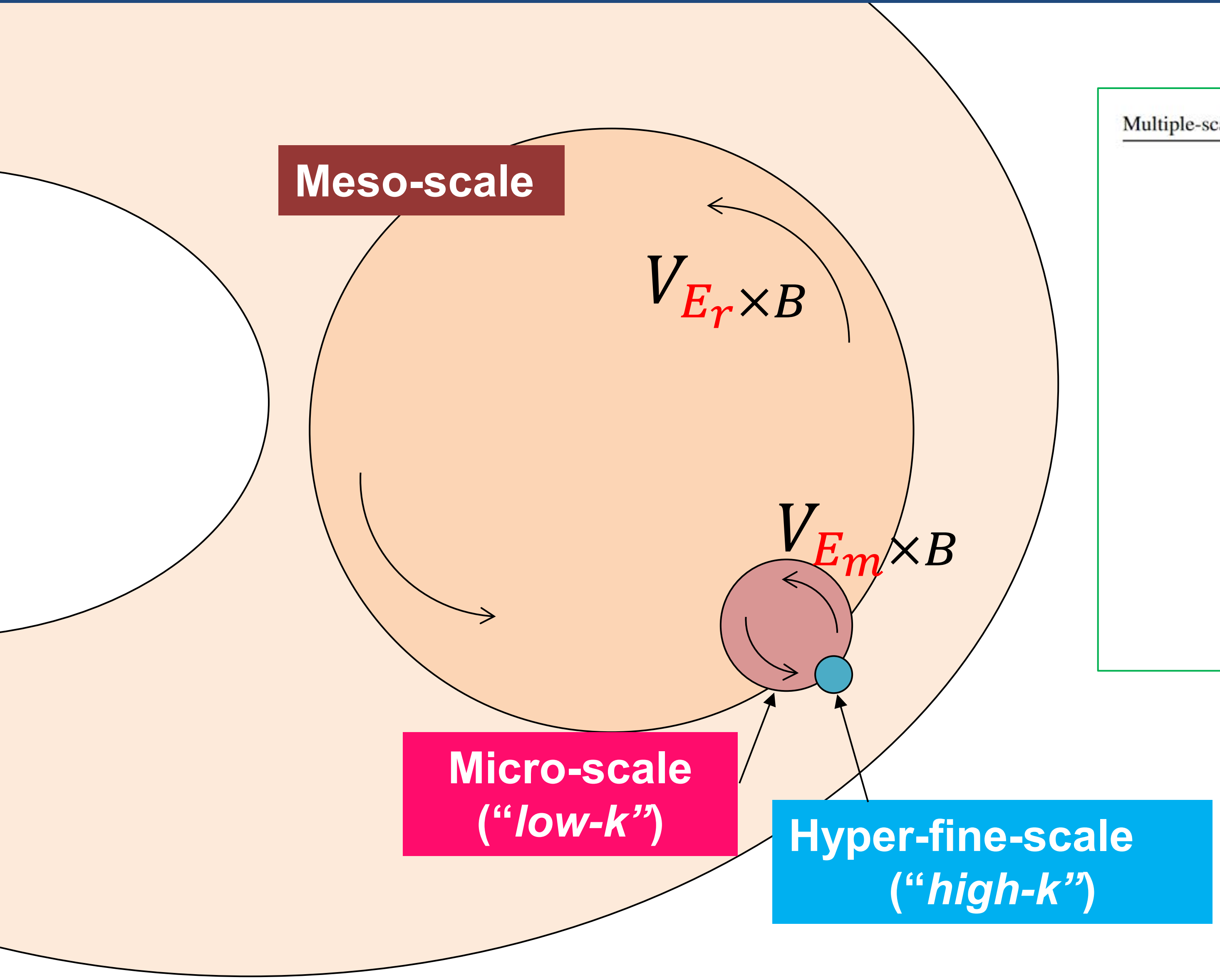




- ✓ Before the bifurcation, the anisotropy of the HF-scale (high-k) component is large (deformed b the micro-scale (low-k) component). After the bifurcation, however, the anisotropy becomes. This turbulent bifurcation qualitatively supports the depiction of [S.I. Itoh+, PPCF 2001].



Hypothesis: multi-scale interactions may be affected by the electric field (shear) at each scale.



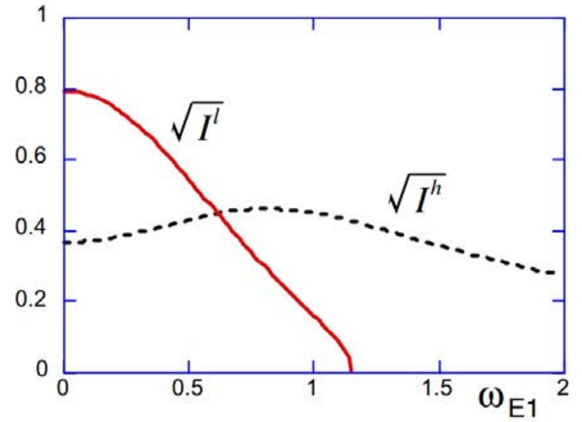

Multiple-scale-length turbulence in plasmas 1089

Figure 14. Fluctuation amplitude $(I^l)^{1/2}$ (full curve) and $(I^h)^{1/2}$ (dashed curve) as functions of the shear of global $E \times B$ velocity. ω_{E1} changes from $\omega_{E1}/\omega_{Ec}^l = 0$ to $\omega_{E1}/\omega_{Ec}^l = 2$. ($(I^l)^{1/2}$ and $(I^h)^{1/2}$ are normalized to $(I_{\mathrm{eff}})^{1/2}$.) The case of the soft transition: $D^l(0) = (I_{\mathrm{eff}})^{1/2}$, $D^h(0) = 0.6(I_{\mathrm{eff}})^{1/2}$ and $\omega_{Ec}^l = \sqrt{0.3}\omega_{Ec}^h$.

S.-I. Itoh and K. Itoh : Plasma Phys. Contr. Fusion 43 (2001) 1055.

✓ Micro-scale turb can suppress hyper-fine scale turb, in the below condition.

$$(L/\rho_i) > \rho_i/\delta$$

Discussion : Does dynamic shearing by micro-scale turbulence occur?

(1) From the mixing length estimation on gyro-Bohm, the amplitude of micro-scale (low-k) turbulence is expressed by

$$\frac{e\phi_m}{T} \sim \frac{\rho_i}{L}$$

and the decorrelation rate of micro-scale (low-k) turbulence γ_m is

$$\gamma_m \sim C_m V_{drift}/\rho_i$$

(2) It is considered the micro-scale (low-k) turbulence is suppressed, when the shearing rate by radial electric field(E_r) increases and $V'_{E\times B} > \gamma_m$.

(3) On the other hand, the effect of this radial electric field on HF-scale (high-k) turbulence is relatively small because it needs to be (ρ_i/δ) times stronger than it is to affect high-frequency turbulence.

(4) Moreover, the estimated electric field produced by the micro-scale (low-k) turbulence vortex E_m is $E_m \sim \phi_m/\rho_i$ and stretching rate from micro-scale turb. to HF-scale (high-k) could be

$$V'_m \sim \frac{V_{drift}}{\rho_i} \sim \left(\frac{L}{\rho_i}\right) V'_{E\times B}$$

Therefore, it is predicted that the micro-scale turbulence vortex will suppress HF-scale (high-k)turbulence under the conditions where $L/\rho_i > \rho_i/\delta$.

Now, Ti = Te = 200 eV, B=0.65T

- $\rho_i = 2.2 \times 10^{-3}$ [m]
- $\rho_e = 5.1 \times 10^{-5}$ [m] ← δ: high-k scale
- $L_{Te} = 7.6 \times 10^{-2}$ [m] ← *L: low-k scale*

➢ $(L/\rho_i) = 35$

➢ $\rho_i/\delta = 43$

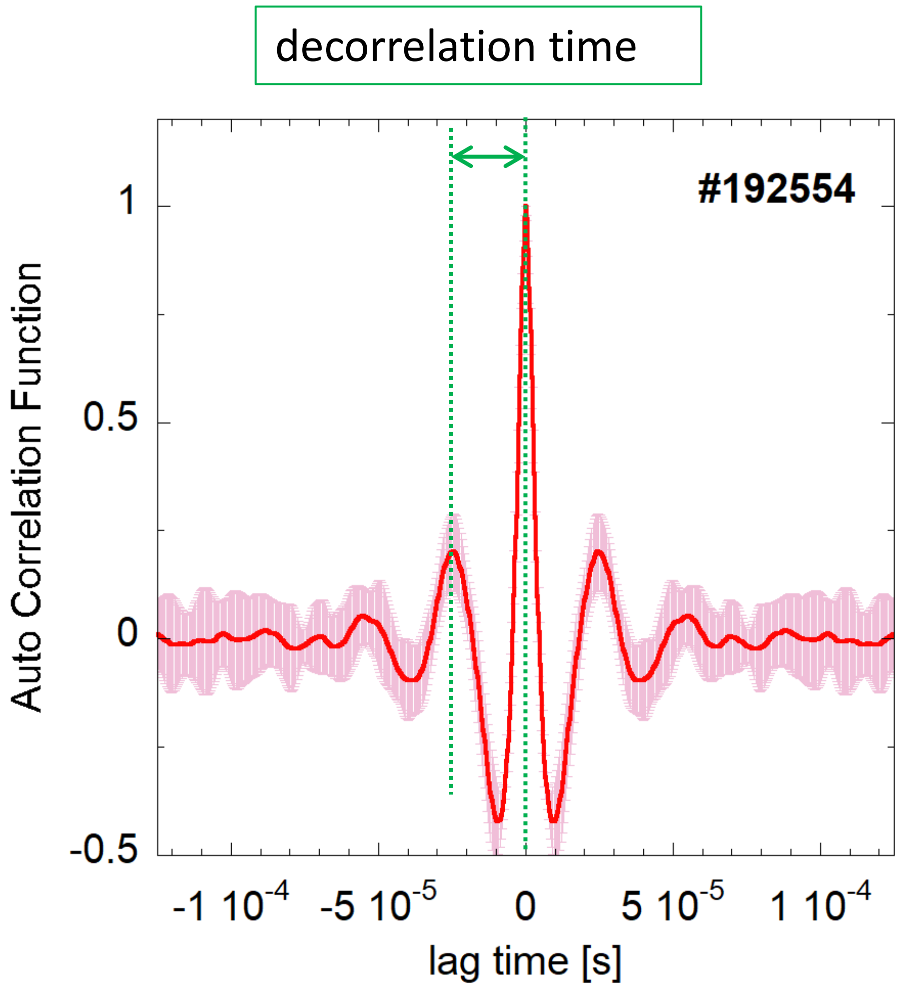
➔ **Condition that shearing by micro-scale (low-k) turbulence affects HF-scale (high-k) turbulence is a valid range.**

Discussion : Does dynamic shearing by micro-scale turbulence occur?

(1) Decorrelation rate of the HF-scale (high-k) turbulence is about $5\text{x}\ 10^4$ [s^{-1}].

(2) On the other hand, the estimated electric field produced by the micro-scale (low-k) turbulence vortex E_m is about 0.1- 1 [kV/m] and its shearing rate is the order of 10^4 - 10^5 [s^{-1}].

The suppression mechanism by the micro-scale (low-k) component is highly plausible and important for the dynamics of the HF-scale (high-k) component.



Summary

We succeeded for the first time in the world in simultaneous measurement of micro-scale (low-k) turbulence and hyper-fine (HF) scale (high-k) turbulence, as well as simultaneous measurement of the anisotropy of HF-scale turbulence at the same spatial location in LHD.

I. **A bifurcation in the turbulent state occurs between the micro-scale (low-k) oscillations and the HP-scale (high-k) ones.** When this bifurcation occurs, the amplitude of the micro-scale component decreases, and that of the HF-scale one increases rapidly.

II. **The change of the anisotropy of HF-scale (high-k) is observed.** Before the bifurcation, the anisotropy of the HF-scale component is large (deformed by the micro-scale component). After the bifurcation, however, the anisotropy becomes smaller. This turbulent bifurcation qualitatively supports the theoretical depiction [1].

III. **The decorrelation rate of the HF-scale (high-k) component is observed.** The degree of deformed due to a vortex motion of the micro-scale component, as evaluated by the commonly-used mixing length model, is found to be as large as or larger than the experimentally-measured decorrelation rate of the HF-scale component. The suppression mechanism by the micro-scale (low-k) component is highly plausible and important for the dynamics of the HF-scale (high-k) component.

IV. **Thus, the experimental results indicate that it is essential to study cross-scale nonlinear interactions, including micro- (low-k) and HF-scale (high-k) components, to understand the physics of high-temperature nuclear fusion plasmas.**

Concept of microwave diagnostics station

✓ **Multimodal measurement**

Concentrate multiple microwave diagnostic systems at the 3-O port to allow synchronous measurement of heterogeneous parameters for turbulence study.