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Global dispersion and nonlinear dynamics in plasmas modeled for JT-60U strongly reversed magnetic shear configuration exhibiting a signature of ITBs from L-mode characteristics

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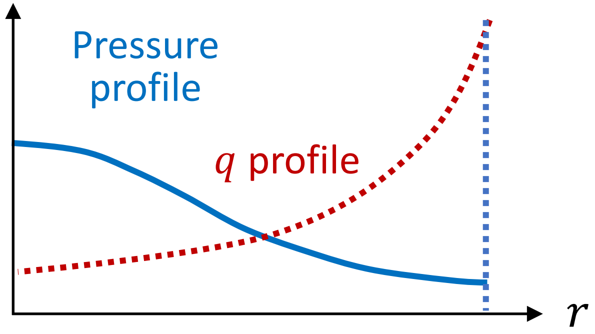
Contents

1. Background : from L-mode plasmas to those with ITBs

- All improved modes, such as H-mode, **Internal Transport barrier (ITB)** etc., in magnetically confined plasmas are realized by **breaking the L-mode**, subject to the **profile constraints**.

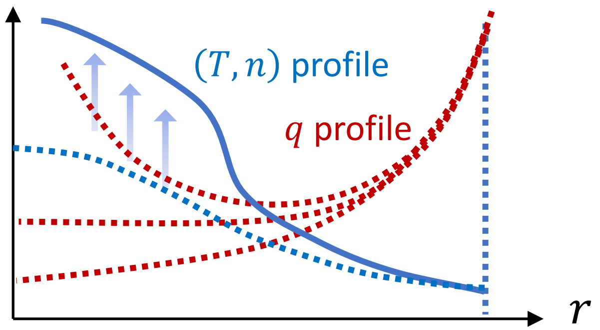
L-mode plasmas



How to Break!!

What is the condition?

Improved modes with ITB



Non-diffusive / non-local dynamics

- Avalanche dynamics
- Bursting / Intermittent dynamics
- Quasi-static ExB shear layer dynamics
- …… …

Hahm, T.S., and Diamond, P., *J. Korean Phys. Soc.* **73,** 747 (2018)
Ryter, F., et al., NF **41**, 537 (2001)
Sauter, O., et al., **PoP** 21, 055906 (2014)

Condition for the ITB formation

- Magnetic structure ? Heating method ?
- Ion ITB, electron ITB, or both ?
- Location, strength, width ?

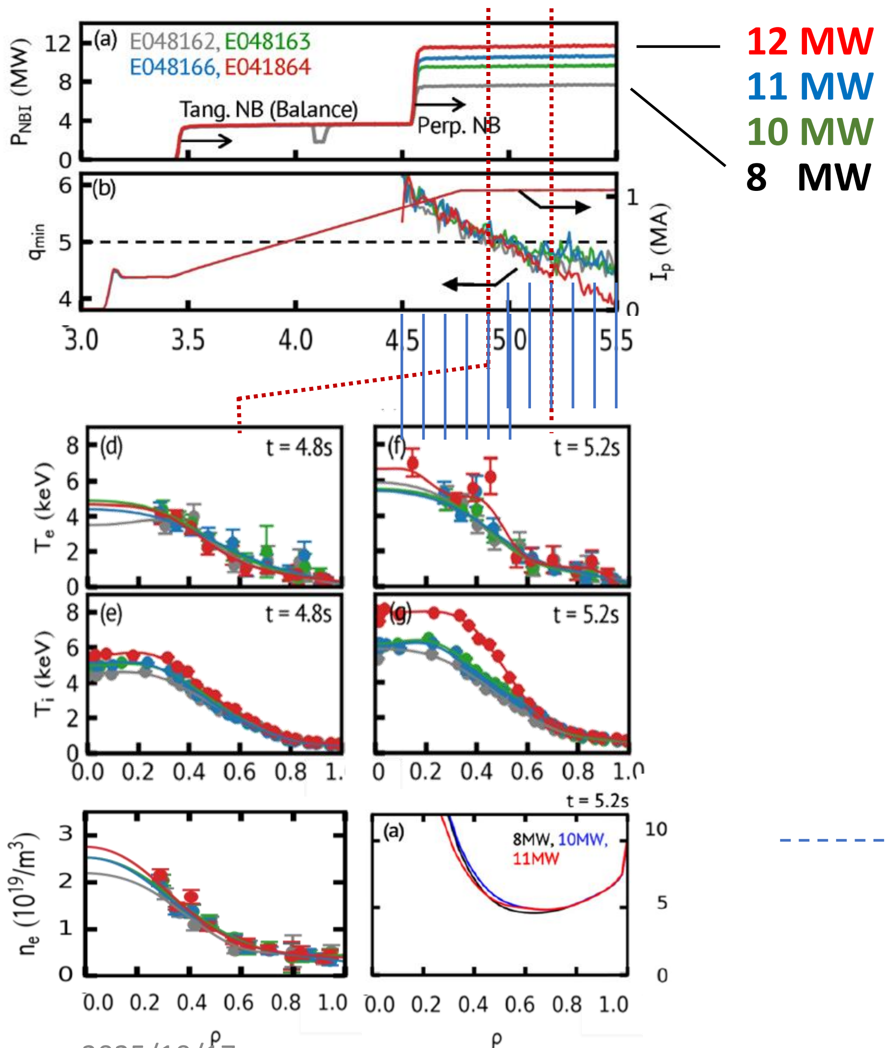
Wolf, R.C., PPCF **45**, R1–R91 (2003)
Connor, J. W., et al., NF 44 (4), R1–R49 (2004)
Ida, K. and Fujita, T.**, PPCF**, **60**, 033001 (2018)

- How L-mode and ITB are connected ? Locally explained or global view is essential ?

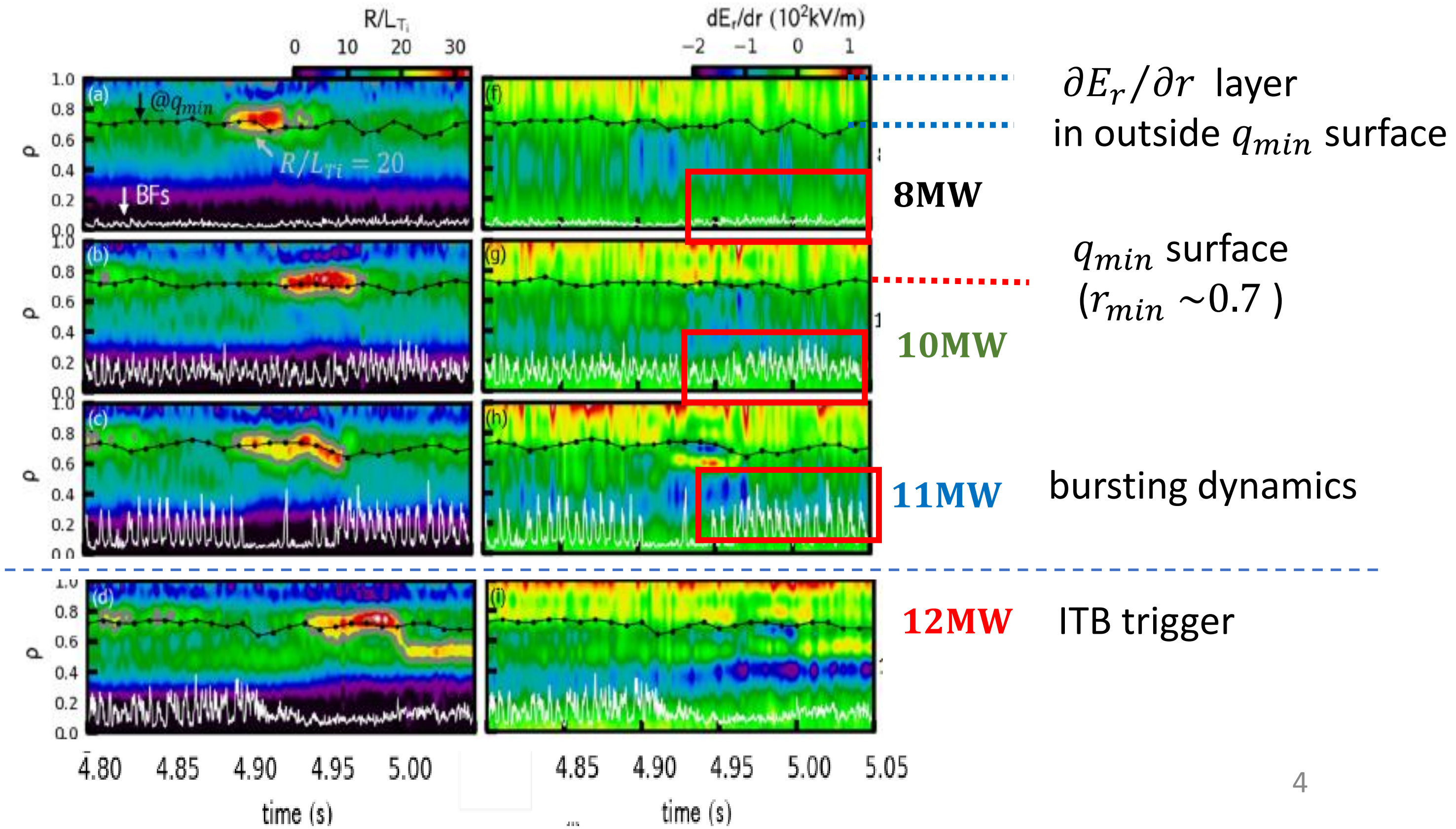
1. Background :　An experiment in JT-60U

- L-mode characteristics in a reversed magnetic shear (RS) plasma and the break, leading to ITBs

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



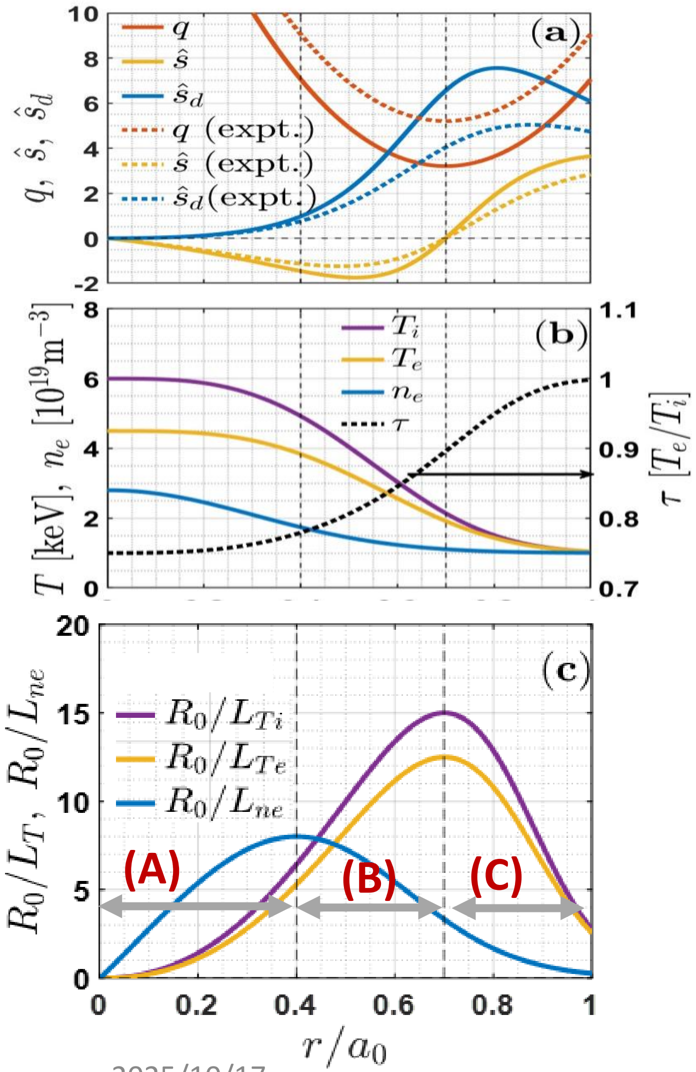
- Exponential **type constrained profile in RS plasma**, weakly depending on the magnetic structure
- **Threshold power** exists (**P_c~12MW**) that ITB is triggered.
- L-mode in RS plasma is dominated by **avalanche dynamics**



2-1. Characteristics of RS L-mode plasma in JT-60U

▶ Modeling of parameters and profiles

Kin, F., Itoh, K., et al. NF 63. 016015 (2022), Scientific Reports 13.19748 (2023)
Zhao, R. et al. Nucl. Fusion 65 056037 (2025)



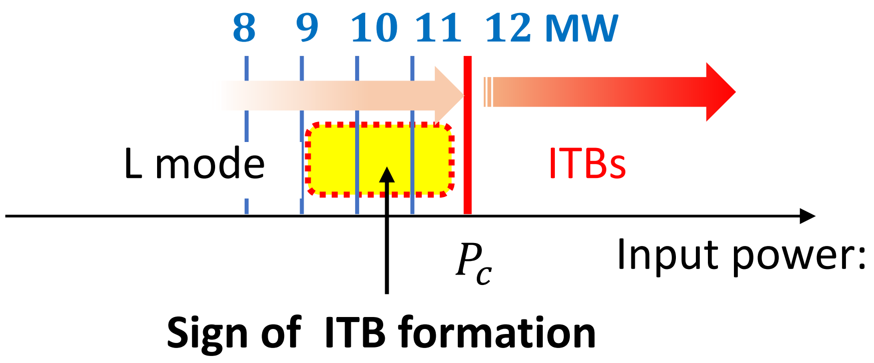
☐ Characteristics of plasma :

- Strongly RS configuration with higher minimum q value (q_{min}~5.2) localized at outside region of r_{min}~0.7.
- Spatially separated nature between density and ion/electron temperature profiles

☆ Density gradient scale length distribution (R_0/L_n) → localized inside region at r~0.34
☆ Ion/electron temperature distribution (R_0/L_T) → localized outside region at r~r_{min}~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**

2-1. Characteristics of RS L-mode plasma in JT-60U

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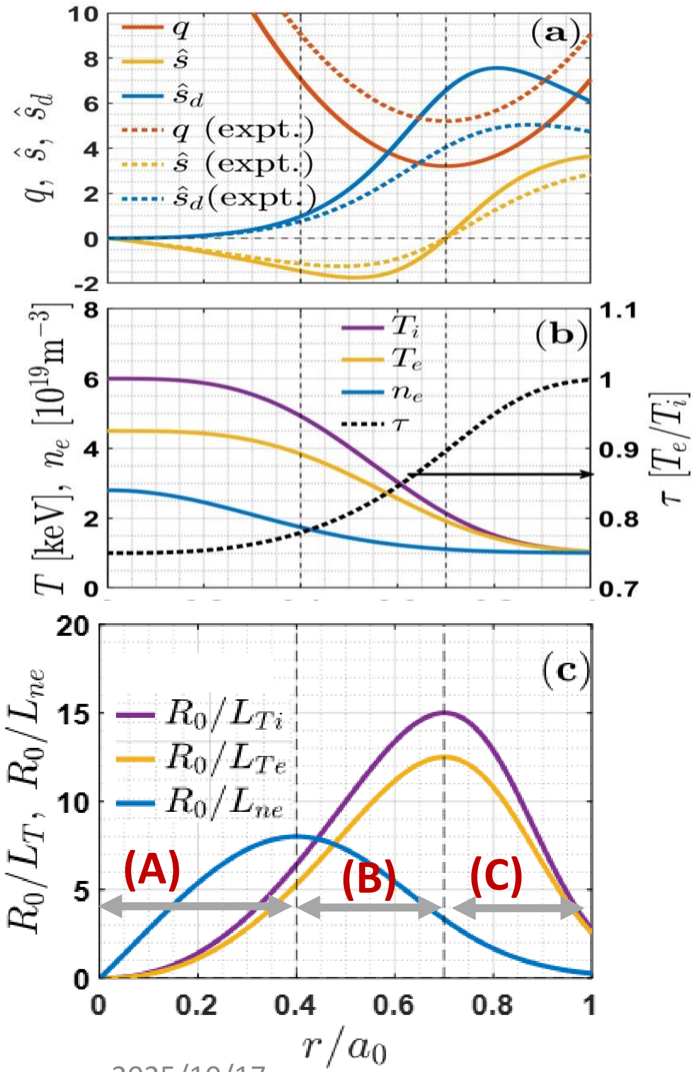


☐ Simplification of parameter and profiles

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

$(R/L_{Ti})_{max} : r = 0.64a_0$ (exp.)$\rightarrow 0.7a_0$,
$(R/L_{Te})_{max} : r = 0.62a_0$(exp.) $\rightarrow 0.7a_0$

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

Imadera K. et al 25th ITEA-FEC, pp TH/P5–8 (2014)
Obrejan K, Imadera K, Li J and Kishimoto Y 2017 *Comput. Phys. Comm.* **216** 8

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

3-1. Simulation results : linear regime

- Spatially separated nature with two independent branches

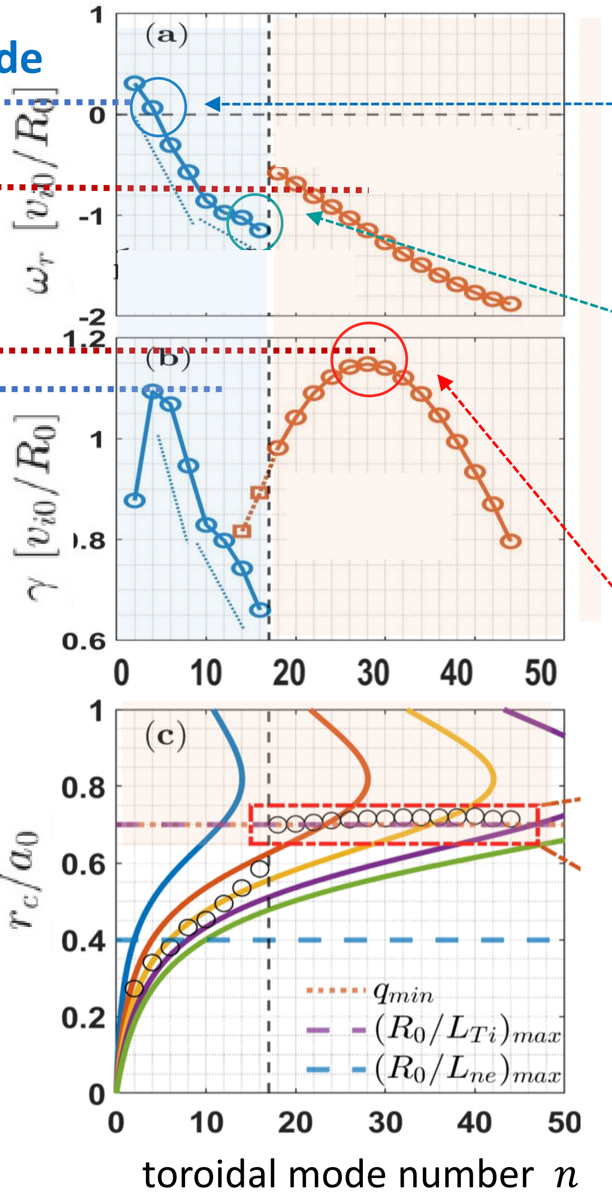
- ∇n-TEM ($\omega_r > 0$)
- Ubiquitous modes ($\omega_r < 0$)
- ITG mode ($\omega_r < 0$)

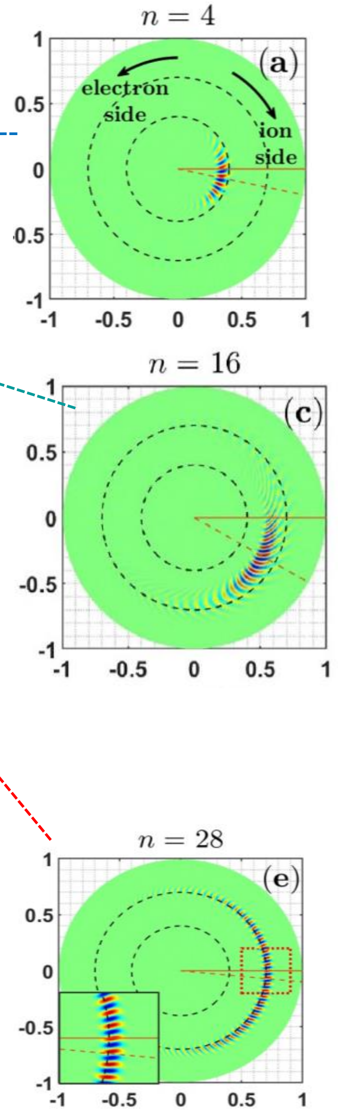
Electron mode

Ion side

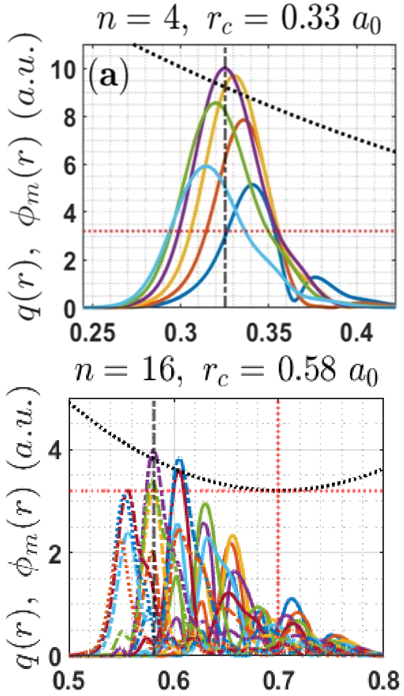
$\gamma_{max}^{out} \sim 1.1$ (n=28)

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

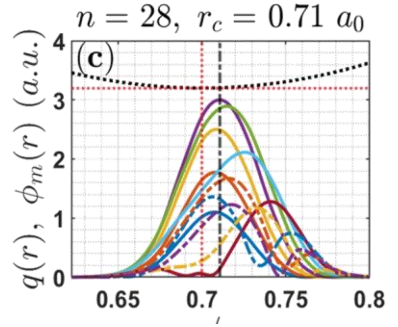




Resonant mode



Non-resonant mode



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

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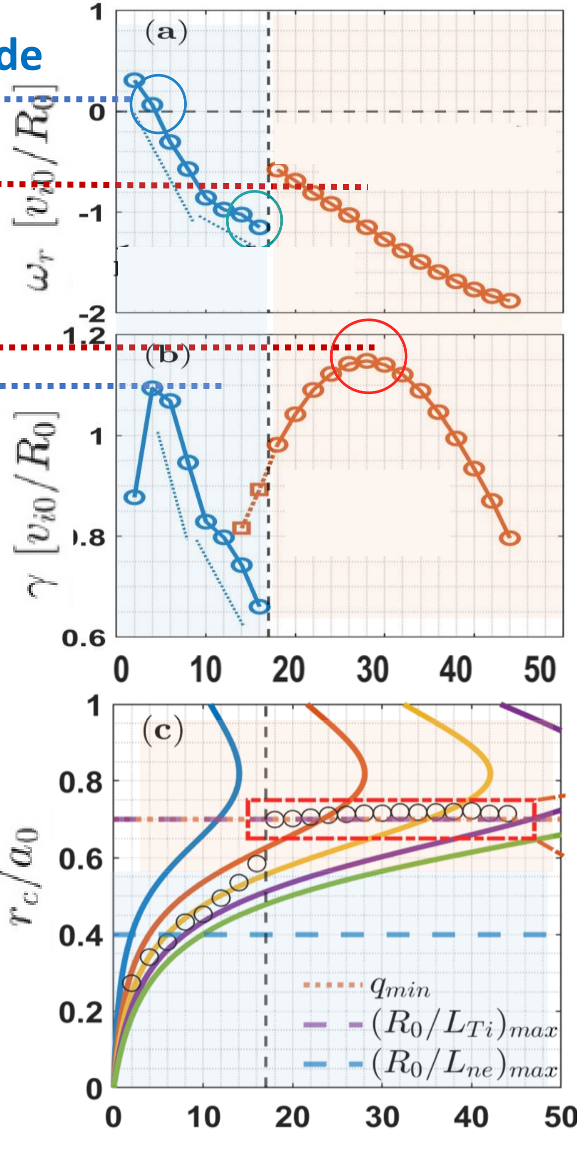
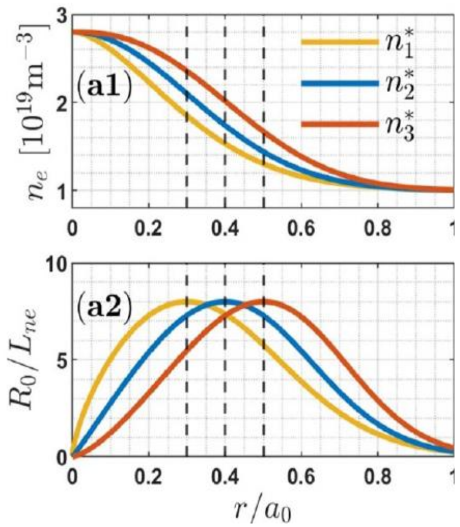
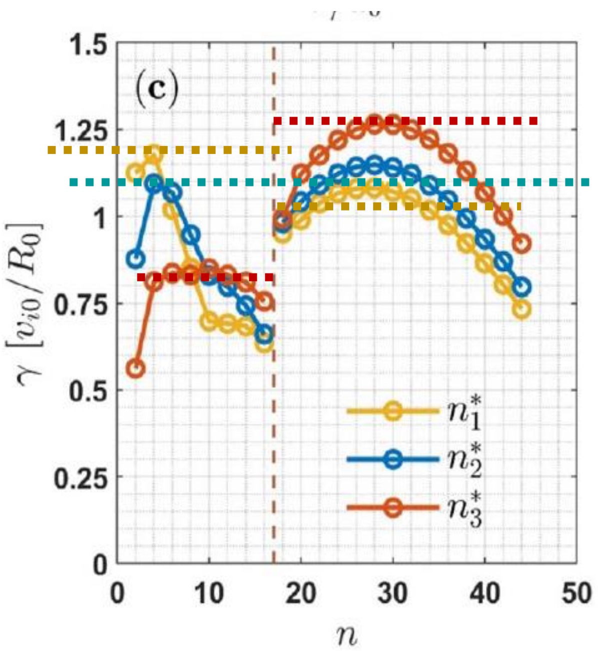


- The artificial change of density profile

Case of density profile



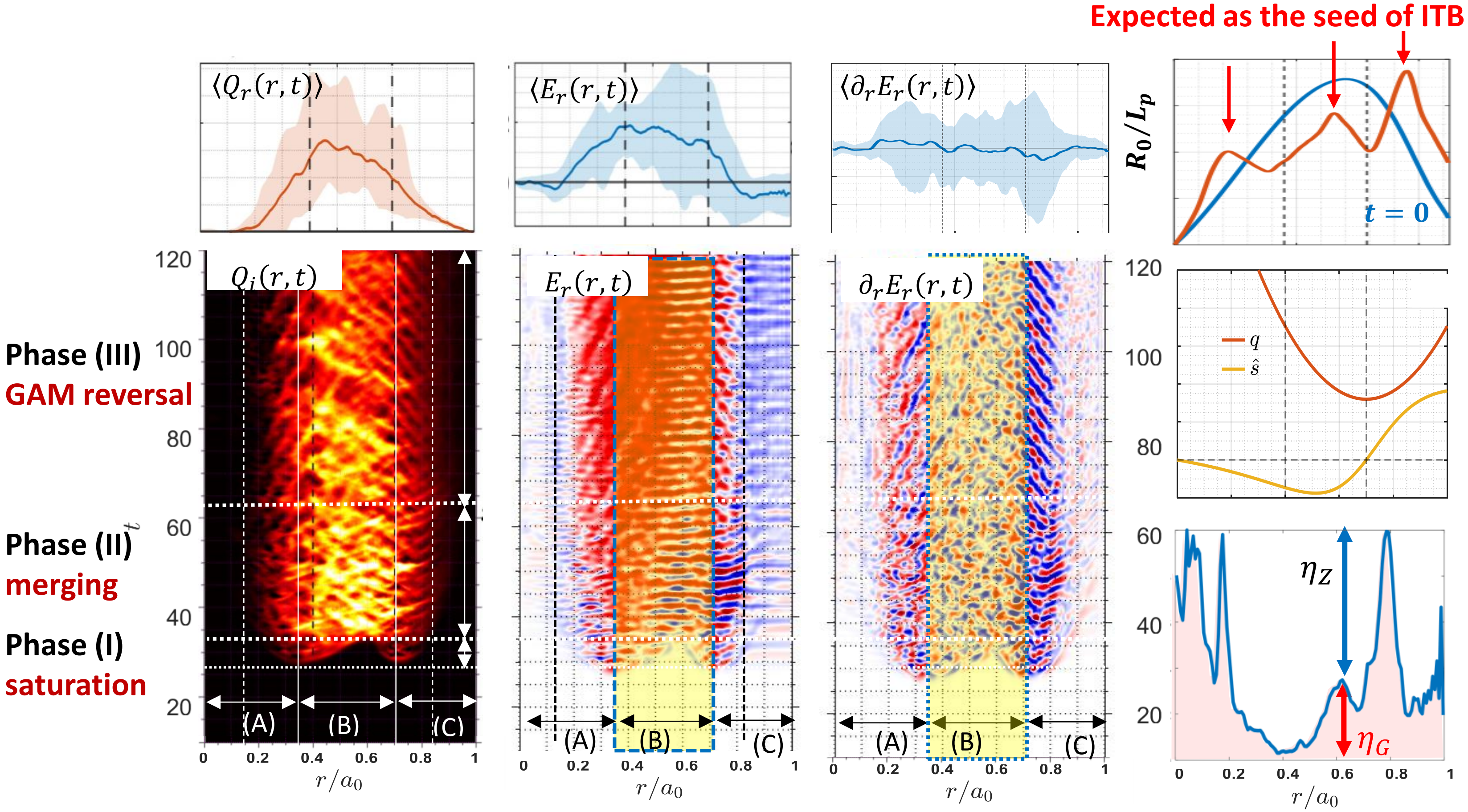


- ☐ Same level of maximum growth rate in inside/outside branch
- ☐ Plasma is self-organized so as not to cause im-balanced large transport.

☆ In-balanced growth rate between inside and outside

4-1. Simulation results : Overall feature of nonlinear regime

- Formation of core turbulence coupled with GAMs and localized suppression layers



2) Flattening of pressure gradient at the q_{min} region and the maximum density gradient/

3) **Steepening** at three different locations, two of which are **inside and outside the q_{min} surface**.

cf. Energy transfer form propagating GAMs to QS-ZFs

Miki et a., PRL 99, 145003 (2007),
Sasaki M. et al., PPCF 51, 085002 (2009)
Hallatschek K. and Biskamp, PRL 86, 1223 (2001)

1) **L-mode core turbulence coupled with GAMs, followed by spreading and merging.**

4) Reversal of **GAM propagation** from the outside, from the location of steeping, to the q_{min}-surface.

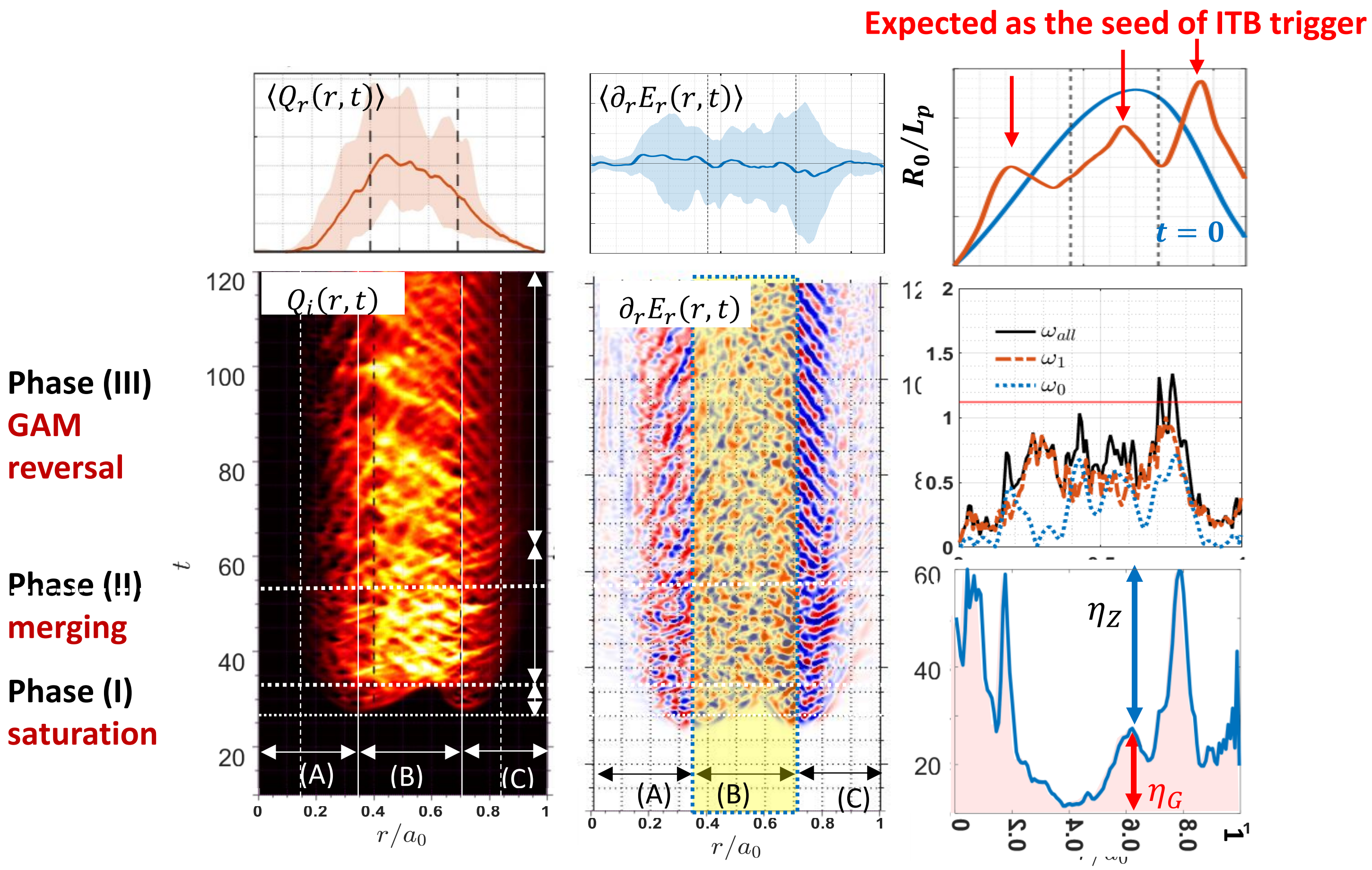
Note : In the region where pressure gradients are steepened, $\partial_r E_r$ is weak, but **the oscillation component is large**

- Transport by avalanches.

(The similar feature take place inside region)

4-1. Simulation results : Overall feature of nonlinear regime

- Formation of core turbulence coupled with GAMs and localized suppression layers



Note : In the region where pressure gradients are steepened, $\partial_r E_r$ is weak, but **the oscillation component is large**

☐ Study of the relation between $E \times B$ shearing and maximum γ_{max}

$\omega_{eff} = \omega_{E\times B} G(F)$:
$G \le 1$: the reduction factor
with $F \equiv \omega_f^2/\Delta\omega_T^2$
ω_f : the fluctuation flow frequency
$\Delta\omega_T$: the turbulence decorrelation rate

The spectrum-weighted mean squared effective shearing rate

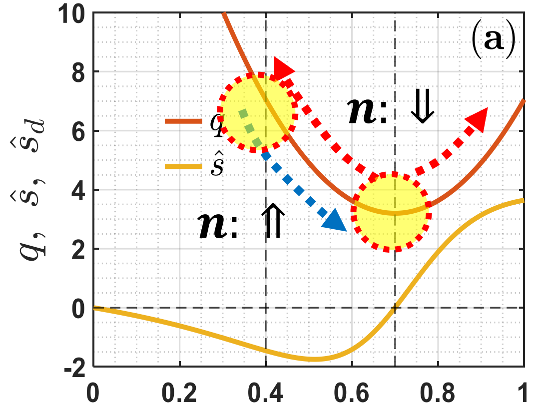
$$\langle \omega_{eff}^2 \rangle = \int \omega_{eff}^2 d\omega_f / \int d\omega_f ,$$

Hahm T.S. et al., PoP 6, 922 (1999)

4-2. Turbulence dynamics through the coupling of “real” space and “Fourier” space

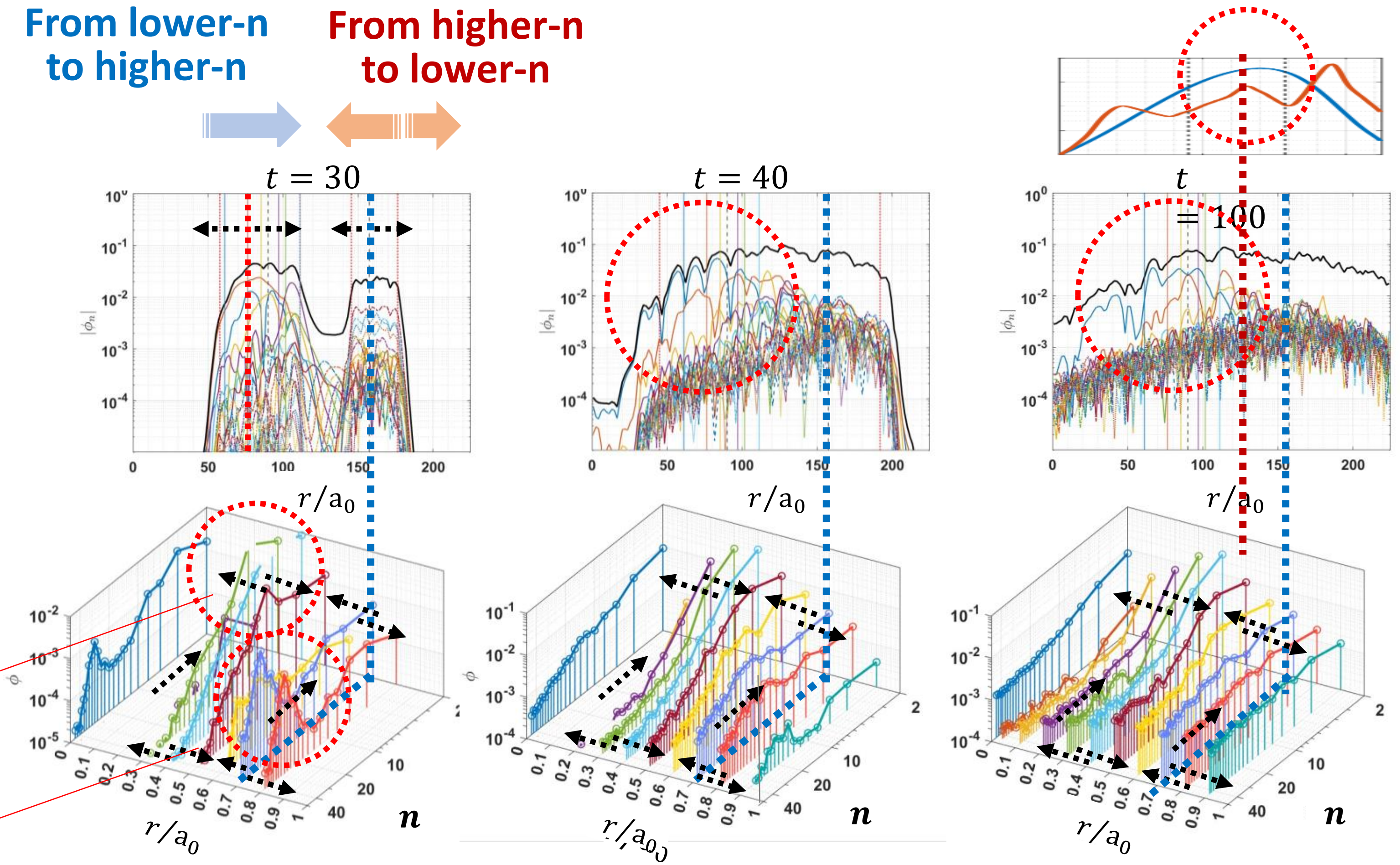
- Local inverse/normal mode cascade in Fourier space is coupled with spatial spreading

- ☐ **Lower-n mode (large scale) with n=2 and 4 tends to be dominant (condensation), while outside is high-k modes**
- ☐ **Edge of low-n mode corresponds to the region of inside steeping**



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

q : ⇓	n: ⇑
q : ⇑	n: ⇓



Inside mode with low-n

Outside mode with high-n

t=30 : Spreading phase

t=40 : Merging and mixing phase

t=100 : Quasi-steady state

5. Conclusion

- We studied the turbulent transport of **strongly RS plasmas**, inspired by **JT-60U discharges**, by setting the **spatially separated two free energy sources**, which exhibits **L-mode** characteristics in **sub-critical regime P_c** while trigger ITBs exceeding it.
- The L-modes are ubiquitous, weakly depending on the magnetic structure, either NS or RS, while the characteristics appear in the relative positional relationship of temperature and density profiles.
- The **linear instability free energy sources** are distributed with **self-organizing manner** in the sub-critical regime so as the plasma not to cause large in-balanced transport in the quasi-steady state.
- Using the advantage of δf-method, we observed **local suppression layers** of turbulence both inside and outside the minimum q surface , with **maintaining the L-mode state** dominated by avalanche type non-diffusive transport, which is considered to be the **sign triggering ITBs**
- **Flux driven simulation**, which studies the crossing dynamics of the L-mode with the sign triggering ITB, is requested to prove the above conjecture.