Investigation of non-local heat transport and its interplay with neoclassical tearing modes (NTMs) in the HL-2A tokamak

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Thanks to contributors: G. Tynan, C. X. Yu, P. Diamond

Outline

- **Introduction**
  - Non-local heat transport
  - Self-organized criticality (SOC) paradigm
- **Experimental results**
  - Identification of SOC characteristic at HL-2A
  - Enhanced SOC dynamics during non-local transport
  - Interplay between non-local transport and NTMs
- **Summary**

Non-local heat transport

Since 1990s, non-local transport has been observed in many devices

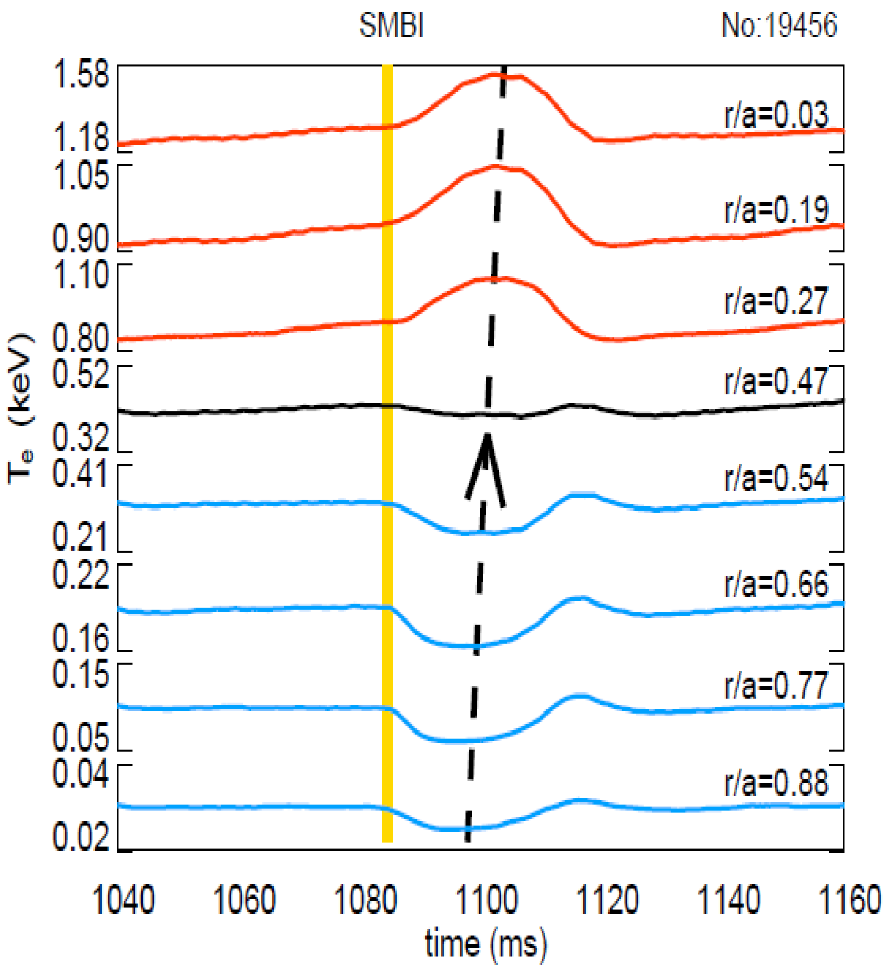
(JET, W7-AS, AUG, Tore-Supra, TFTR, RTP, DⅢ-D, LHD and HL-2A, etc)

Main features:

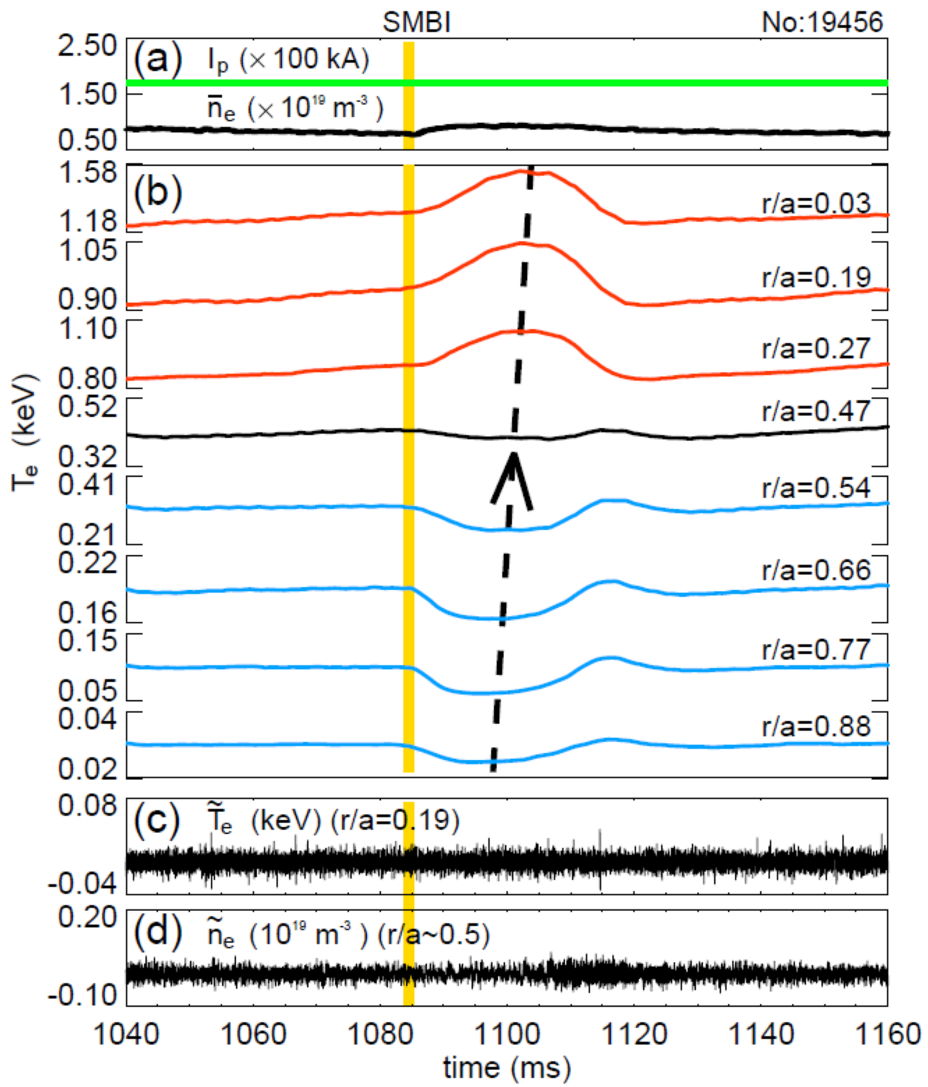
A fast response of the core temperature rising to an edge cooling executed at the plasma periphery.

- **Transient**
- **Long-distance**
- **Reversed polarity response**

(J. D. Callen, PPCF1997)



Non-local heat transport



Non-local heat transport

Proposed models to explain the nonlocal transport:

- **Empirical**

The empirical model connected the core electron heat transport to edge T_e by adding empirical diffusion coefficients or heat flux as a function of volume-averaged T_e, and thus, may predict prompt changes in core T_e by edge cooling.

- **Marginal stability**

The marginal stability presumed that the plasma equilibrium state just lies above certain critical parameters and local turbulent transport and diffusivity are transiently enhanced if any perturbation pushes the plasma beyond the critical values.

- **Self-organized criticality**

The SOC paradigm proposed an interrelation between large-scale transport events and individual turbulent eddies via the avalanche of “sand-pile" modeling. Long-range correlation and self-similarity of fluctuations, power law frequency dependence and large Hurst exponent (>0.5) are key ingredients of the SOC behavior.

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Self-organized criticality (SOC)

Concept:

A property of dynamical systems which have a critical state where a minor perturbation can trigger a power law response (avalanche) of any size and duration.

Features:

- Existence of a critical gradient
- $f^{-\alpha}$ frequency power spectrum, mostly $\alpha \approx 1$
- Radial correlation range >> L_c
- Long-range time correlation >> τ_c
- Radial propagation of avalanches
- Self-similar character in fluctuations …

Methods used for present study:

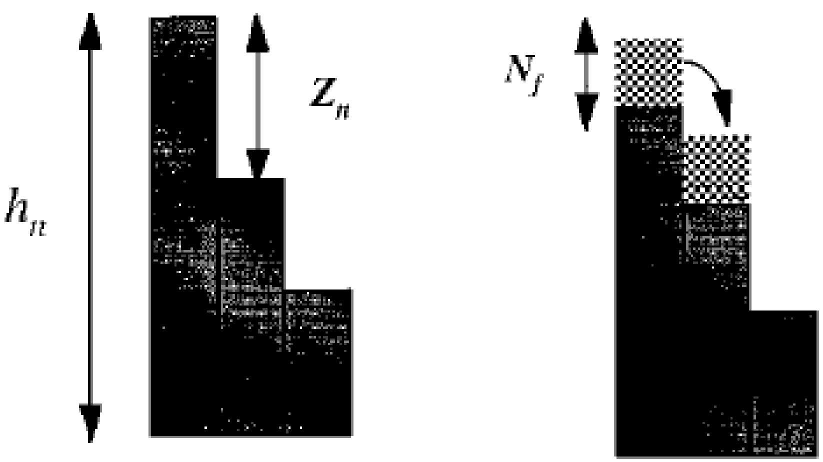
- Frequency power spectrum $S(f)$
- Auto-correlation function (ACF)
- Hurst exponent analysis (R/S *or* structure function)

Sand-pile model (SOC)

Because of the difficulty of accurately modeling large regions and the monumental task of dealing with the data, a simplest model has been constructed to capture the dynamics of interest.

Local gradient $\xrightarrow{\text{Excite (exceeding criticality)}}$ Turbulence transport

Local gradient $\xleftarrow[\text{Relax}]{}$ Turbulence transport



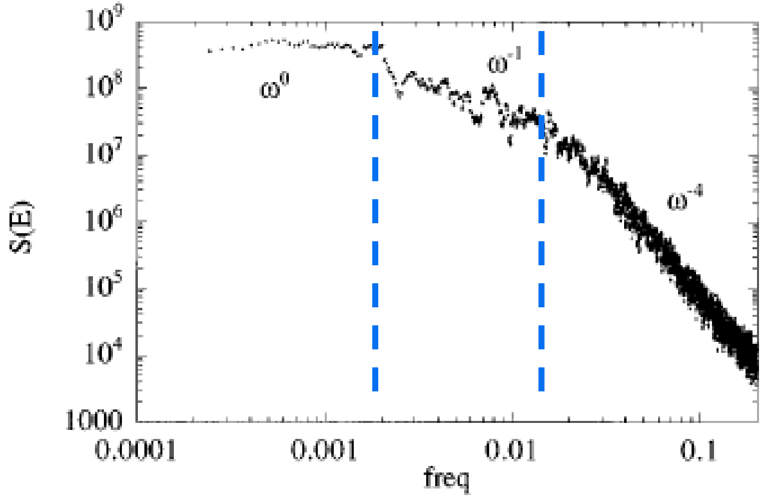
Cellular automata algorithm:

$$\boxed{Z_n > Z_{crit}} \Rightarrow \boxed{\begin{aligned} h_{n,t_{i+1}} &= h_{n,t_i} - N_f \\ h_{n+1,t_{i+1}} &= h_{n+1,t_i} + N_f \end{aligned}}$$

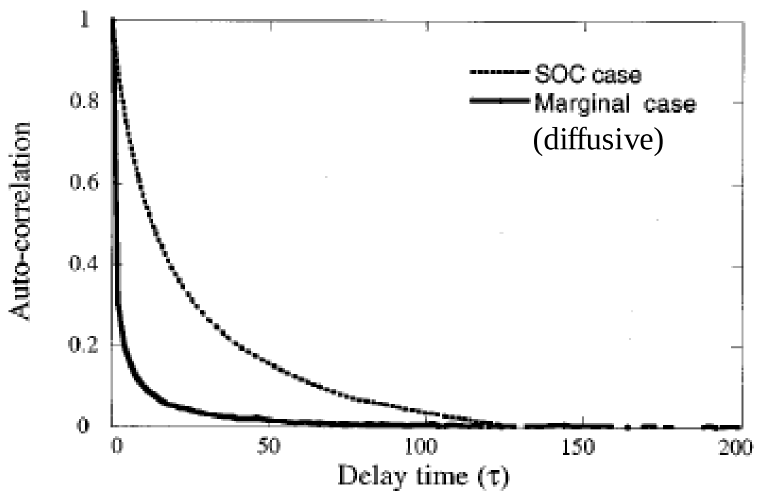
D. E. Newman et al, Phys. Plasma 3,1858 (1996)

Sand-pile model (SOC)

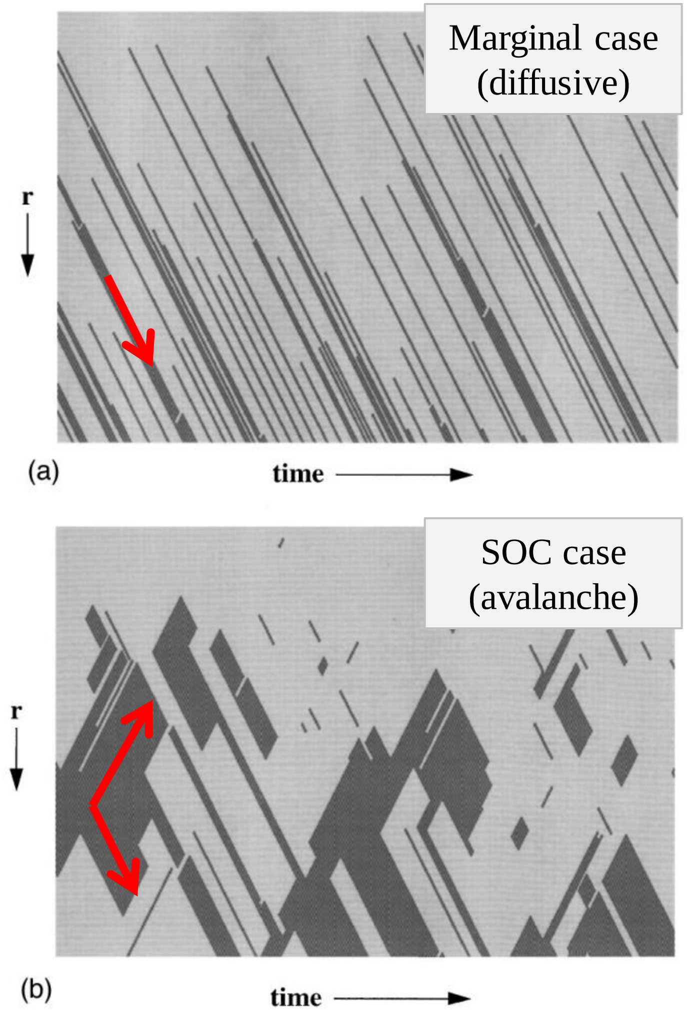
Frequency power spectrum



Auto-correlation function



Trace of grains



D. E. Newman et al, Phys. Plasma 3,1858 (1996)

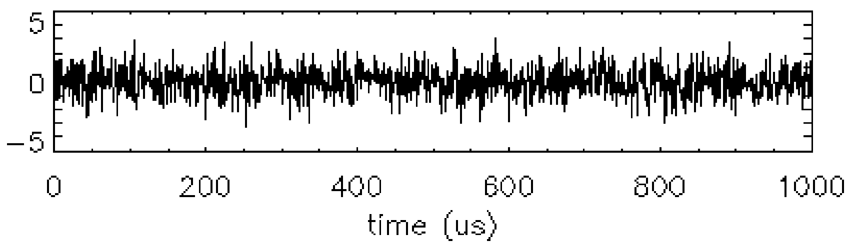
Hurst exponent analysis (R/S)

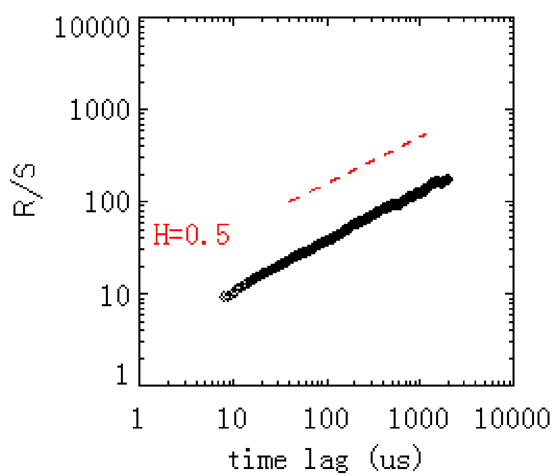
Rescaled range analysis (R/S)

$$X = \{X_t : t = 1, 2, \ldots, n\} \qquad W_k = \sum_{i=1}^{k} X_i - k\overline{X}(n)$$

$$\frac{R(n)}{S(n)} = \frac{\max(0, W_1, W_2 \ldots W_n) - \min(0, W_1, W_2 \ldots W_n)}{\sqrt{\sigma^2(n)}} \xrightarrow[n \to \infty]{} cn^H$$

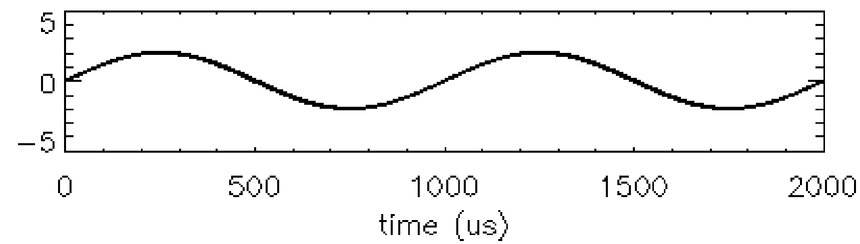
Random noise simulation

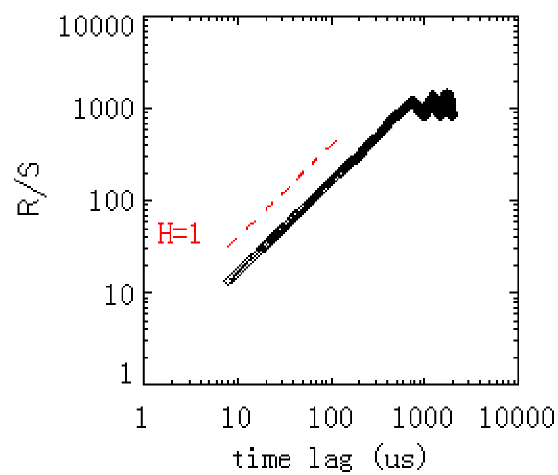




$H \approx 0.5$

Sine function simulation





$H \approx 1$

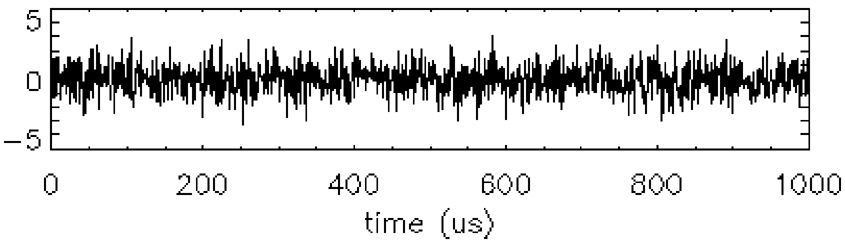
Hurst exponent analysis (SF)

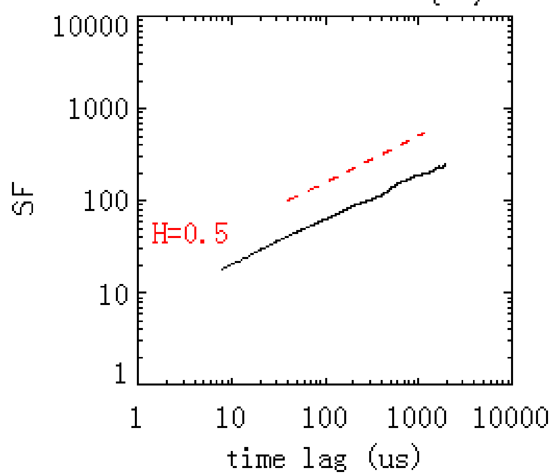
Structure function (SF)

$$X = \{X_t : t = 1, 2, \ldots, n\} \qquad W_k = \sum_{i=1}^{k} X_i$$

$$S_{W,q}(\tau) = \left\langle \left| W(t_i + \tau) - W(t_i) \right|^q \right\rangle \longrightarrow c_q \tau^{qH(q)}$$

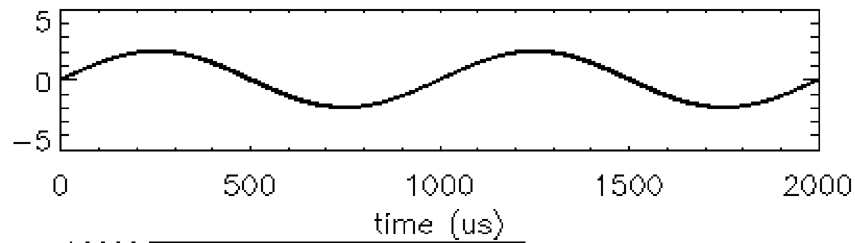
Random noise simulation

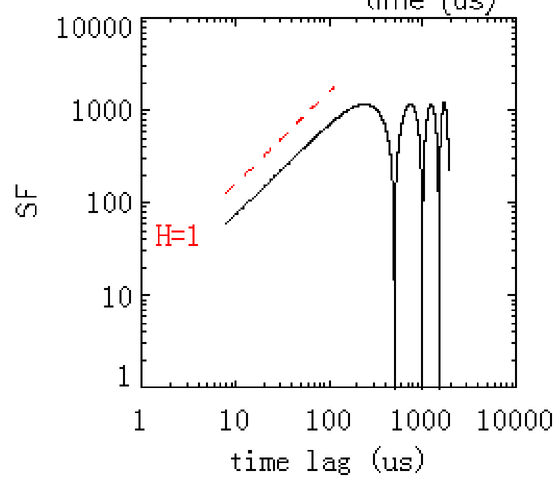




$H \approx 0.5$

Sine function simulation





$H \approx 1$

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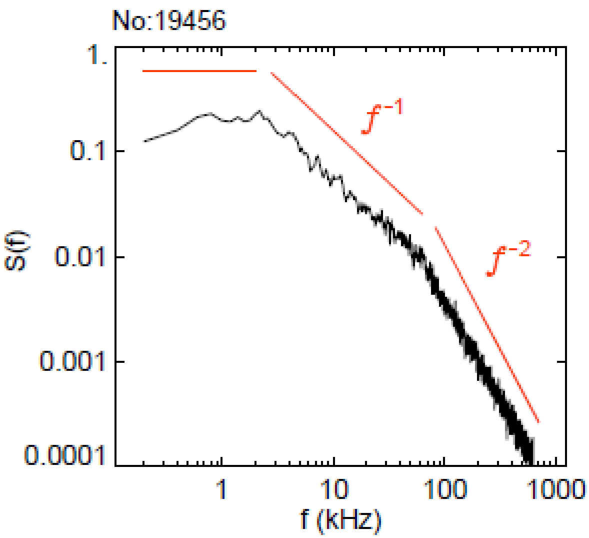
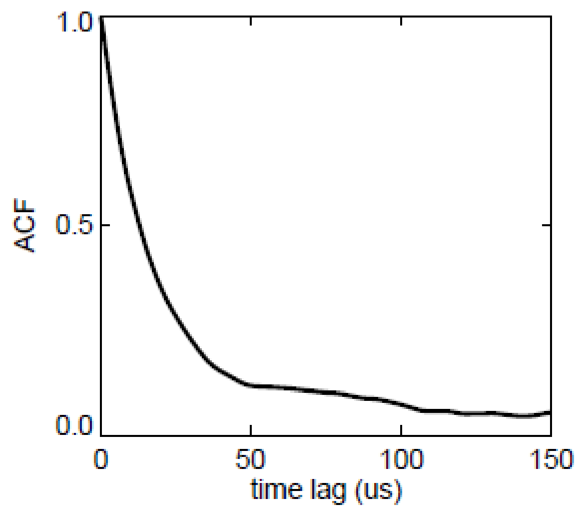
Identification of SOC in normal discharges

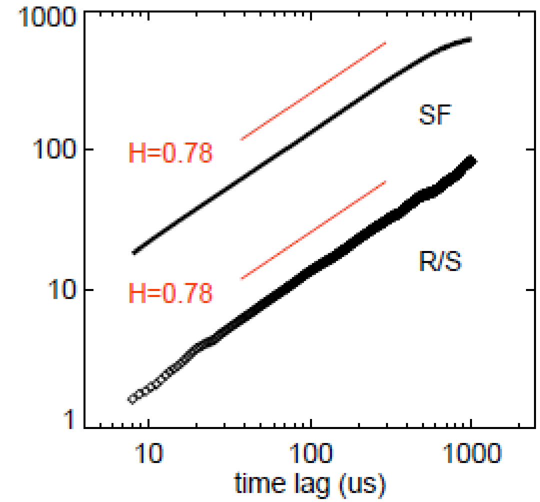
Frequency power spectrum



Auto-correlation function



Hurst exponent



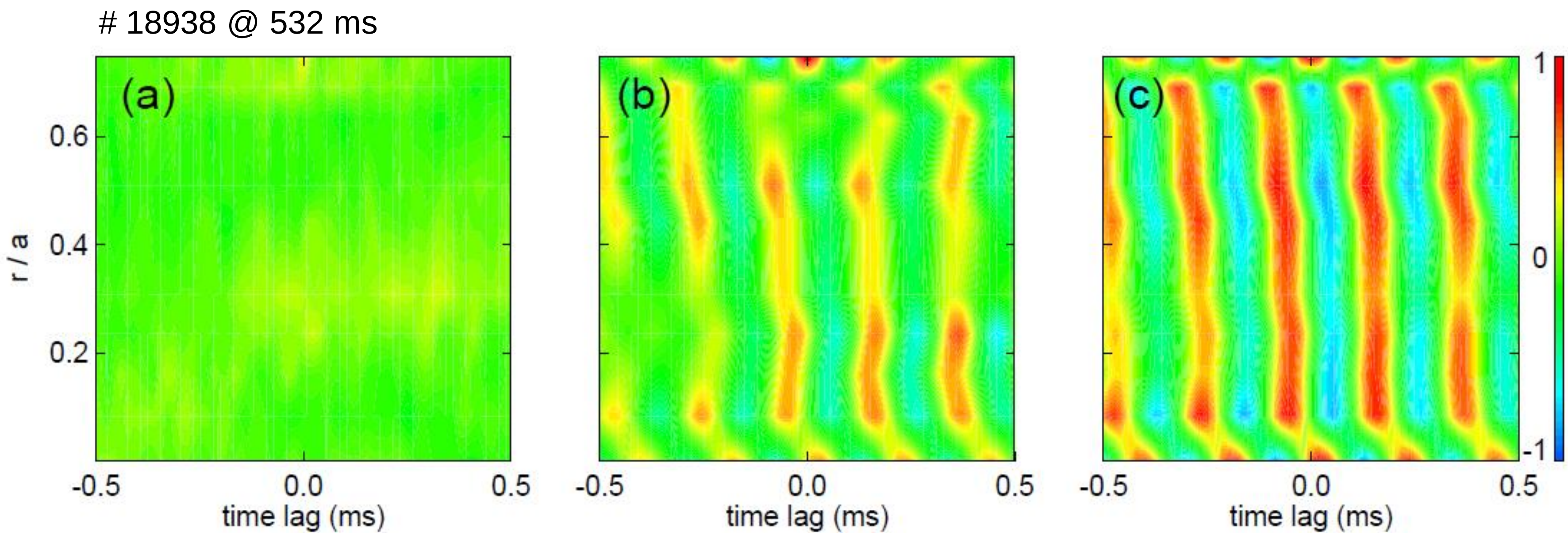
Corresponding to features of SOC system:

f^{-1} dependence in intermediate range	→	overlapping of avalanche transport
Long tail in autocorrelation function	→	long time correlated events
Large value of Hurst parameter	→	self-similarity in turbulent events

Radial propagation of turbulent events

Cross-correlation Hunting:

Contours of CCF between ECE channels with a reference one at r/a=0.75, from time lag -0.5 ms to +0.5 ms. The propagation feature is shown with a band-pass filter.



without filter   2-8 kHz   3-6 kHz

Radial propagation of turbulent events

Cross-correlation Hunting:

Contour-plots of CCF between ECE channels at r/a=0.75, from time lag -0.5ms to +0.5ms. **The dual direction propagation is a significant feature of a SOC system !**

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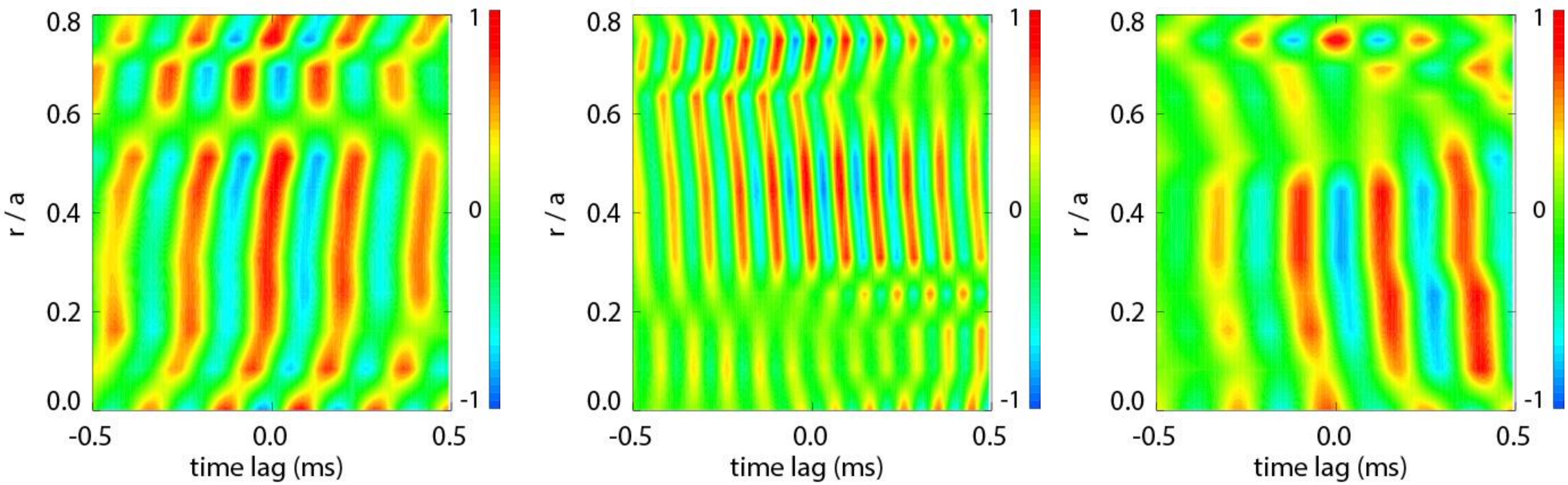

527.5-528.5 ms 3-6 kHz	527.5-528.5 ms 9-12 kHz	531.5-532.5 ms 3-6 kHz
Outward propagation	Inward propagation	Inward propagation

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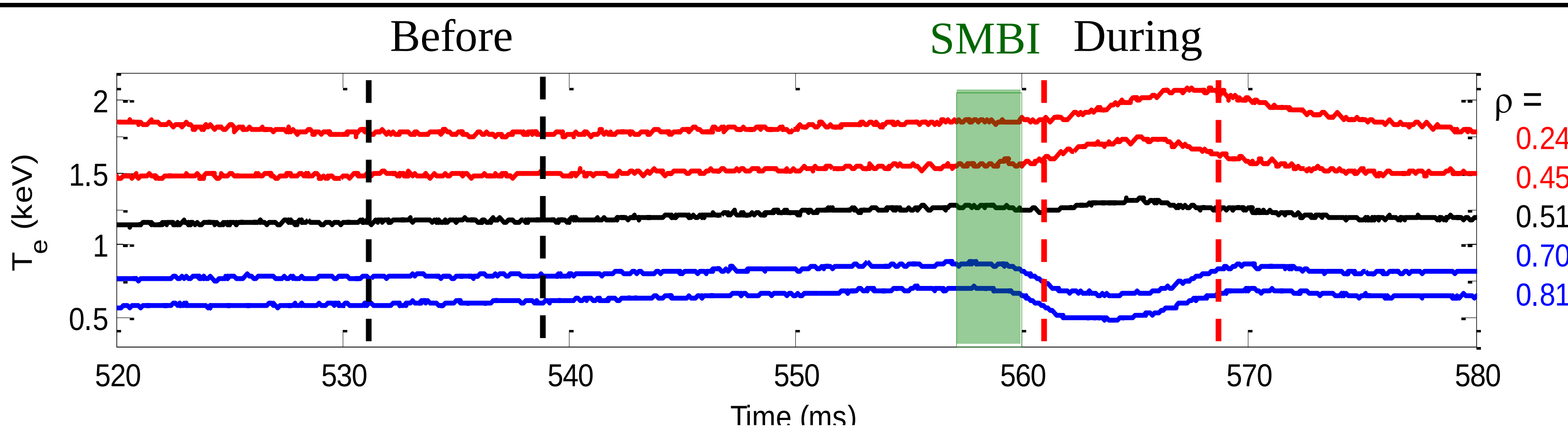
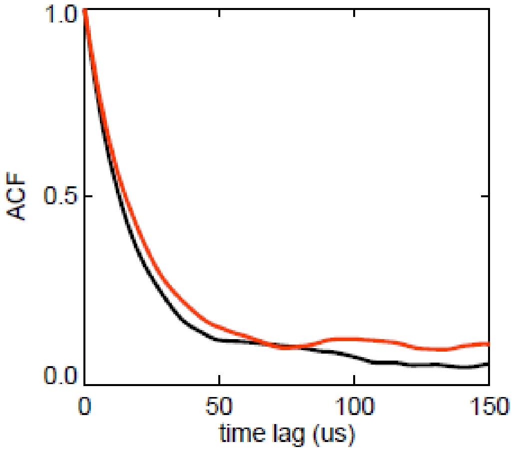
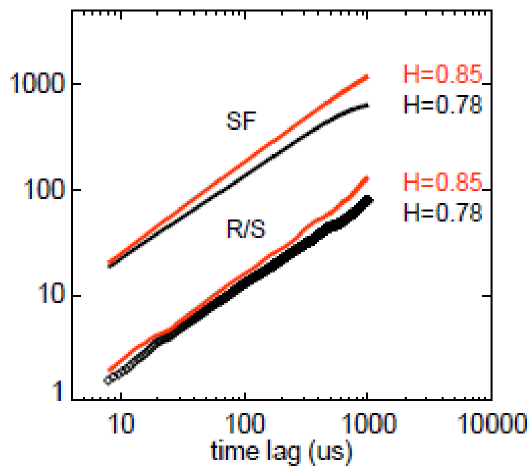
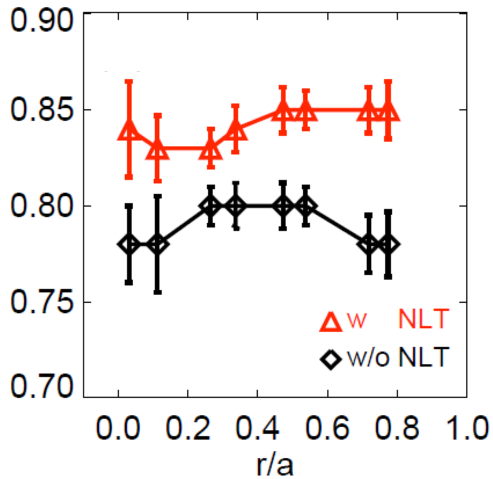
Enhanced SOC behavior during non-local transport





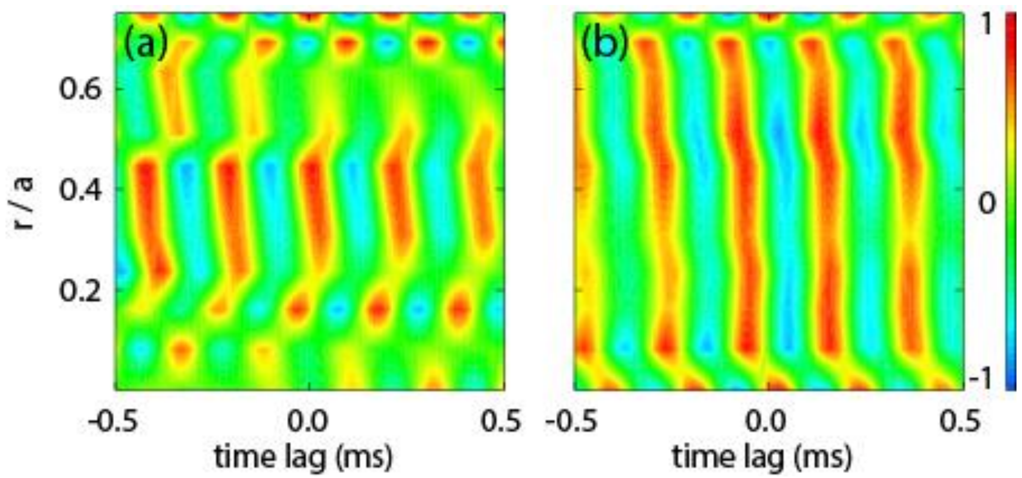




During non-local transport, the time lag in ACF and Hurst parameters are all larger than those before non-locality, indicating an enhanced SOC (avalanche) behavior during the non-local transport.

Enhanced SOC behavior during non-local transport

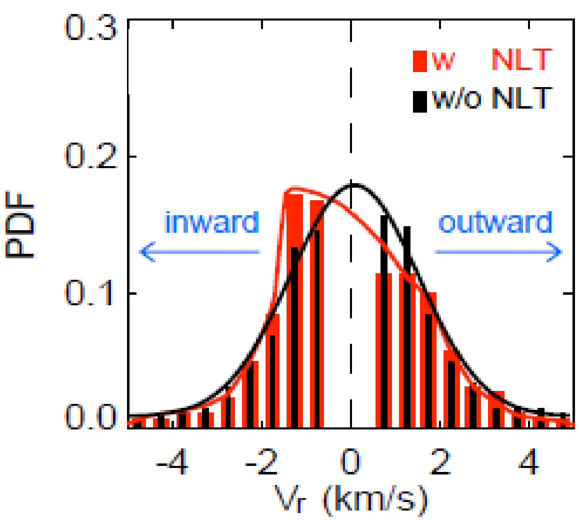
Before non-locality   During non-locality



During non-locality:

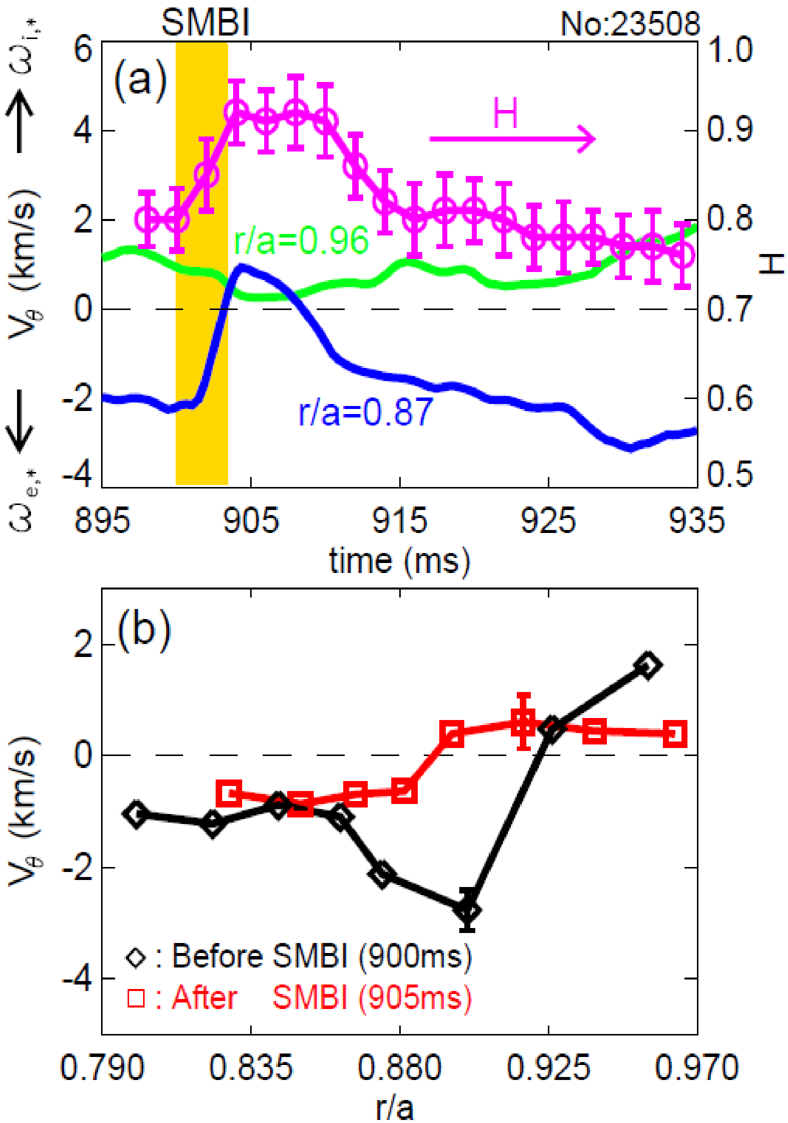
- Correlation length of radial propagation events mostly increase.
- Proportion of inward avalanche propagation increase.

PDF of effective velocity



These enhanced avalanche behaviors during non-locality suggest that the SOC regime could be intimately linked to the non-local transport in HL-2A

Reduced edge flow shear during non-local transport



After the SMBI pulse:

- Poloidal flow shear reduces
- Hurst parameters increase

SMBI (During nonlocal phase)

⇒increase n_e and cooling edge

⇒Reduction of flow shear

⇒the SOC or avalanche-like transport effectively boosted.

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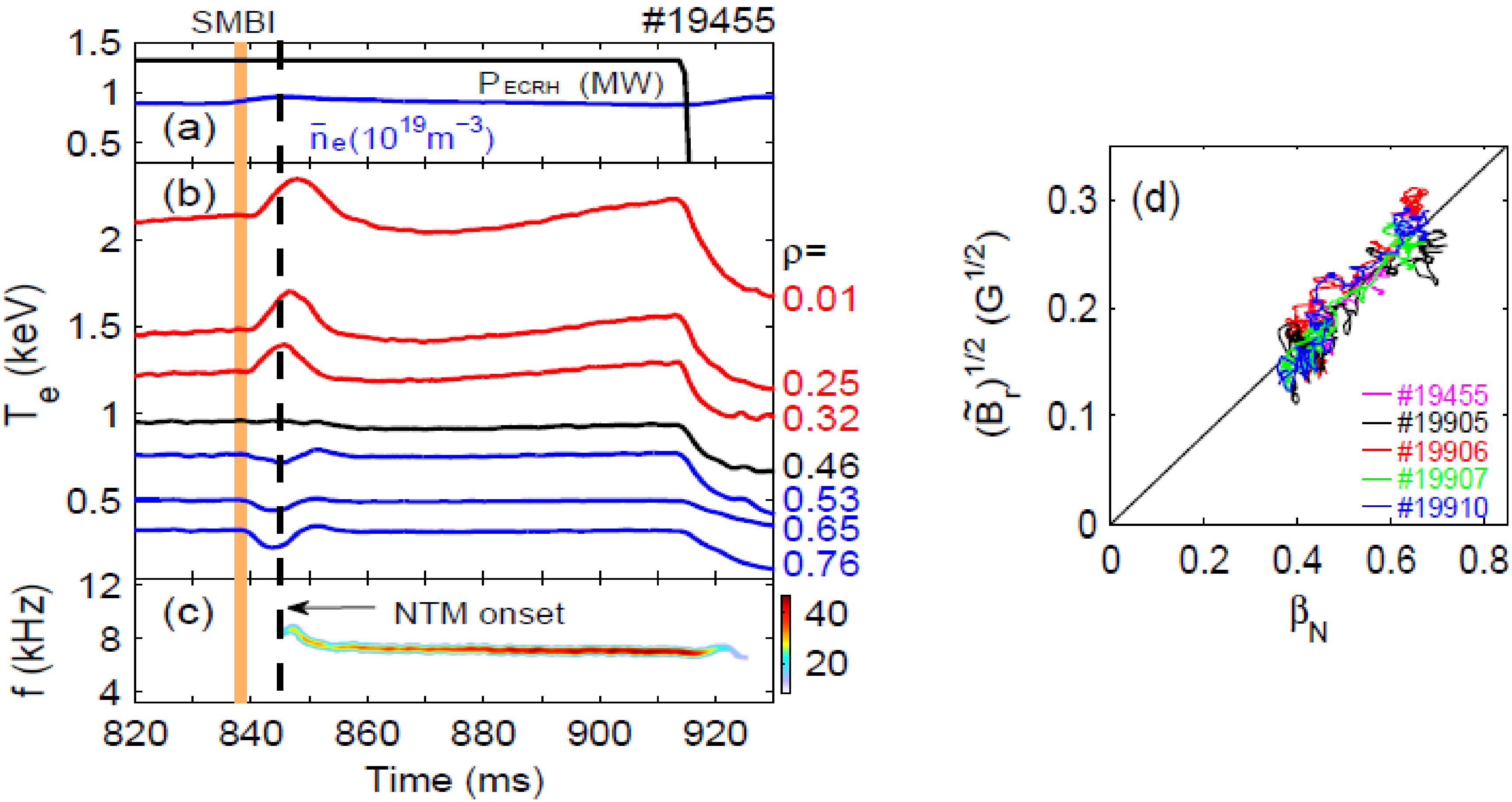
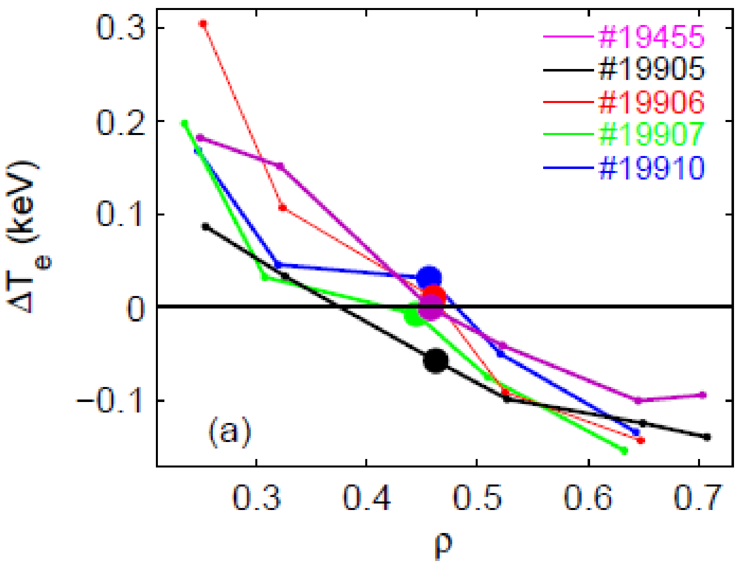
NTMs triggered during the nonlocal phase



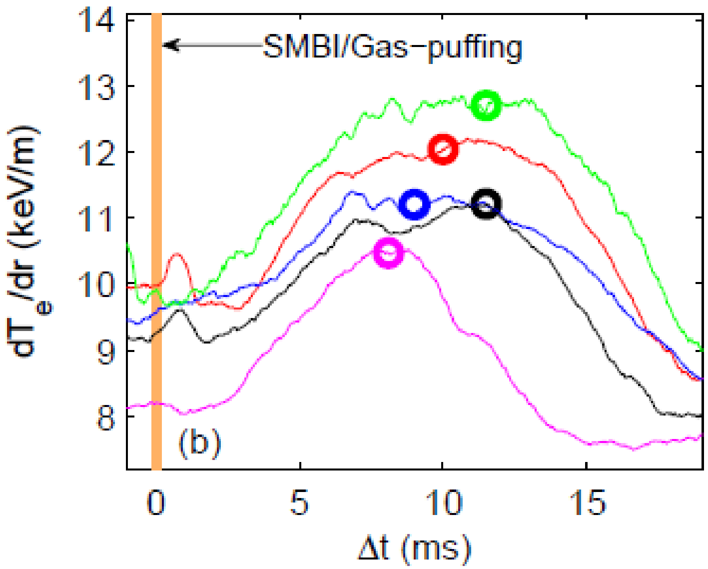
Discharge waveforms with an onset of a 3/2 NTM during the nonlocal transport induced by SMBI (vertical yellow bar) in ECRH-heated plasmas at HL-2A.

Notice: no visible seeding island is observed !

NTMs triggered by increase of local T_e gradient

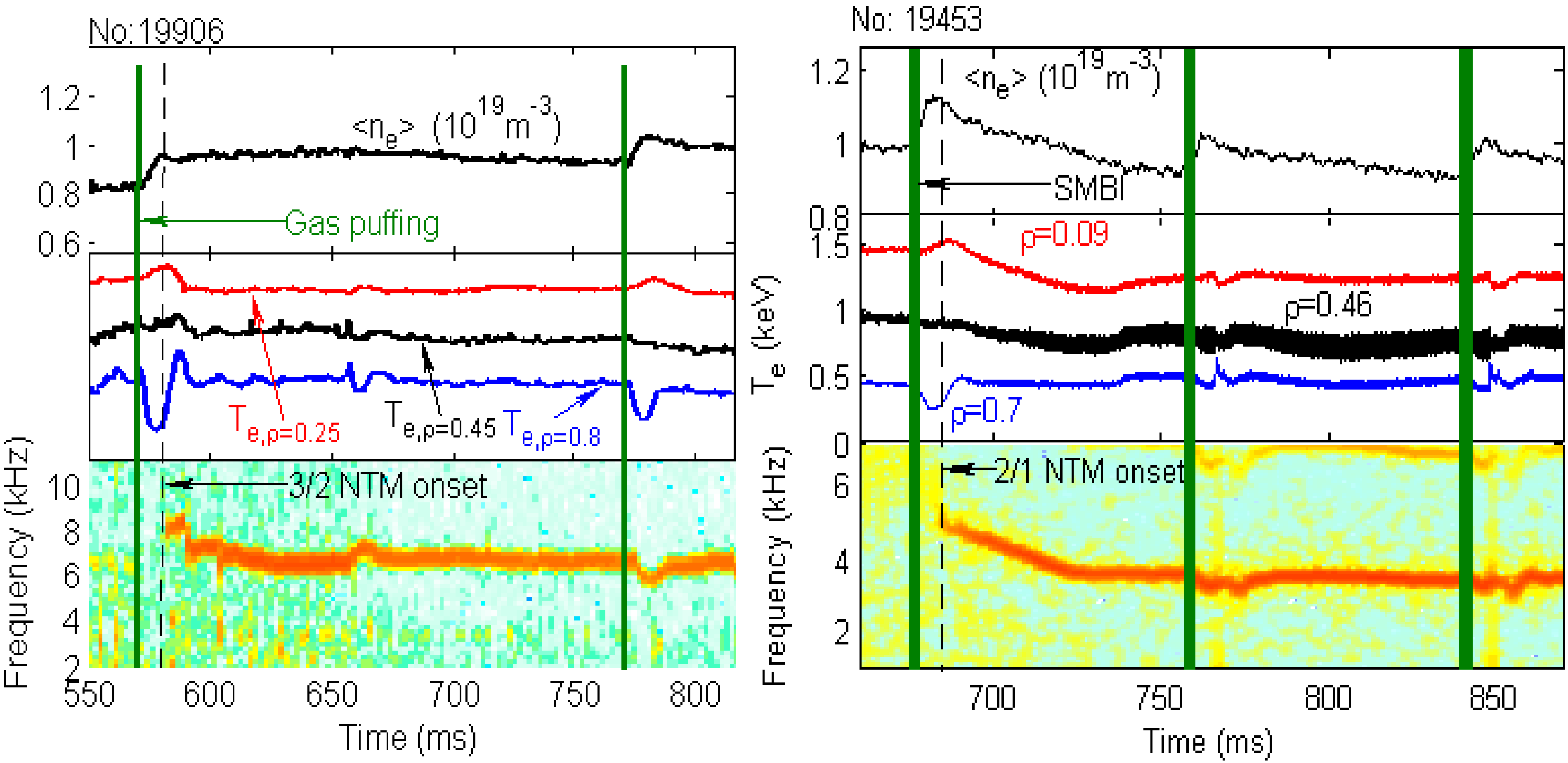


(a) Difference in T_e between the 3/2 NTM onset time and the SMBI/gas puffing time, $\Delta T_e = T_{e,3/2NTM} - T_{e,SMBI/gas\text{-}puff}$, as a function of normalized radii. The solid circles denote the location of q=3/2 surface;



(b) radial gradient of electron temperature (dT_e/dr) between two radial loci around q=3/2 surface as a function of time delay referred to the SMBI/gas puffing time ($\Delta t = t - t_{SMBI/gas\text{-}puff}$) across the nonlocal period. The open circles denote the onset times of the 3/2 NTMs in these shots.

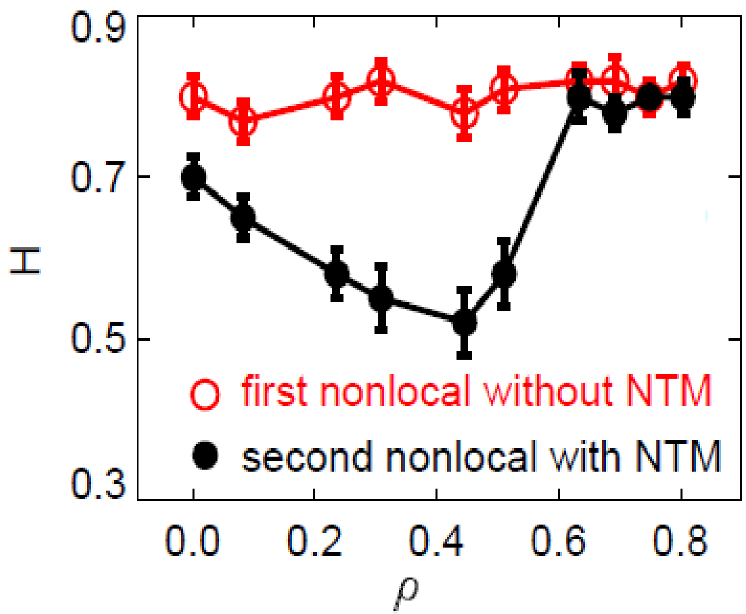
Impact of NTMs on non-local transport

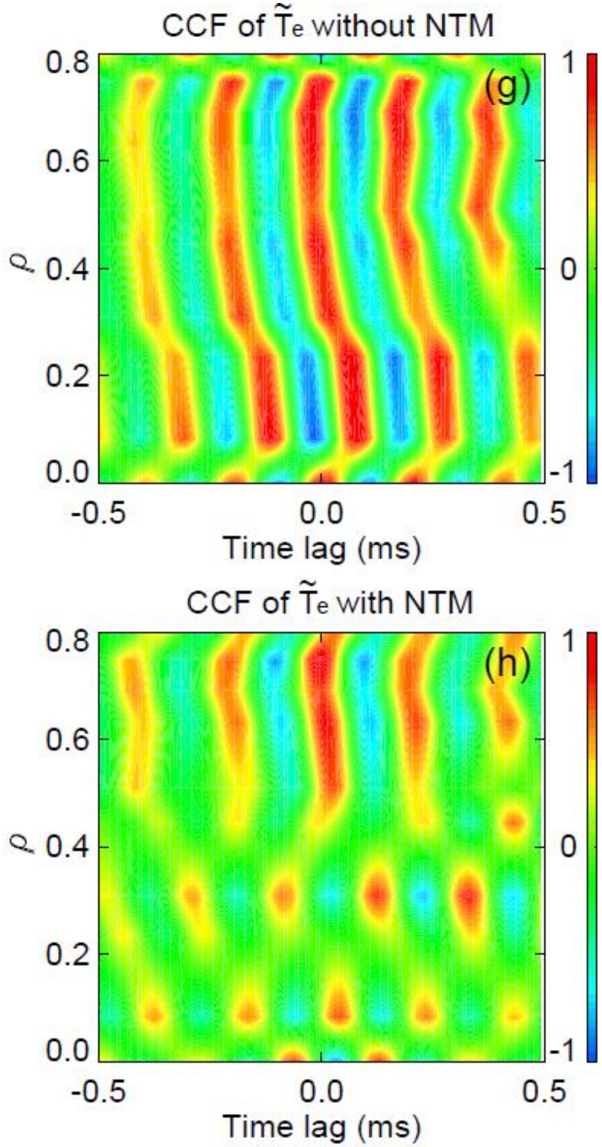


The NTMs impose damping effects on non-local transport.

Why ?

Impact of NTMs on non-local transport

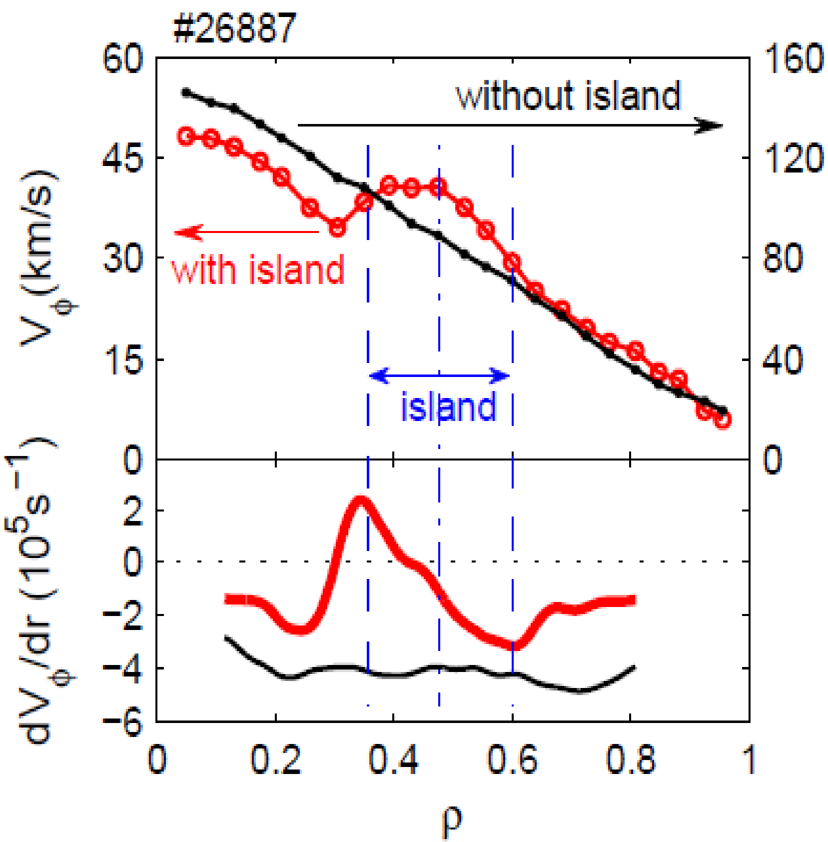




♦ With NTMs, Hurst exponents decrease with the weakened SOC dynamics near the magnetic island.

♦ Avalanche propagation is blocked near the NTM surface of island.

Impact of NTMs on non-local transport



Radial dependence of (a) toroidal flow and (b) toroidal flow shear without (black) and with (red color) the *m/n*=2/1 magnetic island.

With island:

⇒sheared flow is developed inside the island

⇒suppress SOC or avalanche-like transport

⇒reduction of nonlocal transport

Summary

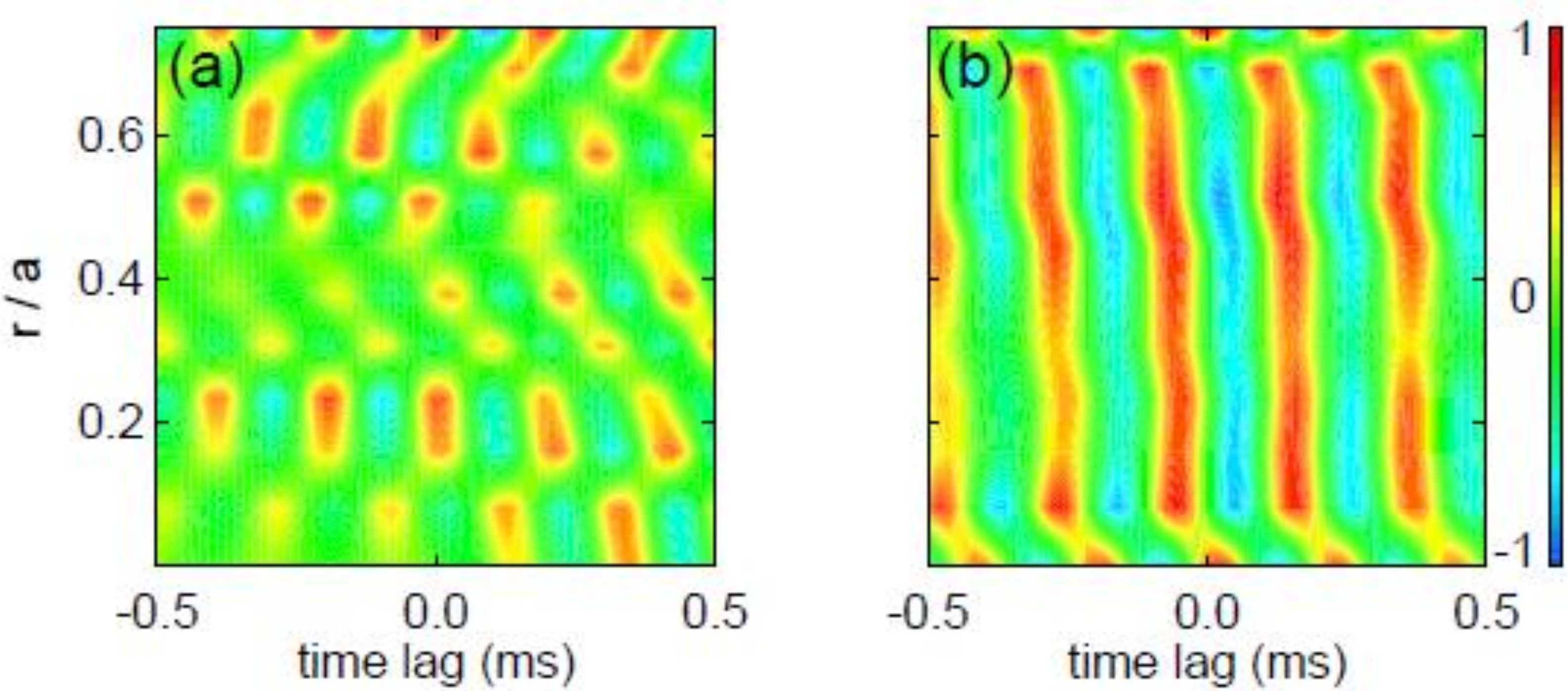
- Characteristics of SOC paradigm have been observed in the HL-2A tokamak.
- During non-local heat transport, SOC (or avalanche behavior) is remarkably enhanced, ***suggesting important role of the SOC dynamics during the nonlocal transport***.
- NTM is triggered during the nonlocality due to increase of local temperature (pressure) gradient, which is related to a large bootstrap current.
- With NTM, the nonlocal effect is weakened owing to suppression of avalanches by locally sheared flows generated inside the magnetic island.

Thanks for your attention

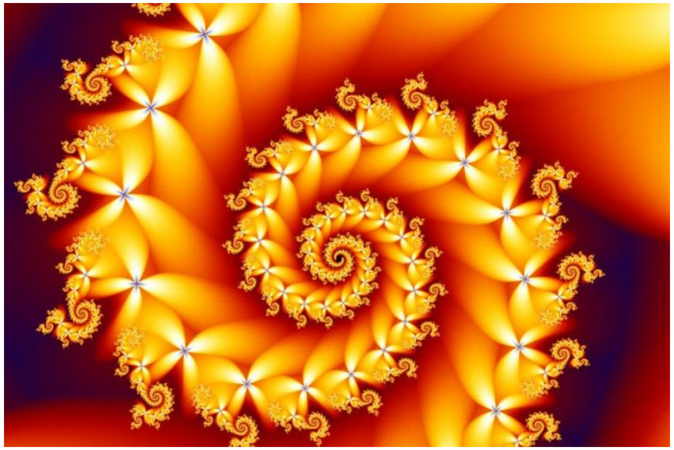
Comparison between noise and ECE signals

Noise simulation

ECE signals during non-locality



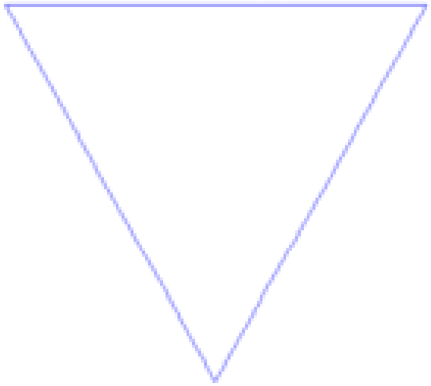
Hurst exponent



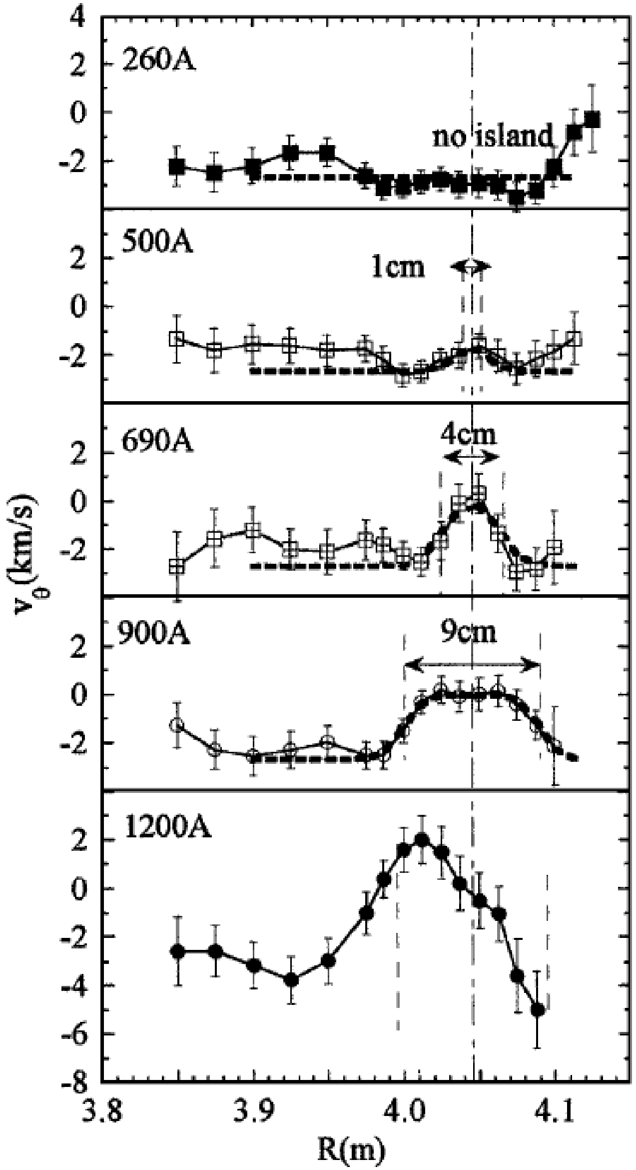
- Originally developed in hydrology by H. E. Hurst in 1950s.
- Self-similarity
- Fractal geometry
- The index of long-range dependence (consistent with SOC feature)

Random series → H=0.5

Determined series → H=1

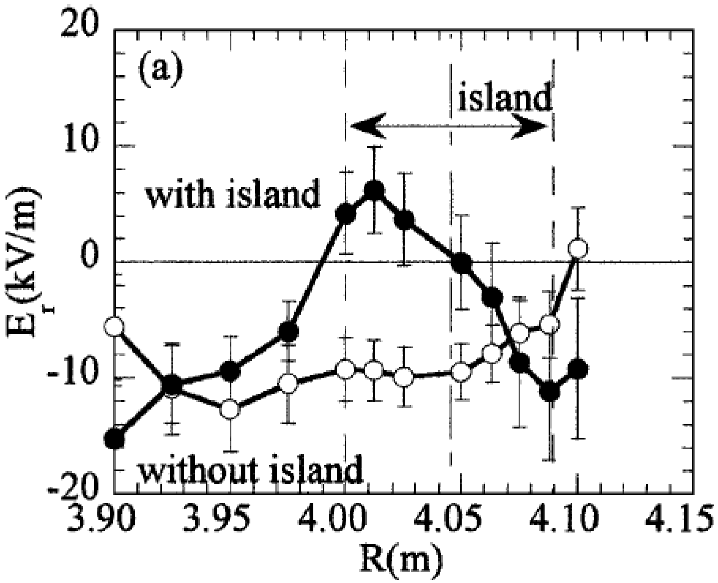


Appendix



Shear flow and resulting radial electric field has been observed in magnetic island of NTM in LHD.

K. Ida et al. Phys. Rev. Lett. 88 (2002) 015002



A possible mechanism of the impeding effect of NTM on avalanche