

The 16th International West Lake Symposium on the “Physics and Fusion and Space Plasmas”, April 9-12, 2026 Hangzhou, China

Linear and nonlinear dynamics in magnetic-shear free plasmas leading to ITBs

Y. KISHIMOTO^{1,2,3,4}

Collaborators: **R. ZHAO**¹, K. IMADERA^{1,2}, J.F. Liu¹, W. WANG⁴, J.Q. LI⁴,
Z.X. WANG⁵, A. ISHIZAWA^{1,2}

¹ Graduate School of Energy Science, Kyoto University, Japan

² Nonlinear/Non-equilibrium Plasma Science Research UNIT, Kyoto University, Japan

³ Institute of Advanced Energy, Kyoto University, Japan

⁴ Southwestern Institute of Physics, China

⁵ Dalian University of Technology, China

kishimoto.yasuaki.84r@st.kyoto-u.ac.jp

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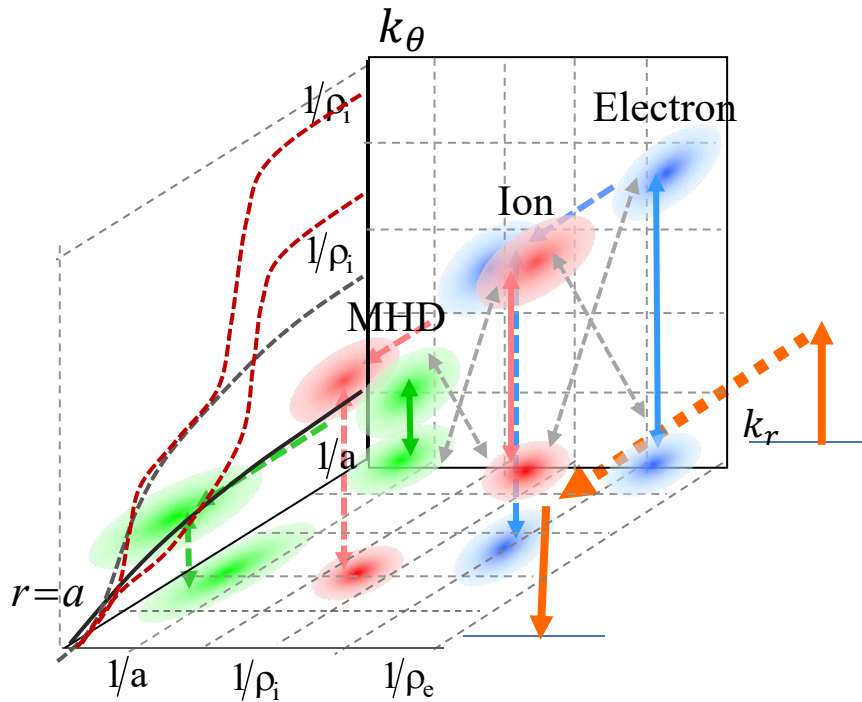
1981 at HIFT (Hiroshima Institute for Fusion Theory)

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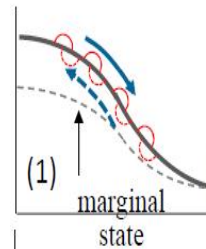
Global characteristics of L-mode plasma

► Non-local dynamics & structures

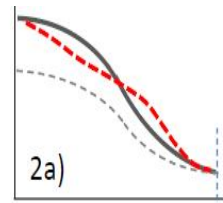


► Key dynamics in L-mode

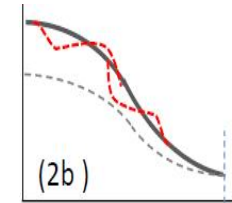
- turbulent spreading
- avalanches
- Intermittent bursts
- ExB shear layers



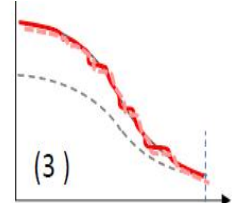
$$\ell_c \sim \rho_i - (L_T \rho_i)^{1/2}$$



$$\ell_c \sim (L_T \rho_i)^{1/2} - L_T$$



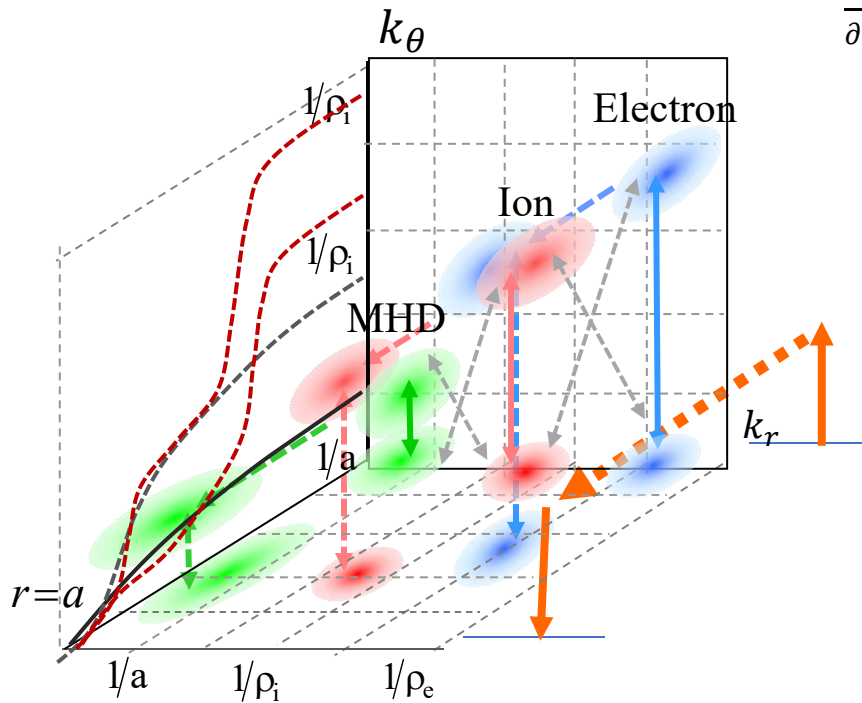
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Global characteristics of L-mode plasma

► Non-local dynamics & structures



- Thermodynamic (1st order) entropy

$$\frac{\partial}{\partial t} \int s^{(1)} d^3 Z + \frac{\partial}{\partial x} \int v_{ExB} s^{(1)} d^3 Z = \mathfrak{R}(x) + C^{(1)} + S_{sin}^{(1)}$$

Heat/particle flux

$$\frac{\partial}{\partial t} \int \int_0^a s^{(1)} d^4 Z = \int_0^a \mathfrak{R}(x) dx + \frac{1}{2} \left(\frac{Q_0}{T_h} - \frac{Q_0}{T_c} \right) \text{reduction} < 0$$

- Phase space entropy (2st order) entropy

$$\frac{\partial}{\partial t} \int s^{(2)} d^3 Z + \frac{\partial}{\partial x} \int v_{ExB} s^{(2)} d^4 Z = -\mathfrak{R}(x) + C^{(2)} + S_{src}^{(2)}$$

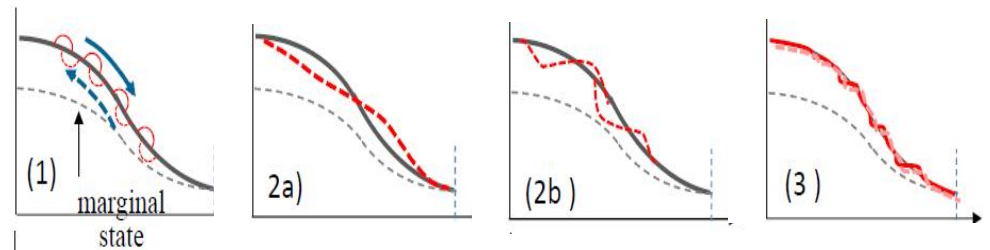
Radial convection

Muto, et al., PoP 28, 082304 (2021)

Kishimoto et al., Phil. Trans. R. Soc. A 381 20210231 (2023)

► Key dynamics in L-mode

- turbulent spreading
- avalanches
- Intermittent bursts
- ExB shear layers



$$\ell_c \sim \rho_i - (L_T \rho_i)^{1/2}$$

$$\ell_c \sim (L_T \rho_i)^{1/2} - L_T$$

$$\ell_c \sim (L_T \rho_i)^{1/2}$$

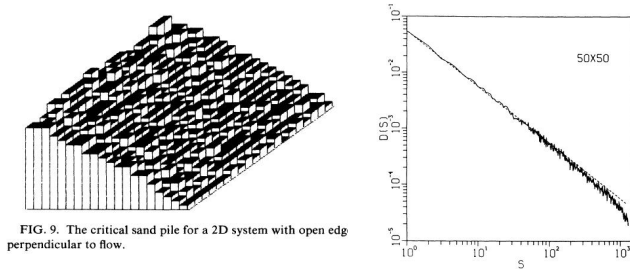
$$\ell_c \sim (L_T \rho_i)^{1/2}$$

Hahm and Diamond, P., J. Korean Phys. Soc. 73, 747 (2018)

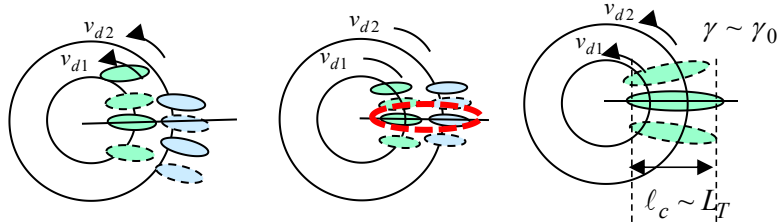
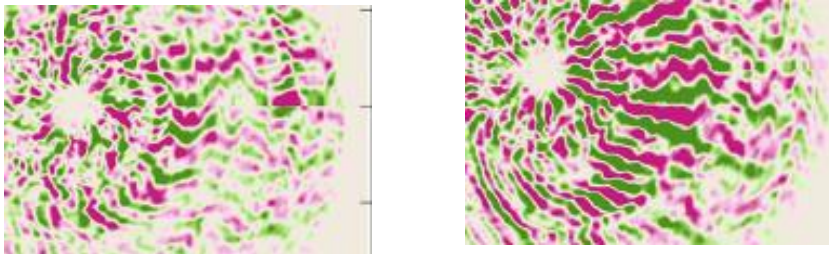
Potential eddy distribution and heat flux PDF

- ▶ Real space based statistical approach directly measuring heat flux eddies

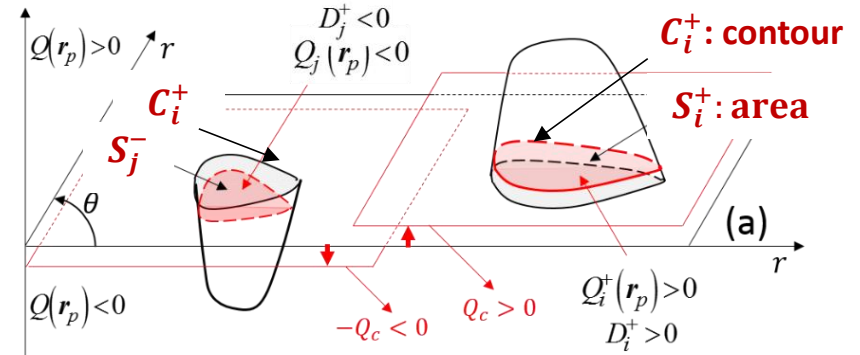
- SOC model: Bal et al., PRA 38, 364 (1998)



- Spontaneous phase alignment of potential eddies, leading to radially extended structure, causing quasi-deterministic burst
- quiescent phase** **bursting phase**



- Definition of heat flux eddy and statistics

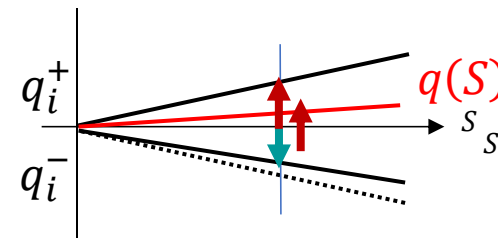


$$q_i^\pm = \int_{S_i^\pm} Q_r(\mathbf{r}) R d\mathbf{r}_p d\phi, \quad \text{Heat flux by } i\text{-th eddy}$$

$$D_i^\pm = q_i^\pm / S_i^\pm \quad \text{Heat flux density for eddy } i.$$

- Mixing length estimate (wave breaking)

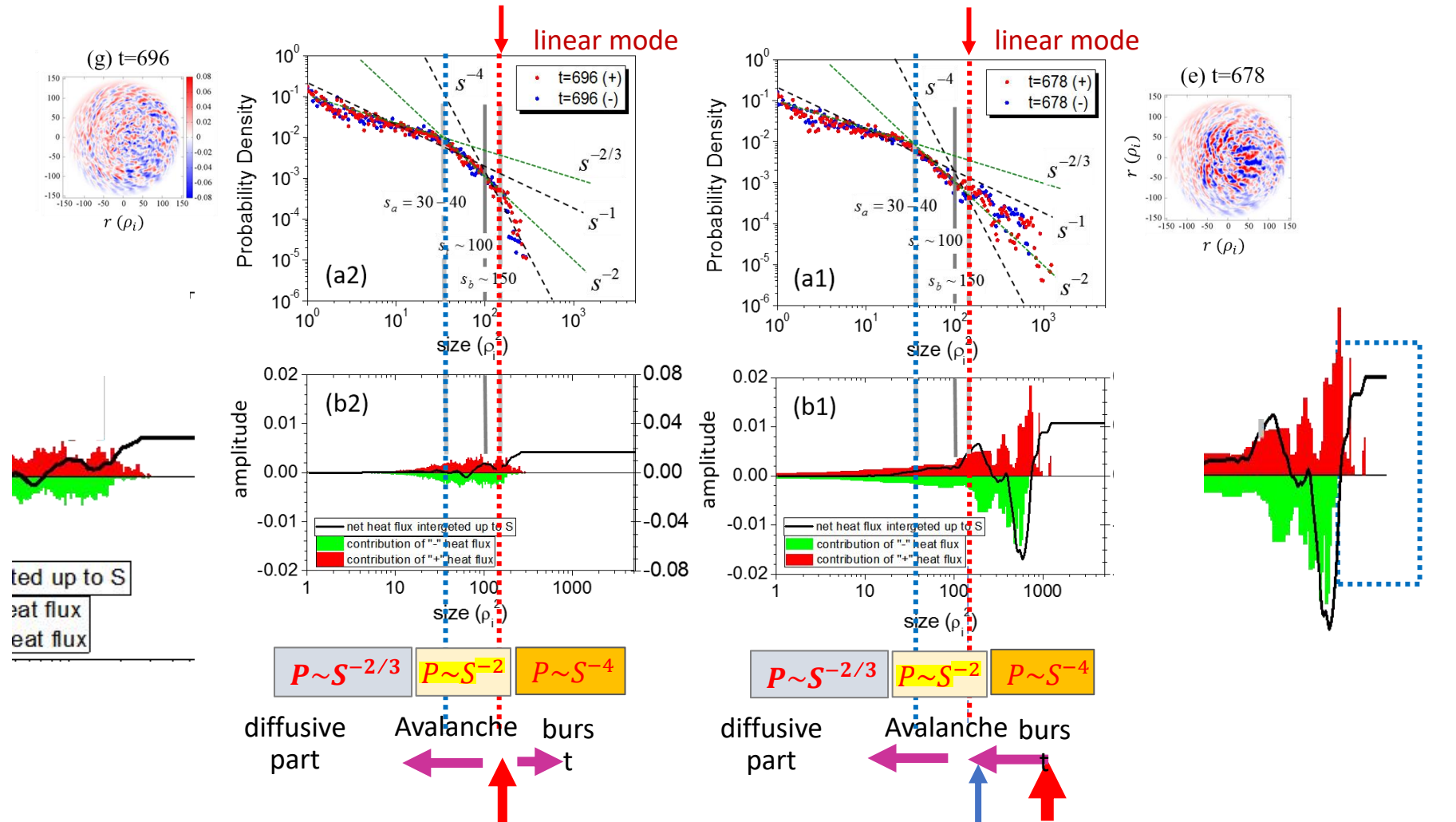
$$\phi_{sat.} \sim \frac{B}{\tau_c k_r k_\theta} \propto \frac{BS}{\tau_c} \quad q \sim |\phi_{sat.}|^2$$



Power law characteristics of heat flux PDF

Wang et al., Nucl._Fusion 58, 056005 (2020)

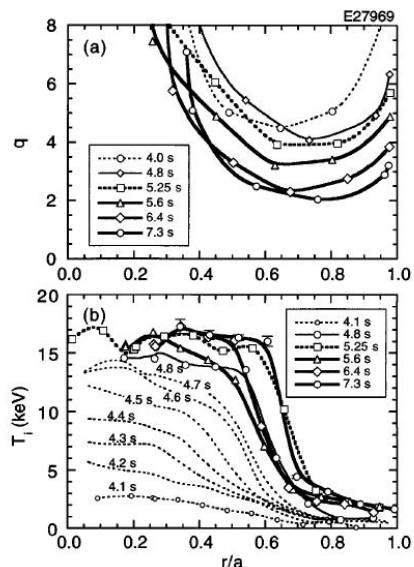
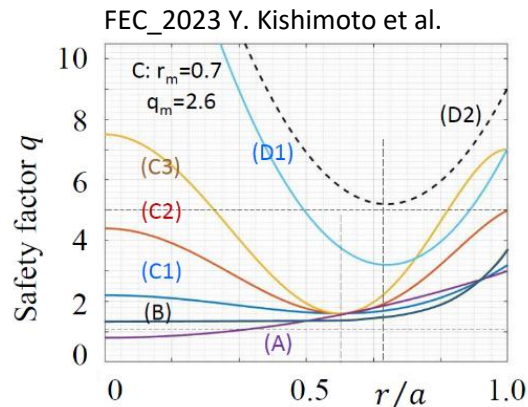
► Heat flux PDFs in quiescent and byrsting cases



- Smaller number of larger size eddies are responsible for the effective heat flux.
- Quasi-linear estimates is likely in **quiescent phase**, but hardly applicable in **bursting phase**

ITB formation from L-mode plasmas

- ▶ All improved modes, such as H-mode, ITB, etc. are realized by breaking the L-mode, subject to the profile constraints.



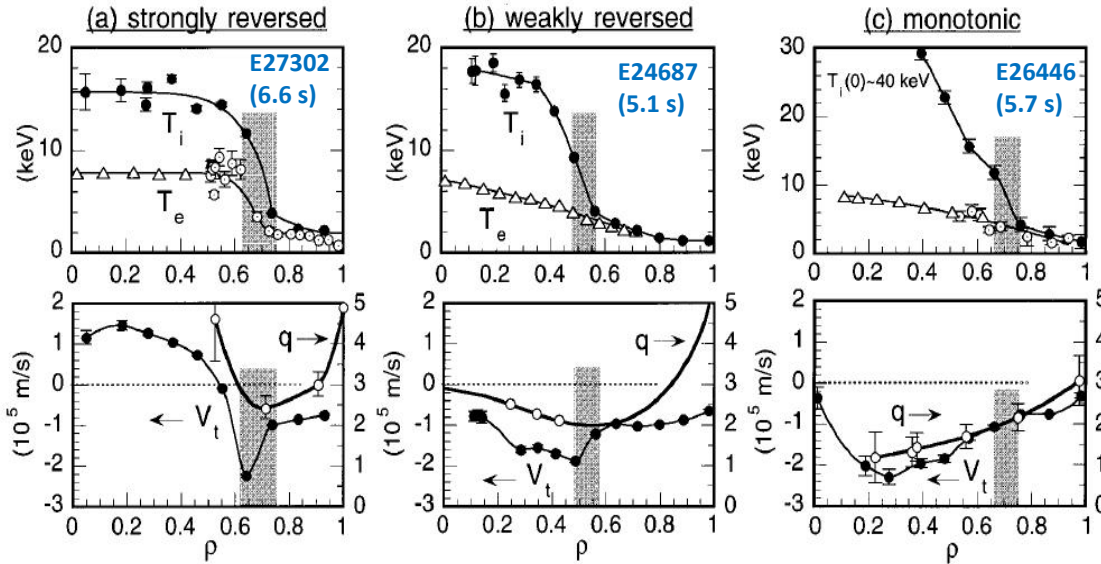
Physical Mechanism for trigger

- **Magnetic structure**: weak (positive/negative, nearly zero), mildly, strongly reversed magnetic shear
- **ExB (Er) flow shear** : externally/intrinsically momentum drive
- **MHD event and rational surface** : Internal kink and sawtooth, LLM, Fish-fish-bone, DTM
- **High Energy ions**: NBI, ICH, EC, LB

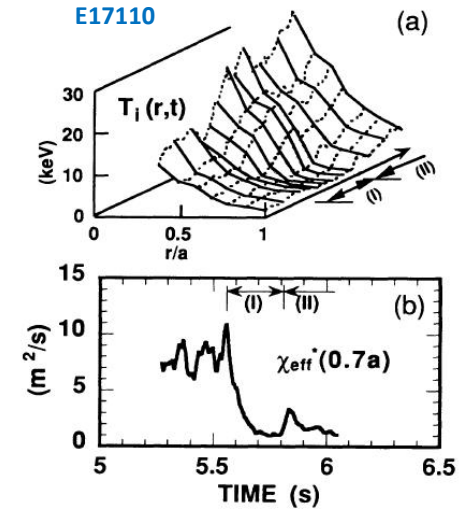
Key subjects

- Trigger/initiation mechanism
- Development and formation dynamics
- Sustainment and stability
- Long time scale evolution
- Control recipe
- Response to external disturbance

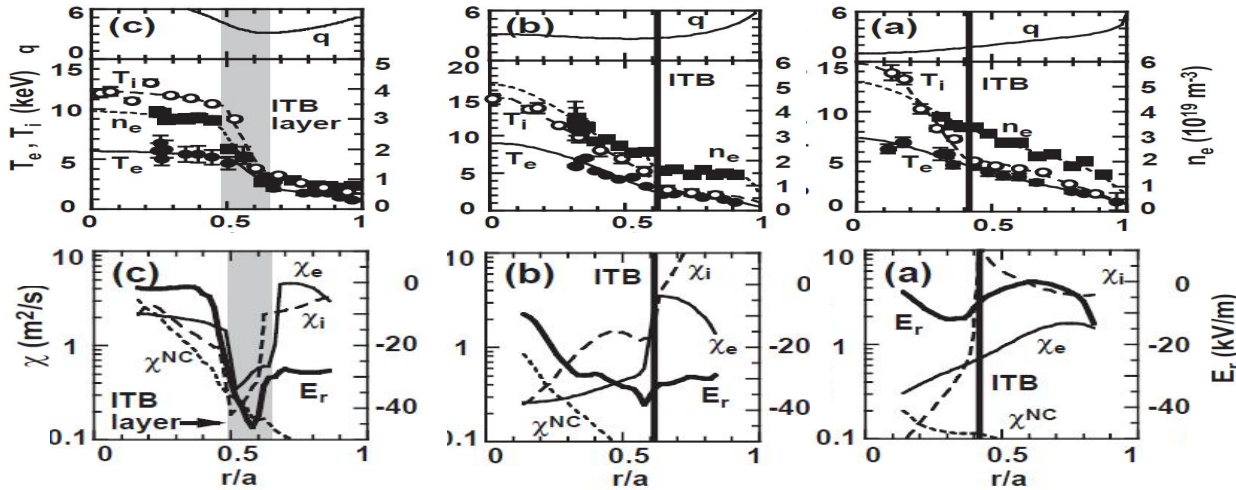
Different ITB formation for different q-profile



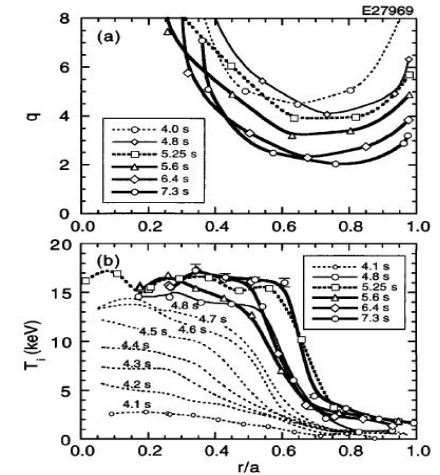
Koide et al., PoP 4, 1623 (1997)



Koide et al., PRL 72, 3662 (1994)



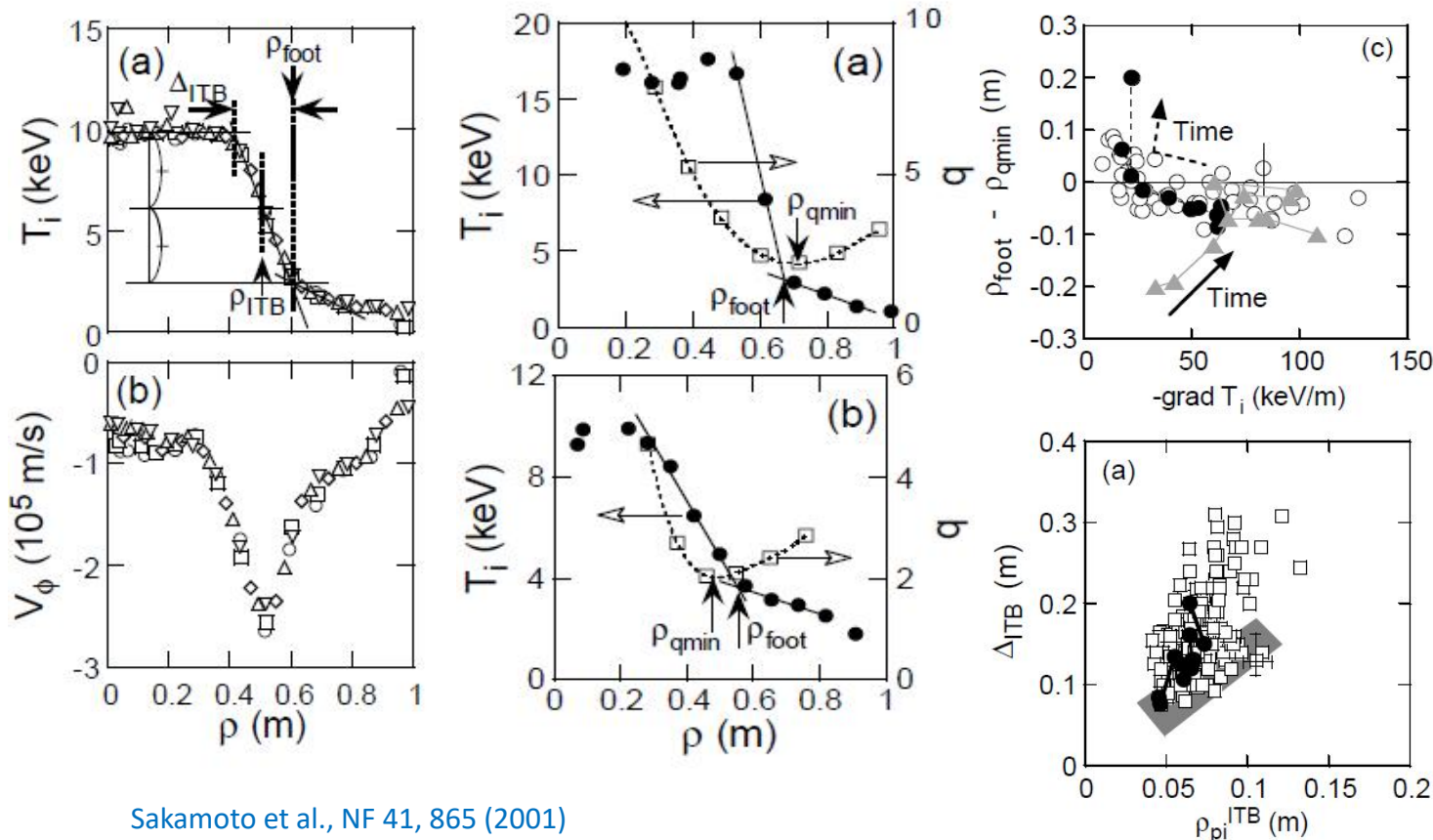
Shirai et al., NF 39, 1713 (1999)



S. Ishida et al., PRL 78, 3917 (1997)

Location of ITB foot for q-minimum surface in RS plasma

- The foot of strong ITB with steep Ti gradient
 → outside propagation of ITB foot, but limited at the q-min, the foot locates in the $\hat{s} < 0$ region
- The foot of weak ITB with reduced Ti gradient
 → outside propagation of ITB foot, but develop across the q-min surface to the in the $\hat{s} > 0$ region
- The lower boundary of the ITB width is proportional to the ion poloidal gyro-radius at the ITB center.



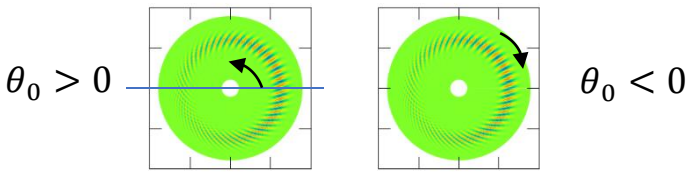
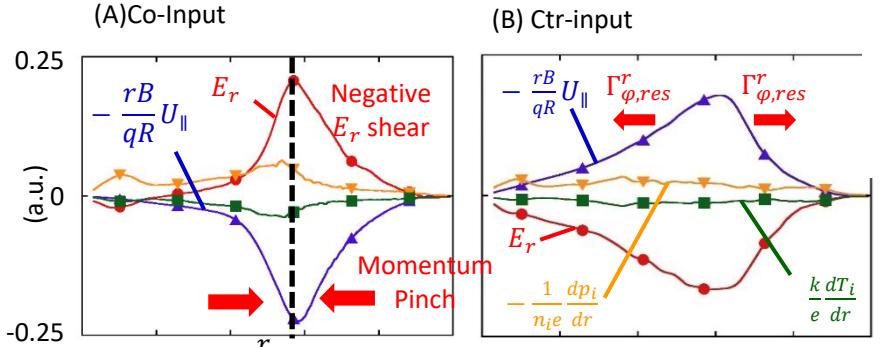
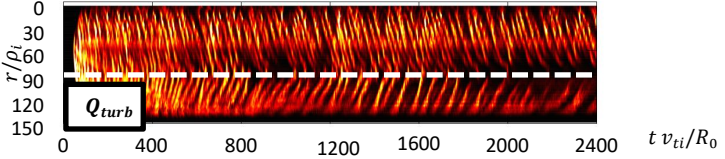
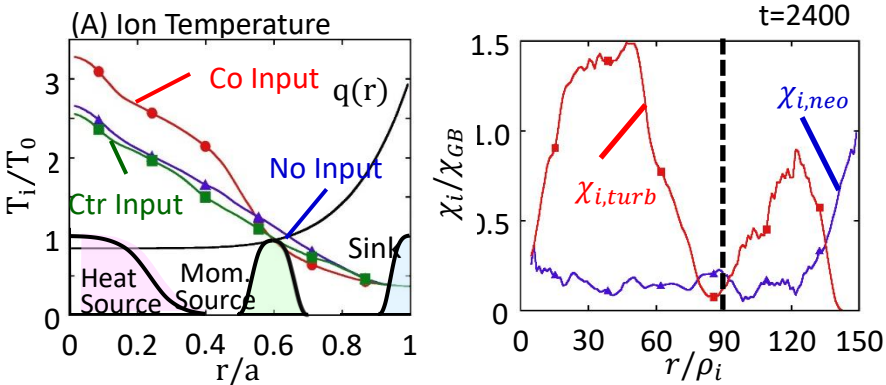
Key dynamics for ITB formation

- Out-ward Propagation
- Stagnation and crossing dynamics at q-min surface
- Two states for ITB foot locating inside/outside the q-min surface

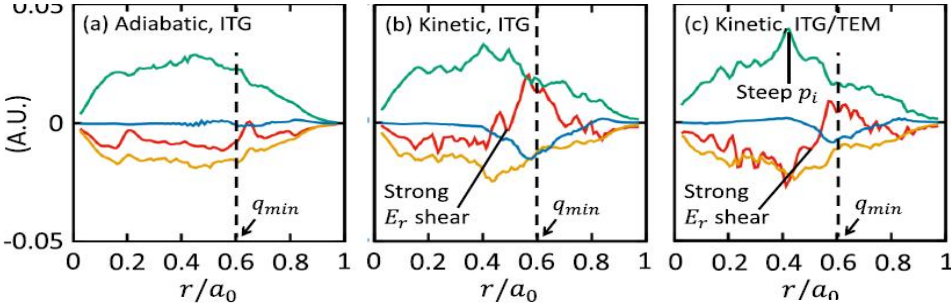
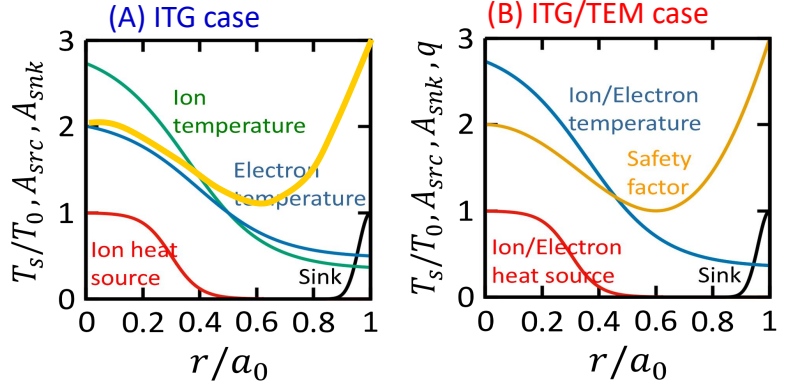
ITB formation of ITB by GK simulation in flux driven system

Imadera and Kishimoto, Nucl. Fusion 64, 086006 (2024)

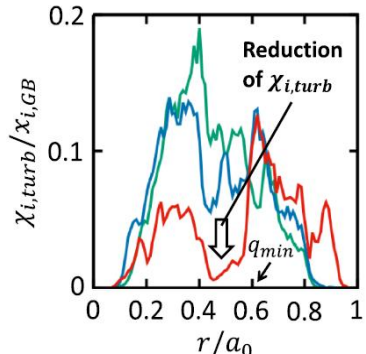
- Momentum input case



- No momentum input (spontaneous) case



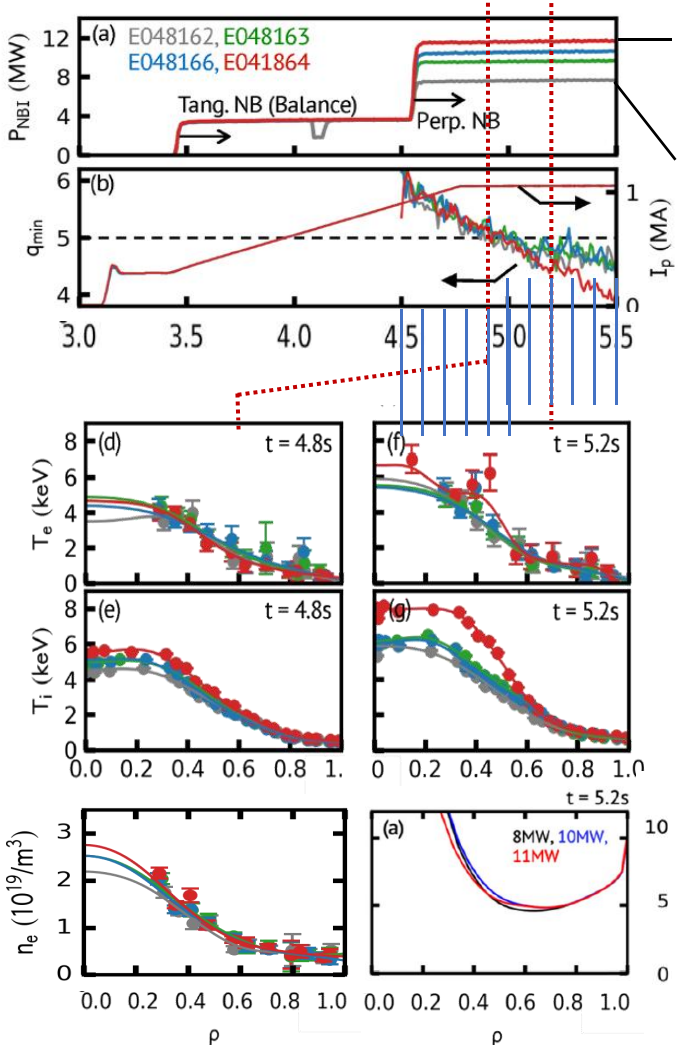
- E_r
- $(k/e)dT_i/dr$
- $-(1/n_i e)dp_i/dr$
- $-(rB/qR)U_{\parallel}$



Experiments in reversed magnetic shear (RS) JT60U plasmas

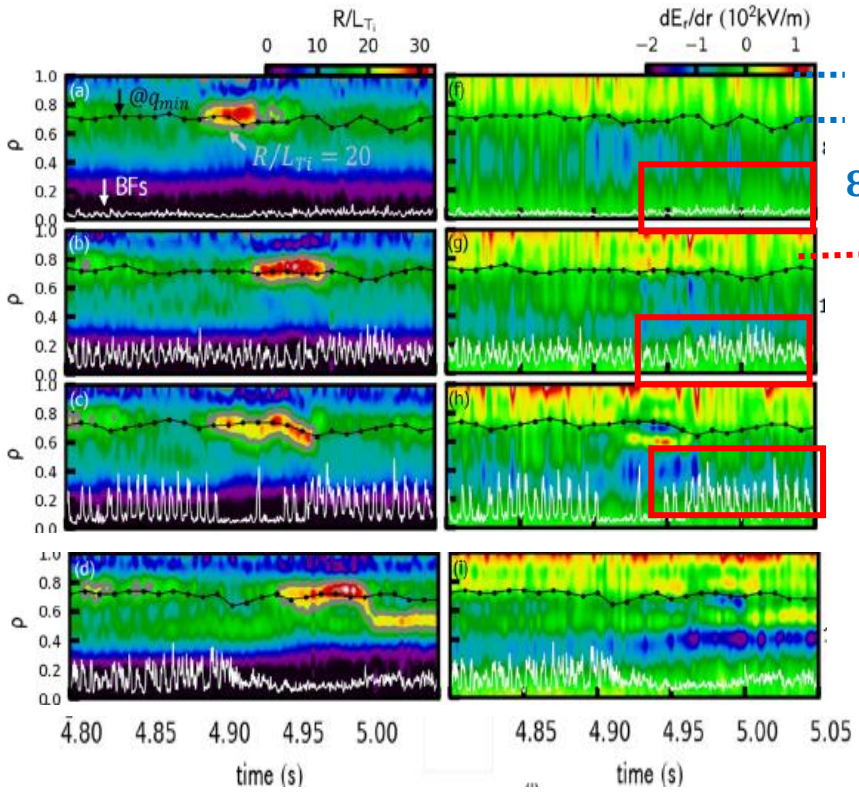
► Trigger to ITB plasmas from a L-mode with strong profile constraints

Kin, F., Itoh, K., et al. NF 63. 016015 (2022), Scientific Reports 13.19748 (2023)



12 MW
11 MW
10 MW
8 MW

- Exponential **type constrained profile** in RS plasma, weakly depending on the magnetic structure
- **Threshold power** exists ($P_c \sim 12 MW$) that ITB is triggered.
- L-mode in RS plasma is dominated by **avalanche dynamics**



$\partial E_r / \partial r$ layer in outside q_{min} surface

8 MW

q_{min} surface ($r_{min} \sim 0.7$)

10 MW

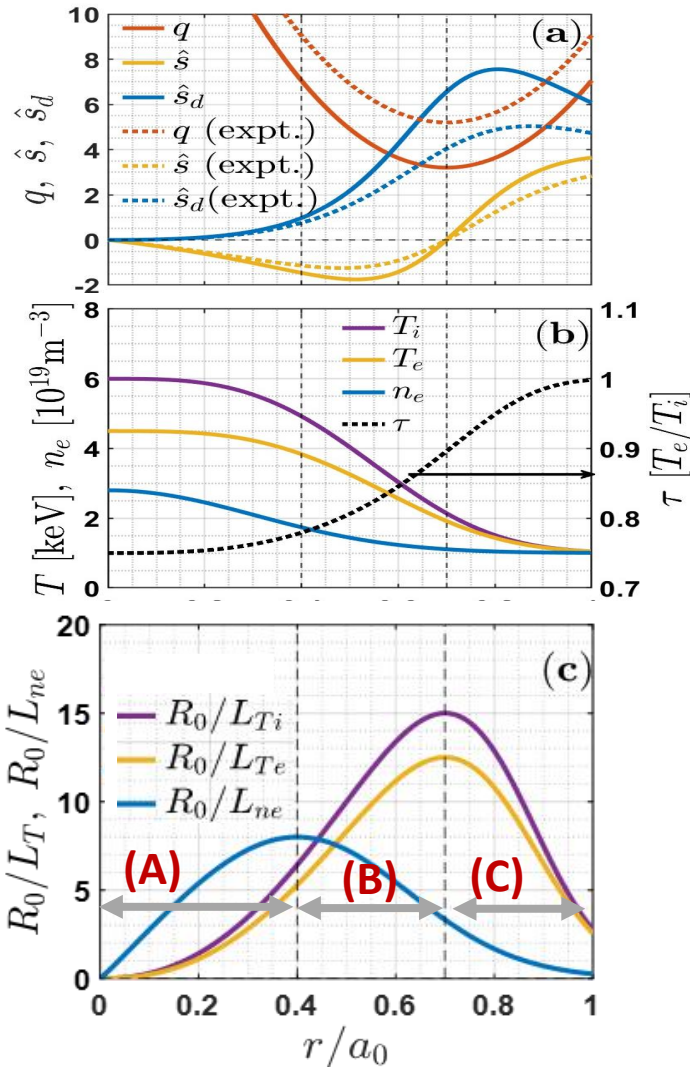
bursting dynamics

11 MW

12 MW ITB trigger

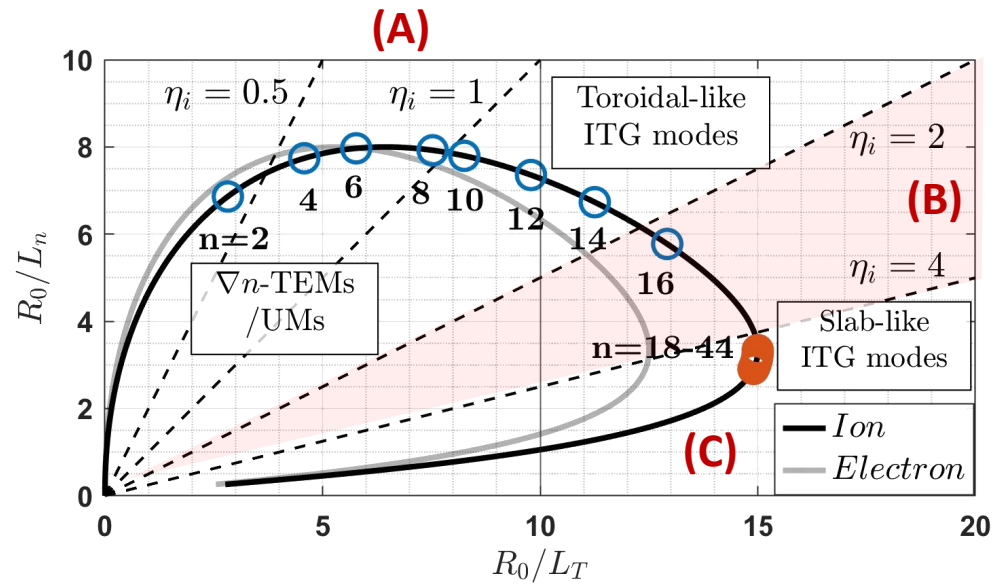
Characteristics of RS L-mode plasma in JT-60U

► Modeling of parameters and profiles



▣ Characteristics of plasma :

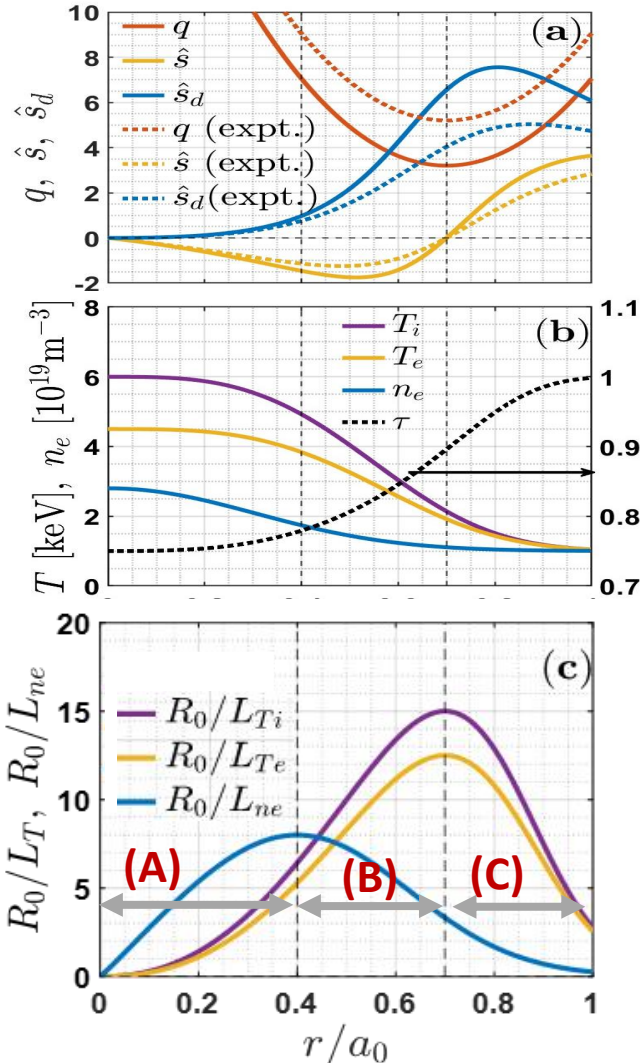
- Strongly RS configuration with higher minimum q value ($q_{min} \sim 5.2$) localized at outside region of $r_{min} \sim 0.7$.
- The system has two different instability free energy source, which divide the system into three regions: (A), (B), (C)



Characteristics of RS L-mode plasma in JT-60U

Zhao, R. et al. Nucl. Fusion 65 056037 (2025)

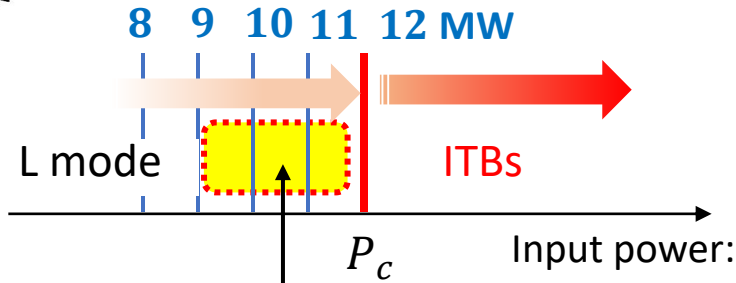
► Modeling of parameters and profiles



▣ Characteristics of plasma :

- Strongly RS configuration with higher minimum q value ($q_{min} \sim 5.2$) localized at outside region of $r_{min} \sim 0.7$.
- The system has two different instability free energy source, which divide the system into three regions: (A), (B), (C)

▣ Strategy : capturing the sign of ITB in L-mode state using δf simulation



δf method : predict the first order plasma response under a given zeroth-order global plasma profile

Sign of ITB formation, with maintaining L-mode characteristics

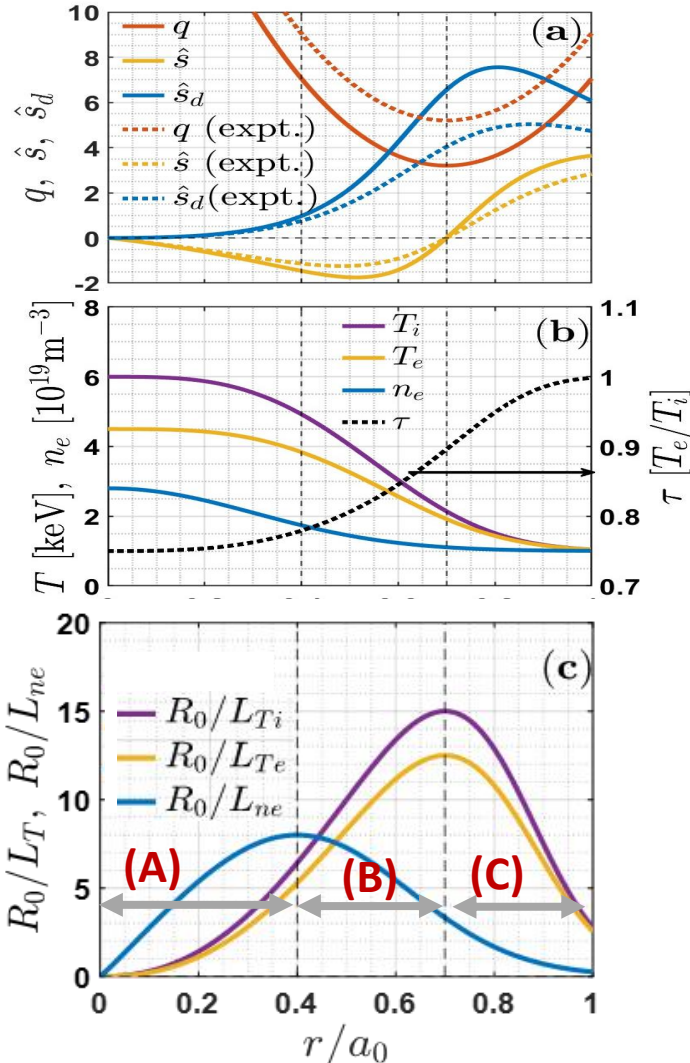
- should be weakly depending on an initial condition since the experiment exhibit L-mode

S. Wang et al, PRL 132, 065106 (2024)

Characteristics of RS L-mode plasma in JT-60U

Zhao, R. et al. Nucl. Fusion 65 056037 (2025)

► Modeling of parameters and profiles



□ Simplification of parameter and profiles

- Toroidal magnetic field: $3.7 \text{ T} \rightarrow 2.23 \text{ T}$ ($a_0/\rho_{i0} = 225$)
- q profiles: $q_{min} = 5.2 \rightarrow 3.2$
- The location of maximum T_i and T_e gradients

$$(R/L_{Ti})_{max} : r = 0.64a_0 \text{ (exp.)} \rightarrow 0.7a_0,$$

$$(R/L_{Te})_{max} : r = 0.62a_0 \text{ (exp.)} \rightarrow 0.7a_0$$

□ δf -based GK system in global toroidal geometry using hybrid electron model

Imadera K. et al 25th IAEA-FEC, pp TH/P5-8 (2014)

Obrejan K, Imadera K, Li J and Kishimoto Y 2017

Comput. Phys. Comm. **216** 8

- $(N_r, N_\theta, N_\phi) = (128, 512, 96)$ using wedge torus (total toroidal mode No: 24)
 → Numerical convergence is confirmed using $N_\phi = 192 \equiv a_0/R_0 = 0.8\text{m}/3.3\text{m} \sim 0.24$, ρ_{i0} for $T_{i0} = 3 \text{ keV}$ is used for normalization.
- Profiles shown in Fig. (a)-(c) are used.

Characteristics of RS L-mode plasma in JT-60U

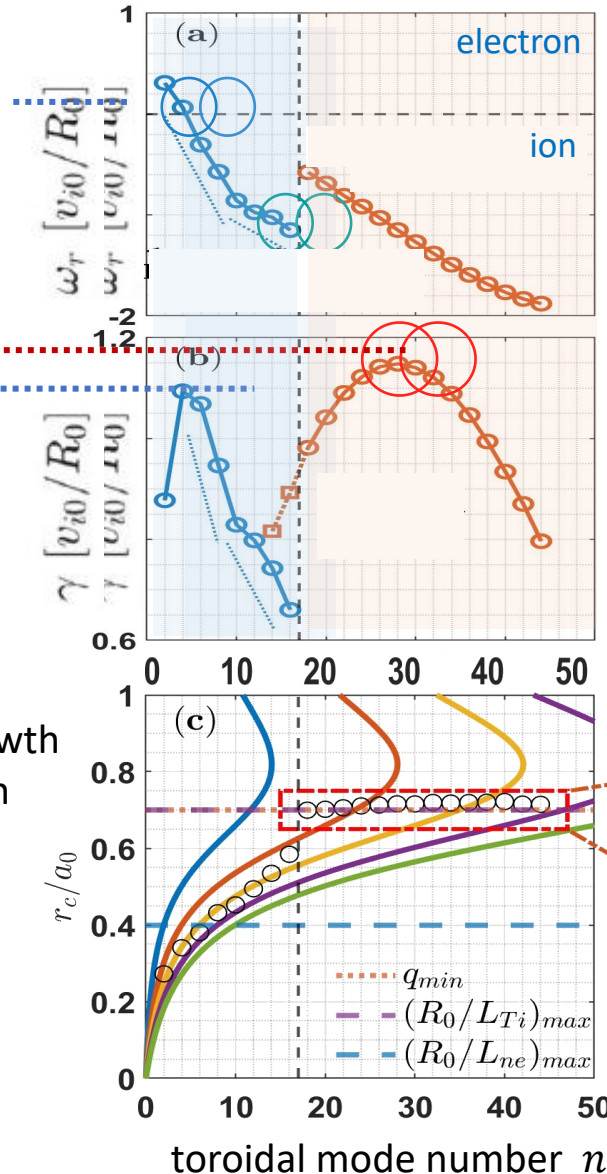
- ▶ Spatially separated nature with two independent branches

- ∇n -TEM ($\omega_r > 0$)
- Ubiquitous modes ($\omega_r < 0$)
- ITG mode ($\omega_r < 0$)

$$\gamma_{max}^{out} \sim 1.1 \quad (n=28)$$

$$\gamma_{max}^{in} \sim 1.08 \quad (n=4)$$

- Same level of maximum growth rate in inside/outside branch
- Plasma is self-organized so as not to cause im-balanced large transport.



toroidal mode number n

Characteristics of RS L-mode plasma in JT-60U

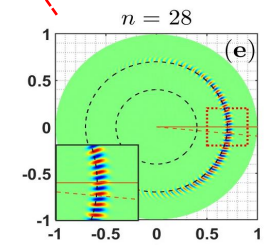
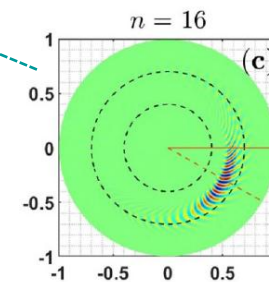
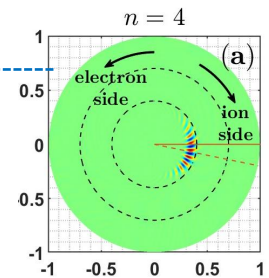
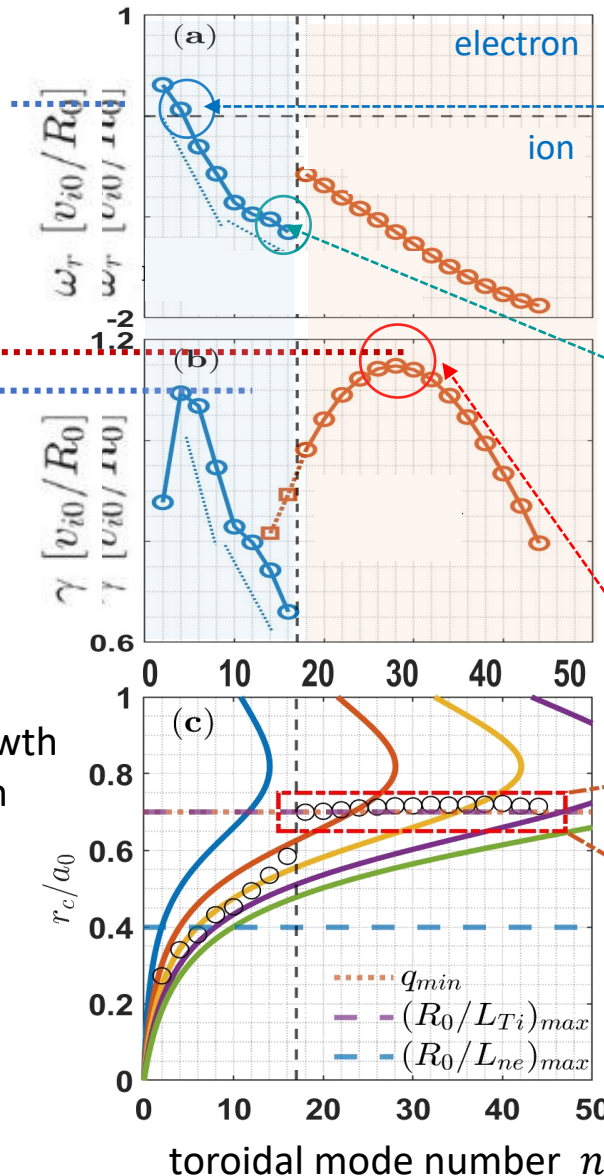
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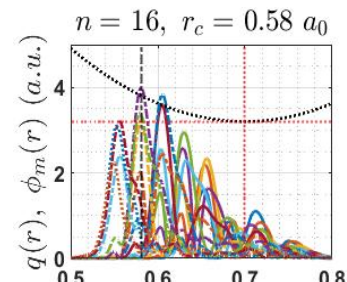
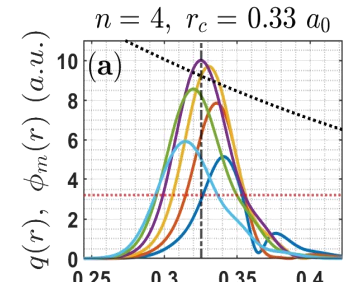
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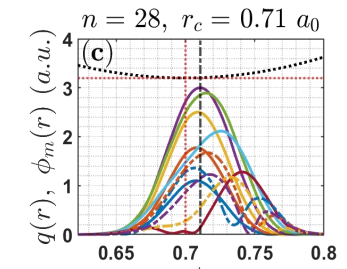
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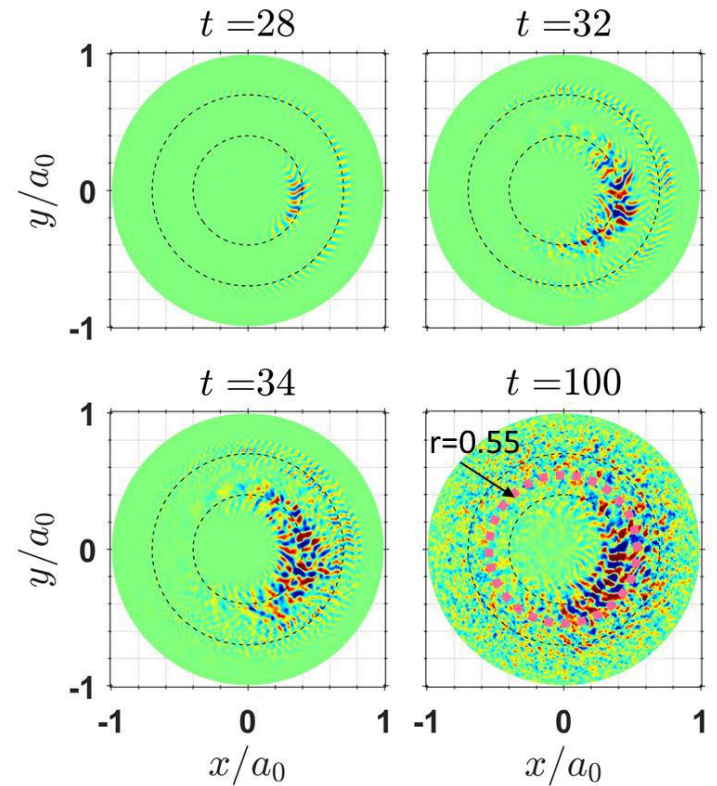
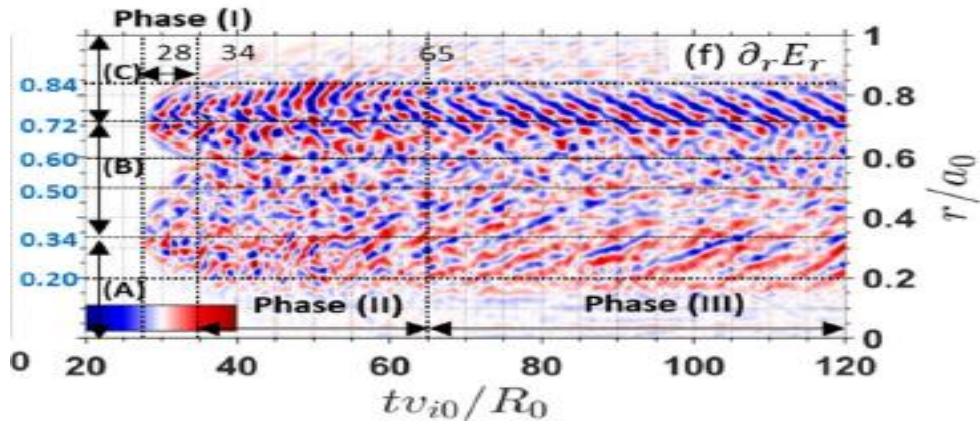
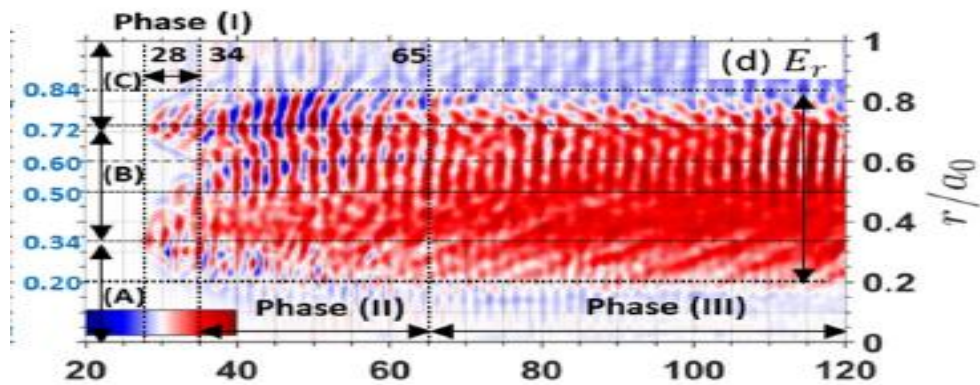
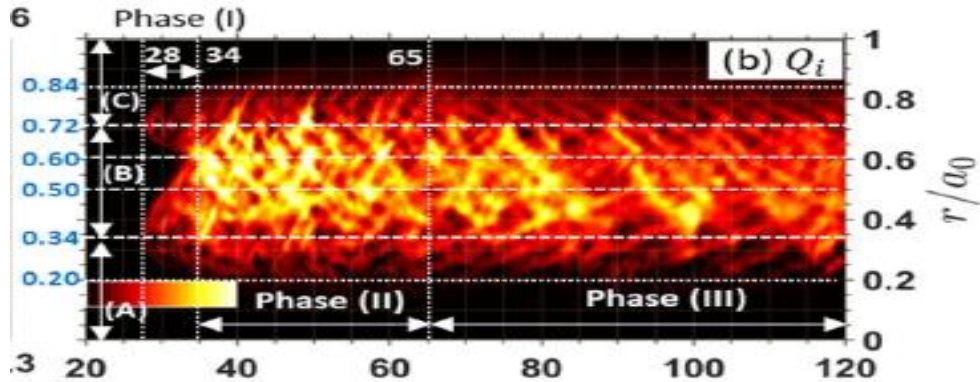
Resonant mode



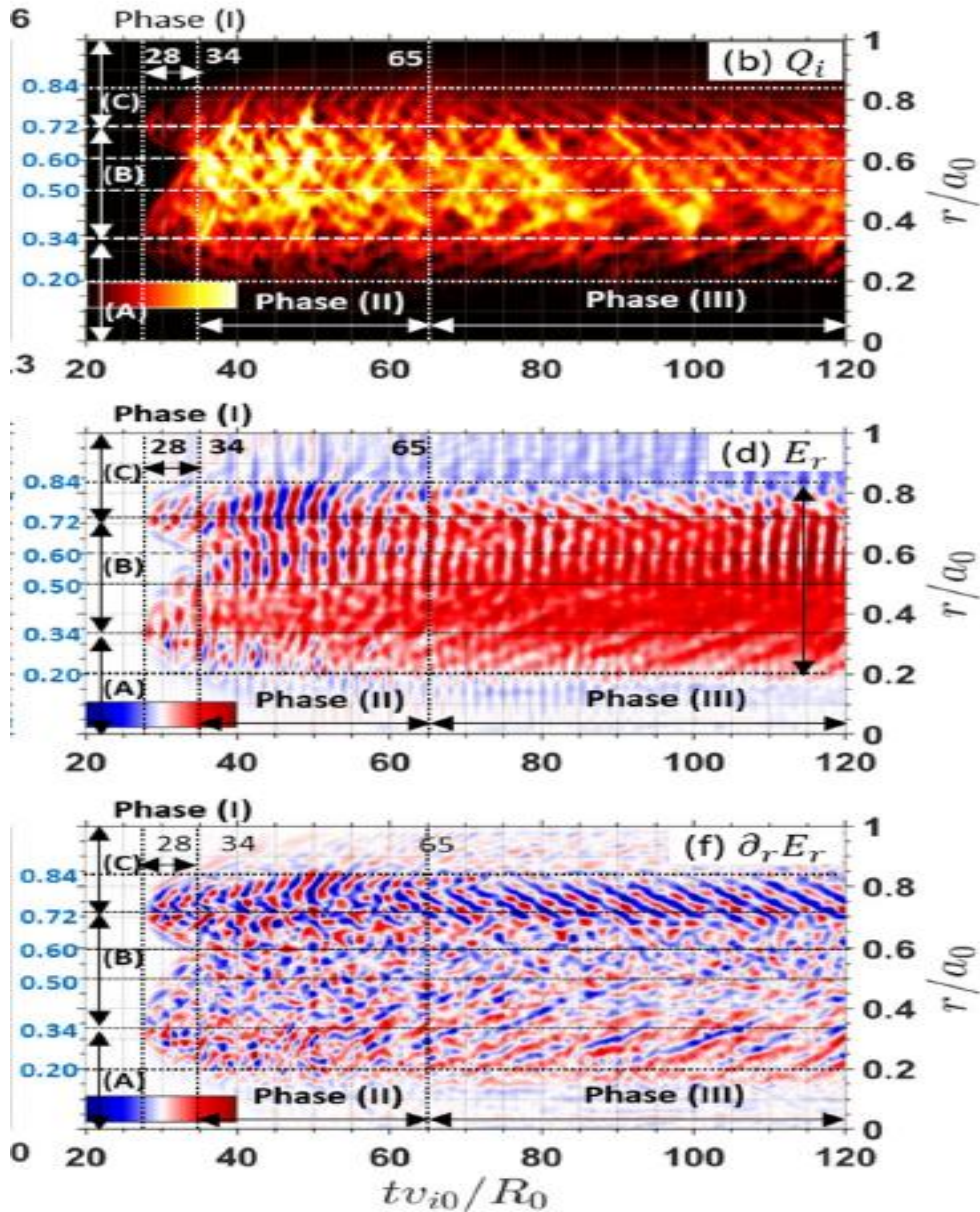
Non-resonant mode



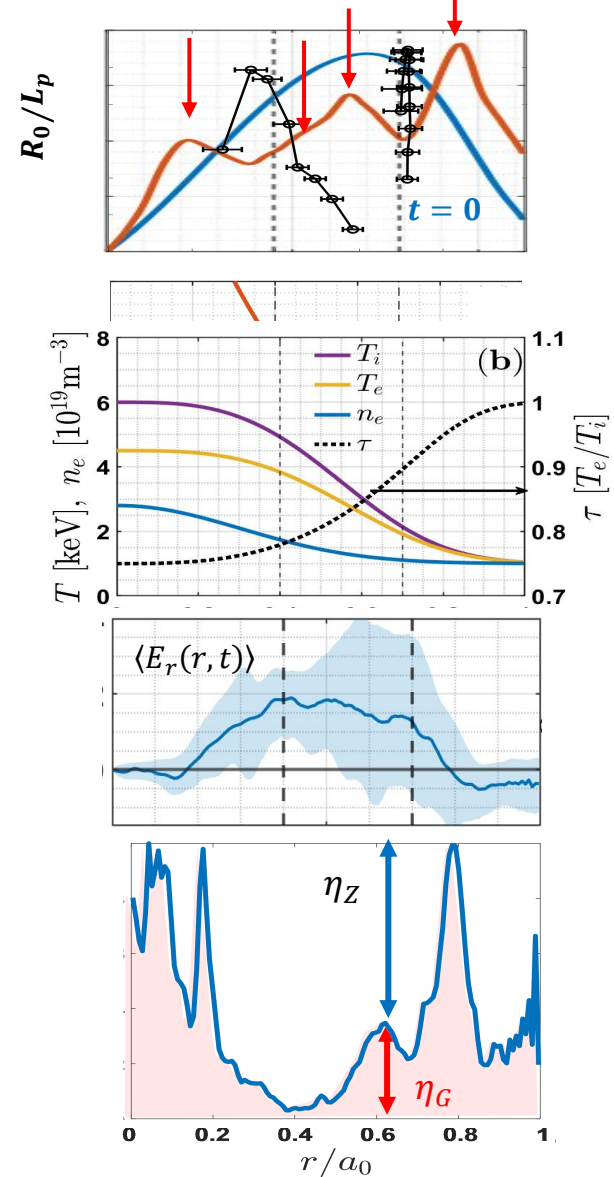
Simulation results : Overall feature of nonlinear regime



Simulation results : Overall feature of nonlinear regime



Expected as the seed of ITB trigger

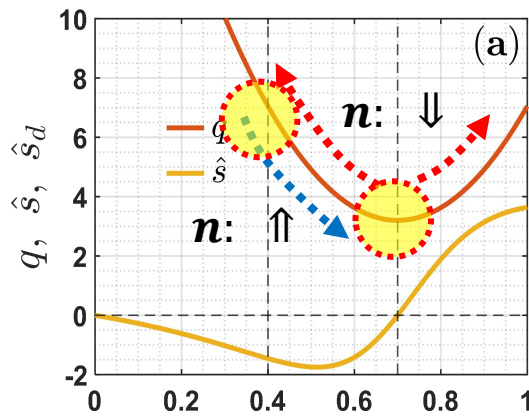
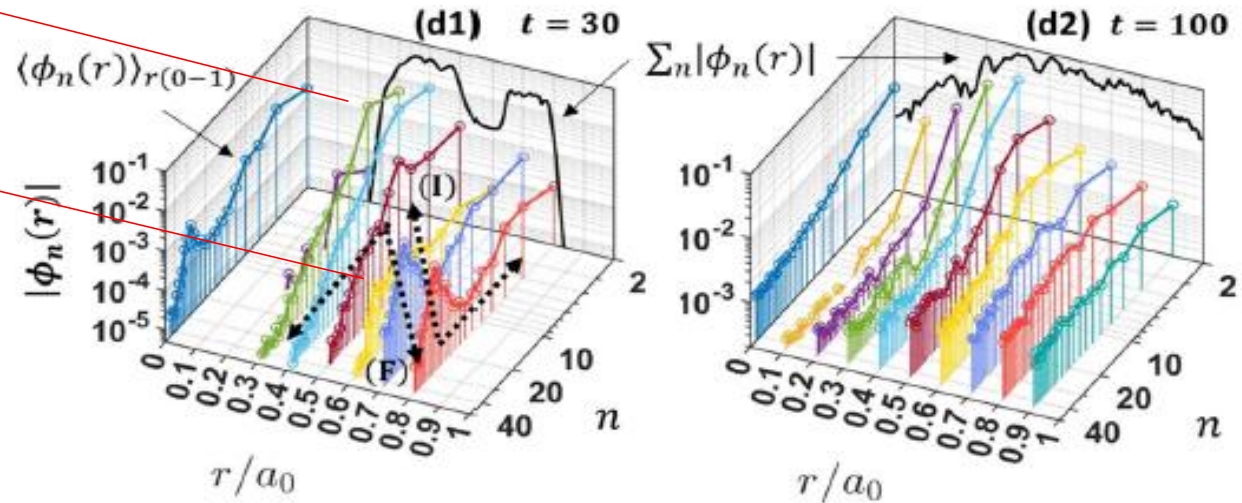


Coupling of turbulence in “real” space and “Fourier” space

- ▶ Local inverse/forward mode cascade in Fourier space is coupled with spatial spreading

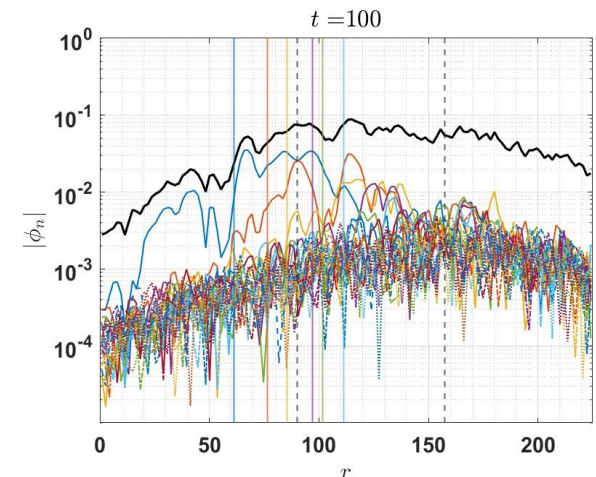
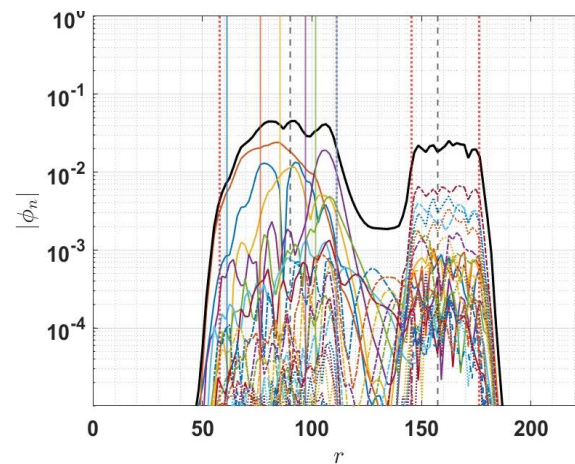
Inside mode with low- n

Outside mode with high- n



$$q = \frac{m}{n}$$

q :	\downarrow	—
\hat{q} :	\uparrow	—
n :	\downarrow	



Conclusion

- Using global δf gyrokinetic simulations, we investigate turbulent transport in strongly reversed shear plasmas.
- JT60U strongly RS plasmas shows L-mode characteristics in subcritical regime with two instability free energy sources, which develops two counter spreading turbulence coupled with GAM.
- They collides leading to a turbulence state dominated by intermittent bursts, maintain a L-mode state.
- Localized turbulence suppression layers are observed both inside and outside the q_{min} surface, while the plasma remains in an L-mode state dominated by avalanche-like, non-diffusive transport.
- These features are likely to be signs form which ITB formation is triggered once heat input exceeds the threshold heating power.