Progress in understanding physical mechanisms behind enhanced confinement regimes of tokamak plasmas

T.S. Hahm

Seoul National University

Ackn: G.J. Choi, M.J. Choi, A. Garofalo, H.G. Jhang, J.M. Kwon, Y.S. Na and J.K. Park

Presented at 3rd Trilateral International Workshop on
Energetic Particle Physics, Nov 9, 2022

Personal Recollection of Research Trend Evolution

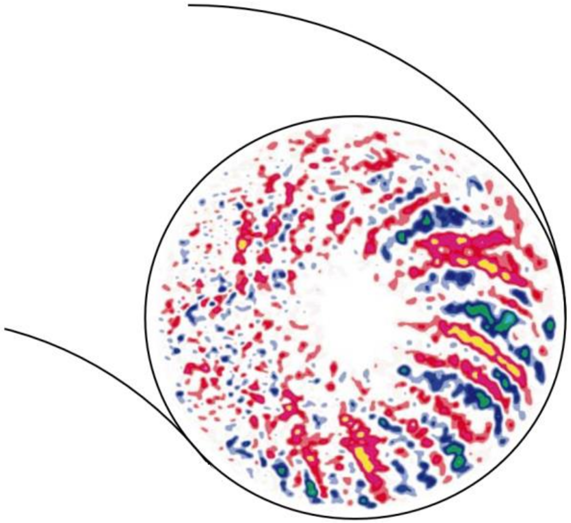
- Emphasis on Illustrations of Key Physical Concepts.
- Not a historical review.
- Mostly on electrostatic turbulence with ion gyroradius or larger scale in tokamak plasmas in the absence of large scale MHD activities.

Outline

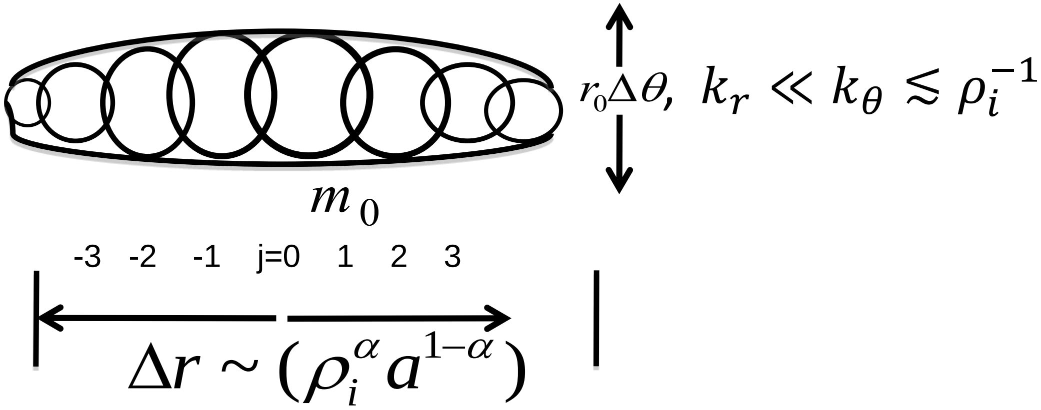
- Radially Elongated Eddies
- E×B Shear Reduction of Turbulence
- Physics of Zonal Flows
- Turbulence Spreading
- Self-Organized-Criticality
- Avalanches and E×B Staircase
- Recent Progress in Experiments

Radially Elongated Eddy is a Natural Structure in Tokamak Plasma Turbulence

- Efficient for free energy relaxation and heat transport.
- E×B convective nonlinearity is reduced as $k_r \to 0$, and the elongated eddy saturates at large amplitude.
- In toroidal plasmas, neighboring poloidal harmonics (located at each rational surface) couple to form a Global Eigenmode.



Courtesy: Z. Lin (1998)



$r_0\Delta\theta,\ k_r \ll k_\theta \lesssim \rho_i^{-1}$

m_0

-3 -2 -1 j=0 1 2 3

$$\Delta r \sim (\rho_i^{\alpha} a^{1-\alpha})$$

meso-scopic scale

[S.C. Cowley, R.M. Kulsrud and R. Sudan, PFB (1991)]
[F. Romanelli and F. Zonca, PFB (1993)]

Meso-scale eddies lead to Poor Confinement

- $\Delta r \sim \sqrt{\rho_i a}$ can lead to Bohm scaling, $\chi \sim \frac{cT}{eB}$

  $\sim$ Experimental Results.

- Early global gyrokinetic simulations of toroidal ITG modes

  [W. Horton, D.I. Choi and W. Tang, PF (1981)] reported a similar trend.

  [S.E. Parker, W.W. Lee and R.A. Santoro, PRL (1993)]
  [Y. Kishimoto *et al*., PoP (1996)]

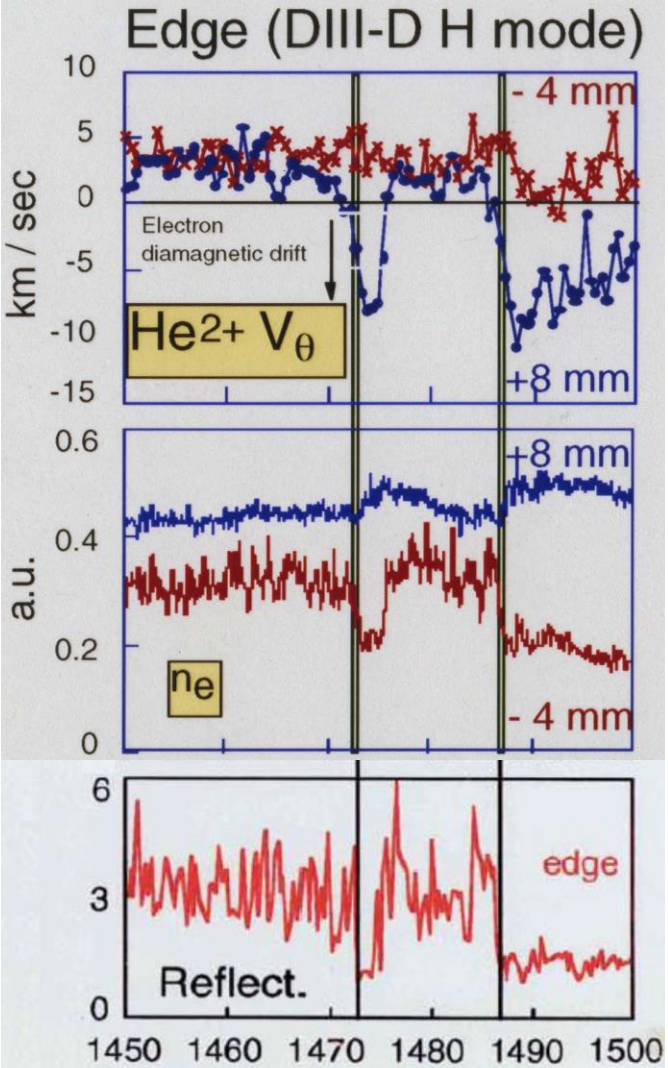
$$\chi \sim \frac{\Delta r^2}{\Delta t} \sim \frac{\rho_i a}{\omega_*^{-1}} \sim \frac{cT}{eB}$$

Outline

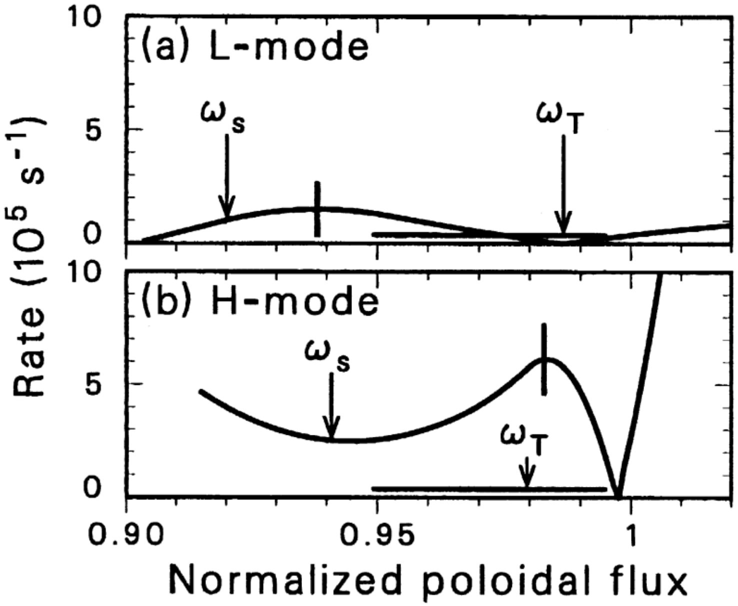
- Radially Elongated Eddies
- E×B Shear Reduction of Turbulence
- Physics of Zonal Flows
- Turbulence Spreading
- Self-Organized-Criticality
- Avalanches and E×B Staircase

Reviews on this topic: [K.H. Burrell, PoP **4**, 1499 (1997)]
[T.S. Hahm, PPCF **44**, A87 (2002)]

E×B Shear plays a crucial role in H-mode Transition



[Moyer *et al*., PoP (1995)]



[Coda, Porkolab and Burrell, PRA (2000)]

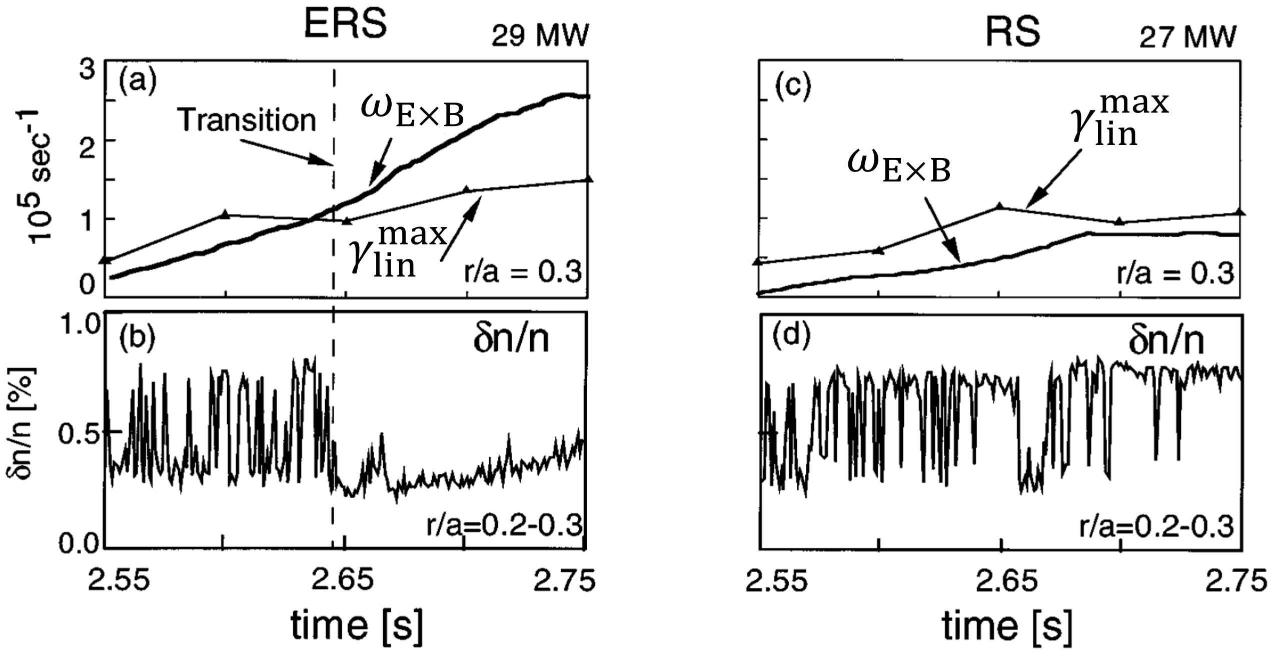
ω_S: E×B Shearing Rate in Cylinder [Biglari-Diamond-Terry, PFB (1990)]

ω_T: turbulence decorrelation rate

E×B Shear and Ion Thermal Internal Transport Barrier

[Mazzucato *et al*., Phys. Rev. Lett. (1996)], [Synakowski *et al*., Phys. Plasmas (1997)]

Transition to Enhanced Reversed Shear state with Internal Transport Barrier



No ITB
although
magnetic shear
is reversed

TFTR

- ERS transition occurred when E×B shearing rate $\omega_{\mathrm{E\times B}}$ exceeds maximum turbulence growth rate $\gamma_{\mathrm{lin}}^{\mathrm{max}}$.

$$\omega_{\mathrm{E\times B}} = \frac{\Delta r_0}{\Delta l_\perp} \frac{(RB_\theta)^2}{B} \frac{\partial}{\partial \psi} \left(\frac{E_r}{RB_\theta} \right)$$

[Hahm and Burrell, PoP ‘95]

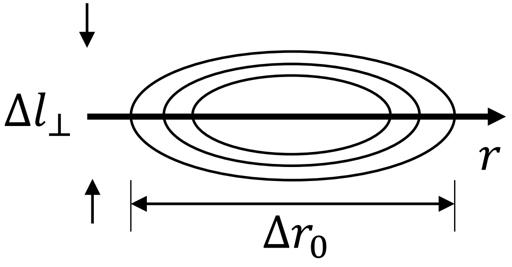
E×B Shearing Rate in Toroidal Geometry

- [T.S. Hahm and K.H. Burrell, Phys. Plasmas **2**, 1648 (1995)]:
  E×B shearing rate in **general toroidal geometry**

$$\omega_{\mathrm{E\times B}} = \frac{\Delta r_0}{\Delta l_\perp}\frac{(RB_\theta)^2}{B}\frac{\partial}{\partial\psi}\left(\frac{E_r}{RB_\theta}\right)$$

E×B shear effect can come

- $\frac{\partial}{\partial\psi}\left(\frac{E_r}{RB_\theta}\right)$ from u_θ and ∇P_i (TFTR ERS, H-mode)
  or from u_ϕ (DIII-D NCS, VH, QH; JET OS, RS, …) : using radial force balance
- $\frac{(RB_\theta)^2}{B}$ In-out asymmetry
  Evidence from DIII-D, Pronounced for STs
- $\frac{\Delta r_0}{\Delta l_\perp}$ Eddy shape dependence
  Typically assumed to be 1
  Stronger shearing for radially elongated eddy



- Validations made possible by developments of Experimental Diagnostics for E_r, B_θ, and fluctuations.
- Useful Rule of Thumb compared to γ_{lin} from Gyrofluid Simulations [Waltz *et al*., PoP '94].

Outline

- Radially Elongated Eddies

- E×B Shear Reduction of Turbulence

- Physics of Zonal Flows

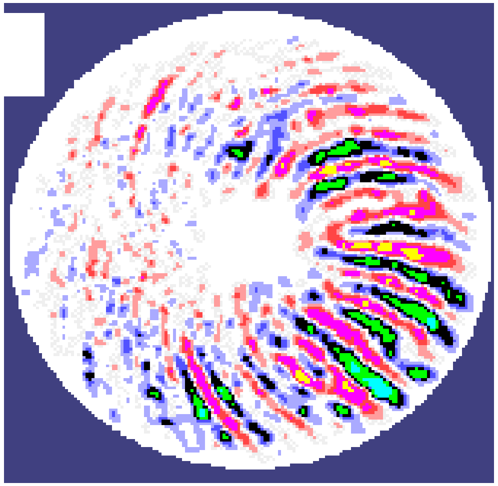
- Turbulence Spreading

- Self-Organized-Criticality

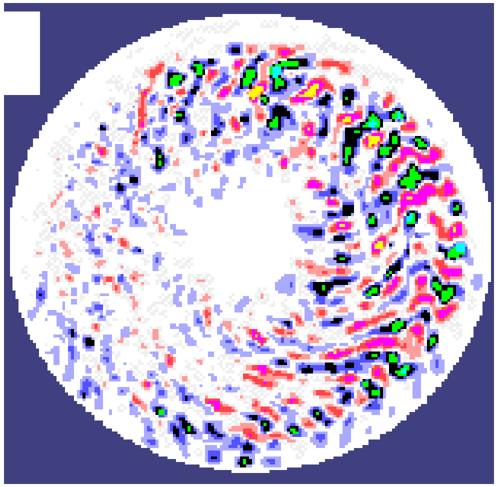
- Avalanches and E×B Staircase

Review: [Diamond, Itoh, Itoh and Hahm, PPCF **47**, R35 (2005)]

Sheared Zonal Flow Regulates Turbulent Eddy Size and Transport

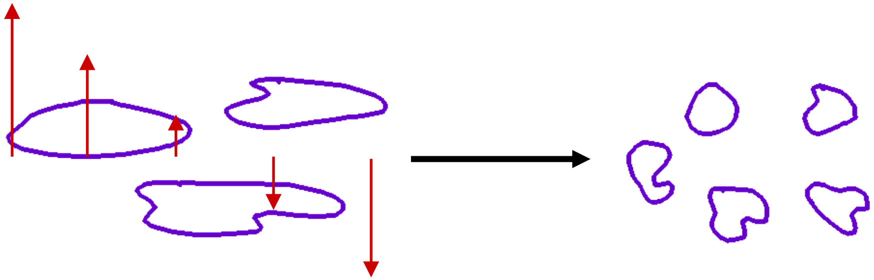


No flow



With flow

- Externally driven E×B Shear Flows were used before for the direct control of the turbulence. [H-mode, ITBs, …]
- Self-generated E×B zonal flow from turbulence reduces radial size of eddies.

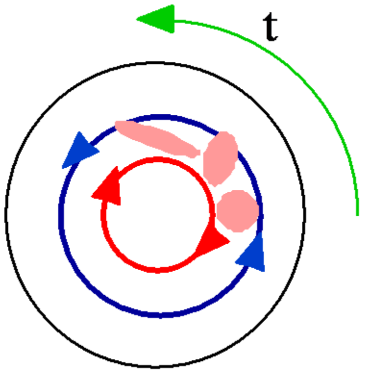


- Breakup of radially elongated structures reduces transport.

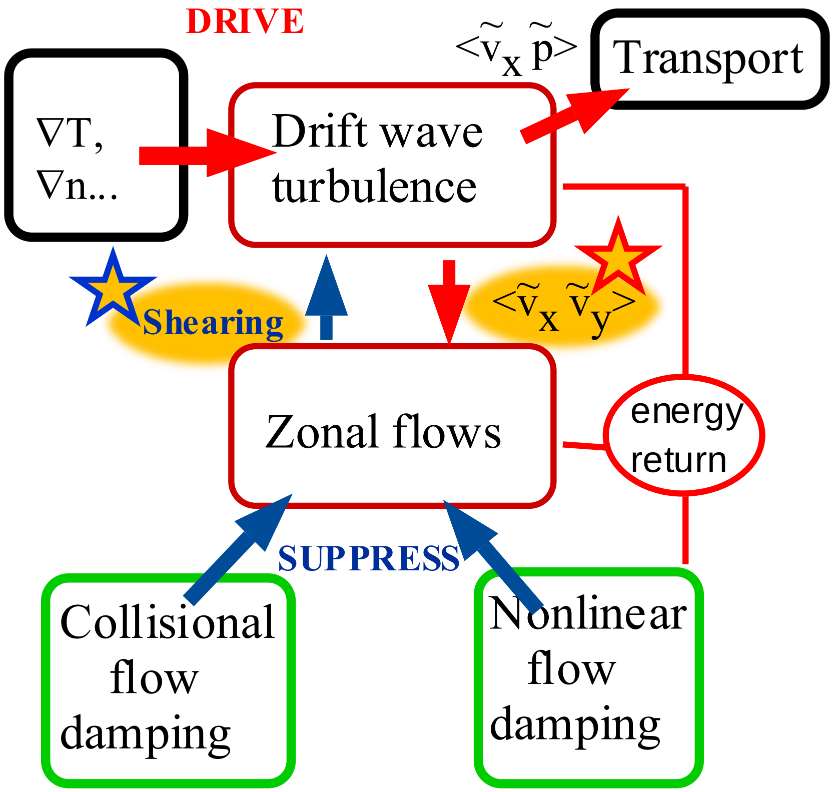
[Lin, Hahm, Lee, Tang and White, Science (1998)]

Basic Physics of Zonal Flow

from [Diamond, Itoh, Itoh and Hahm, “Zonal Flows in Plasma – a Review” PPCF (2005)]



Suppression of DW by Shearing



DRIVE

∇T, ∇n...

Drift wave turbulence

$\langle \tilde{v}_x \tilde{p} \rangle$

Transport

Shearing

$\langle \tilde{v}_x \tilde{v}_y \rangle$

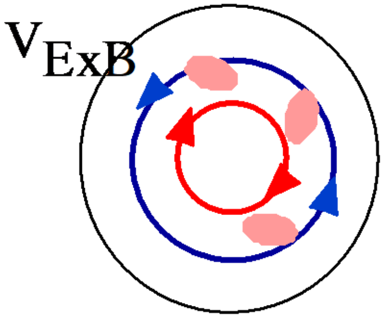
Zonal flows

energy return

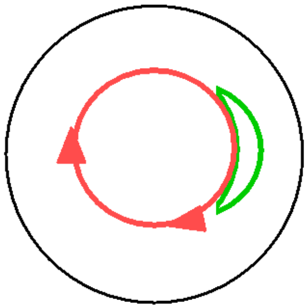
SUPPRESS

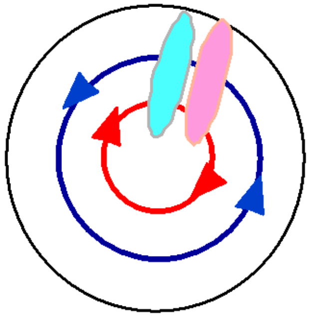
Collisional flow damping

Nonlinear flow damping



Generation by Vortex Tilting

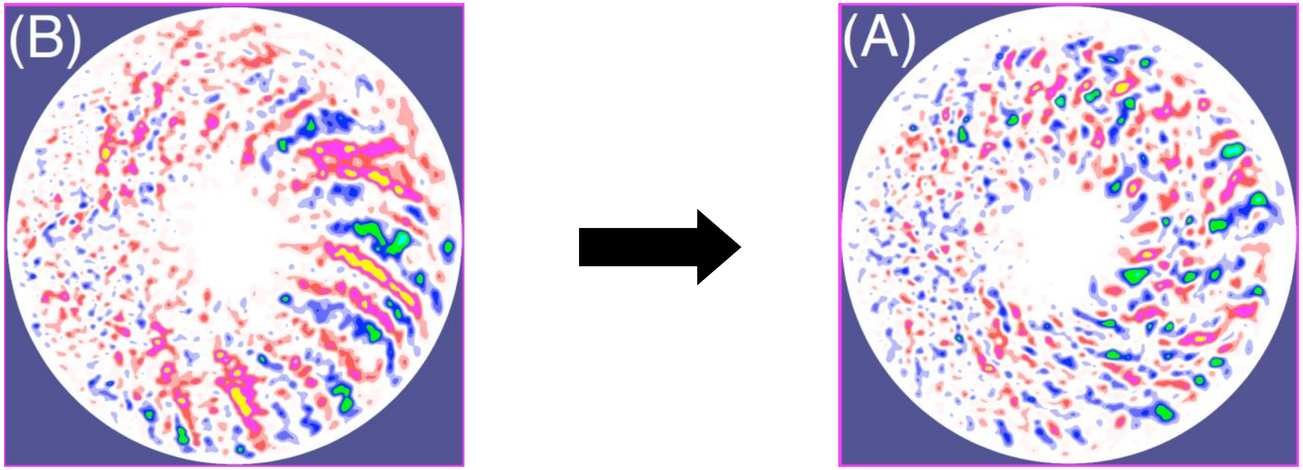




Damping by Collisions

Duality of Flow Generation and Random Shearing of Eddies

Based on Conservation laws: Wave-kinetic equation for details.



$\omega_k \gg \omega_{\mathrm{ZF}}$ → Drift Wave Action Density N_k is conserved.

(adiabatic invariant)

From $\omega_{\mathrm{DW}} = \dfrac{k_\theta v_*}{1 + k_\perp^2 \rho_s^2}$, shearing → $k_r^2 \nearrow$ → Drift Wave Energy $E_k = N_k \omega_k \searrow$

Since total energy is conserved between Zonal Flow and Drift Wave, energy for ZF generation is extracted from DWs.

[Diamond *et al*., IAEA-FEC '98]

Zonal Flow Generation via Modulation in Toroidal Geometry

[Chen, Lin and White, Phys. Plasmas (2000)]

$\Phi_{\mathrm{DW}}\,(k_r)$

"Drift Wave"

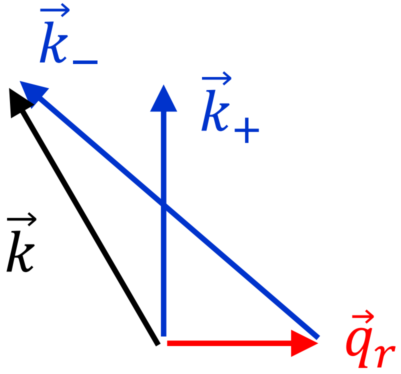
Modulation via $\Phi_{\mathrm{ZF}}\,(q_r)$

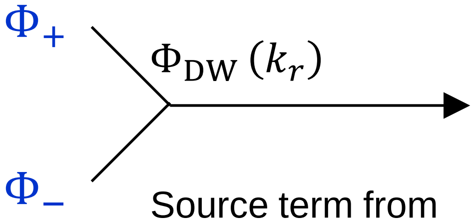
$$\Phi_+(\vec{k}_+ = \vec{k} + \vec{q}_r) \propto \frac{\Phi_{\mathrm{DW}}}{D_+}\Phi_{\mathrm{ZF}}$$

$$\Phi_-(\vec{k}_- = \vec{k} - \vec{q}_r) \propto \frac{\Phi_{\mathrm{DW}}}{D_-}\Phi_{\mathrm{ZF}}$$

"Side-bands"
DW produced.

from E×B nonlinearity





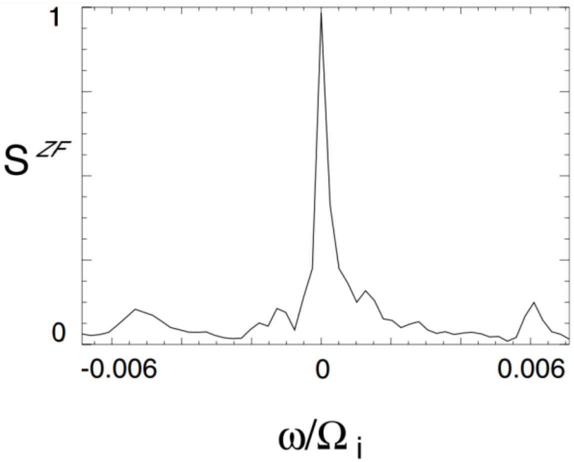
$$\frac{q^2}{\sqrt{\epsilon}}\gamma_{\mathrm{ZF}}\Phi_{\mathrm{ZF}} \propto \frac{\Phi_{\mathrm{DW}}^2}{D(\gamma_{\mathrm{ZF}})}\Phi_{\mathrm{ZF}}$$

Source term from
Hasegawa-Mima
nonlinearity

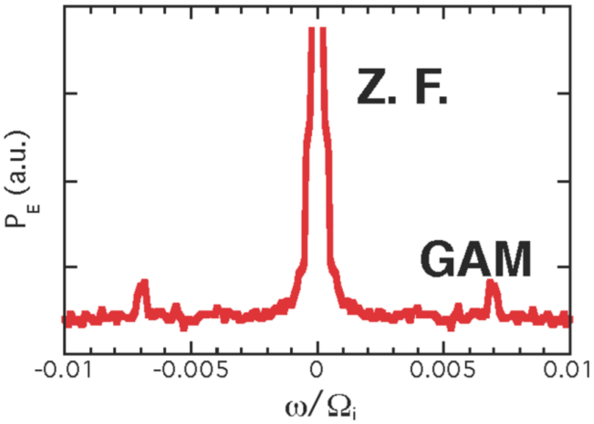
Neoclassically enhanced
Polarization in long term
[Rosenbluth-Hinton, PRL '98]

Characterization of Zonal Flow Properties from Simulations Motivated Experimental Measurements

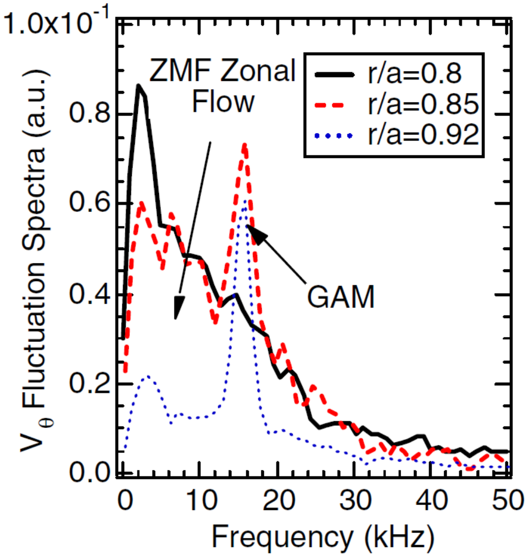
- Zero-frequency Zonal Flows are dominant in core plasmas.



from GTC Simulation by
Z. Lin *et al*.
[T.S. Hahm *et al*., PPCF ‘00]



[A. Fujisawa *et al*., PRL ‘04]
from Stellarator (CHS)



[D.K. Gupta, G. McKee *et al*., PRL ‘06]
from Tokamak (DIII-D)

Key Physics Mechanisms behind Size Scaling of Confinement

- **Global Toroidal ITG eigenmode**
  [Horton-Choi-Tang, PF '81], [Cowley-Kulsrud-Sudan, PFB '91], [Romanelli-Zonca, PFB '93], [Parker-Lee-Santoro, PRL '93], [Kishimoto *et al*., PoP '96]

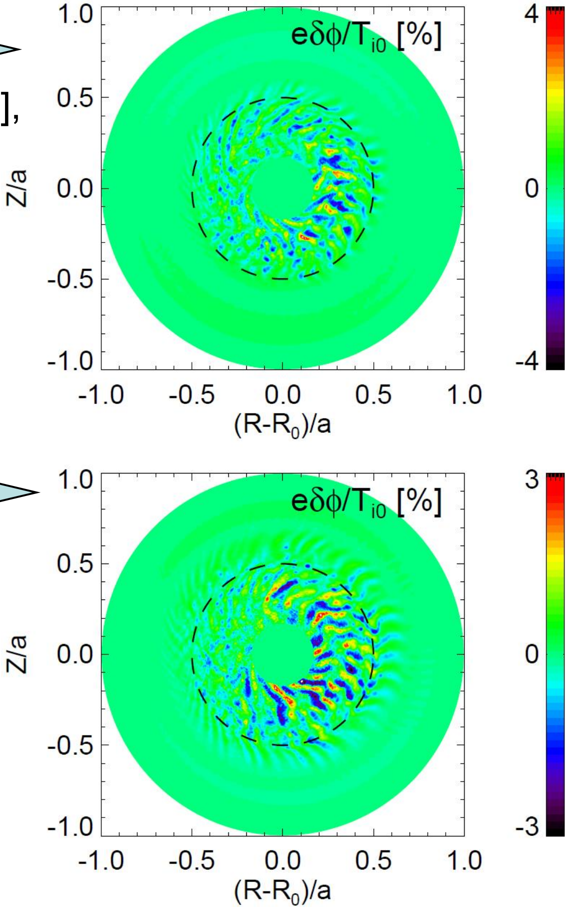
Bohm Scaling? $\chi_{\text{Bohm}} \propto \frac{cT}{eB}$

- **Self-regulation by Zonal Flows**
  [Hasegawa-Wakatani, PRL '87], …
  [Diamond, Itoh, Itoh and Hahm, Review in PPCF '05]

GyroBohm Scaling! $\chi_{\text{gB}} \propto \left(\frac{\rho_i}{a}\right) \chi_{\text{Bohm}}$

Paradigm Shift

But, <u>not final story.</u>



Density fluctuations from a gKPSP simulation of ITG in a toroidal plasma [Yi, Kwon, Diamond *et al.,* PoP '14]

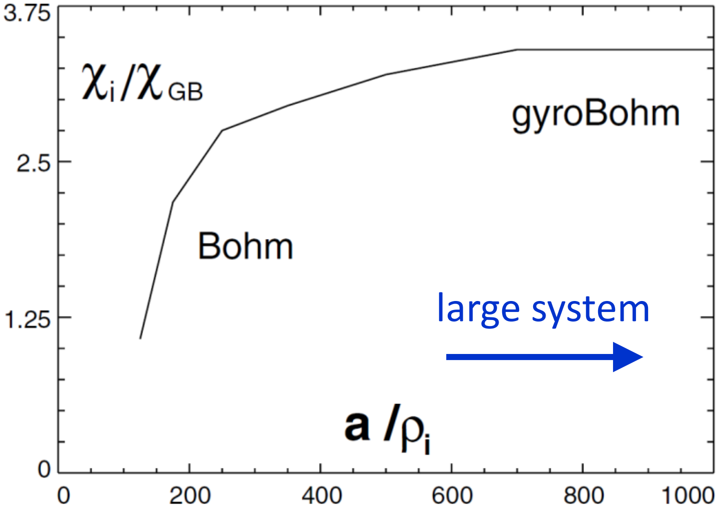
Outline

- Radially Elongated Eddies
- E×B Shear Reduction of Turbulence
- Physics of Zonal Flows
- Turbulence Spreading
- Self-Organized-Criticality
- Avalanches and E×B Staircase

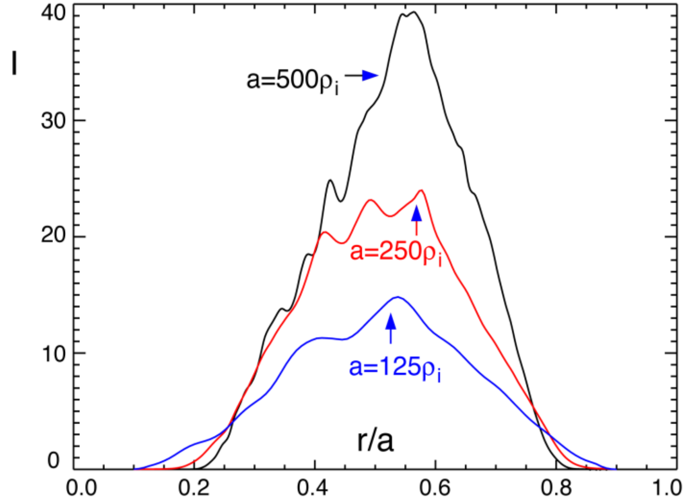
Review on this topic: [Hahm and Diamond, JKPS **73**, 747 (2018)]

Turbulent Spreading is related to Deviation from GyroBohm Scaling

- Non-zero fluctuations in the linearly stable zone widely observed in many global grokinetic simulations [Sydora, Parker, Kishimoto, Lin, Villard, …].
- [Garbet *et al*., NF **34**, 963 (1994)] discussed spreading from toroidal mode coupling in the context of transient transport.
- GK simulations reporting deviation from “gyroBohm” scaling for moderate system size motivated theoretical research revival [Hahm, APS-invited ‘01].



[Lin, Hahm, Lee *et al*., PRL ‘02]
also [McMillan *et al*., PRL ‘10]



Range of fluctuation spreading into linearly stable zone: GK simulation: $\Delta \approx 25\,\rho_i$

Simple Model of Turbulence Spreading

[Hahm, Diamond, Lin, Itoh and Itoh, PPCF **46**, A323 (2004)]

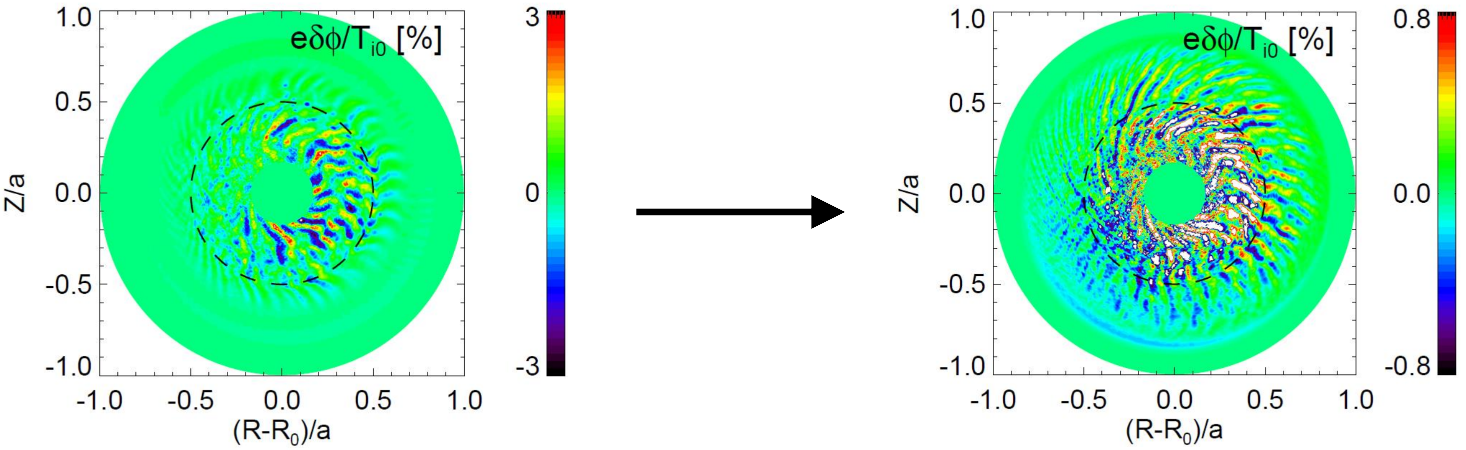
$$\frac{\partial}{\partial t} I = \gamma(x) I - \alpha I^2 + \chi_0 \frac{\partial}{\partial x}\left(I \frac{\partial}{\partial x} I\right)$$

[Fisher-Kolmogorov]

- $\gamma(x)$: “local” growth rate, α : a local nonlinear coupling.
- $\chi_0 I = \chi_i$: a turbulent diffusivity.
- I : turbulence intensity, $\sum_{\mathbf{k}} \mathrm{Modes} \sim \sum \mathrm{Eddies}.$

$$\frac{\partial}{\partial t}\int_{x-\Delta}^{x+\Delta} dx'\, I(x',t) \sim \chi_0 I \left.\frac{\partial I}{\partial x}\right|_{x-\Delta}^{x+\Delta} + \cdots$$

- **Profile of Fluctuation Intensity** is crucial to its Spatio-temporal Evolution.
- Estimations based on the simple model is in reasonable agreement with GK simulation results.

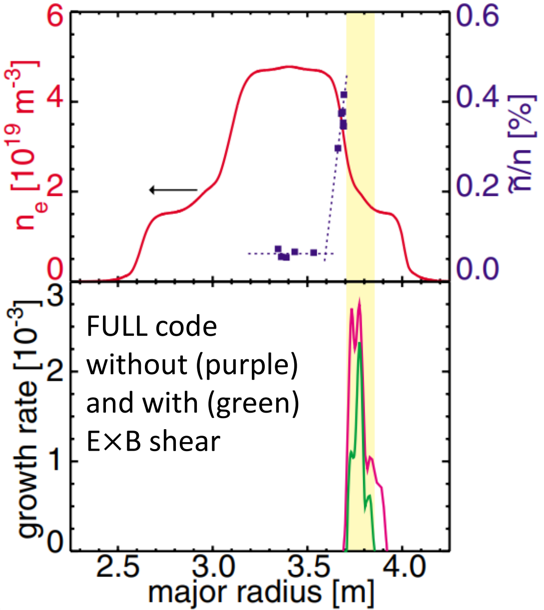


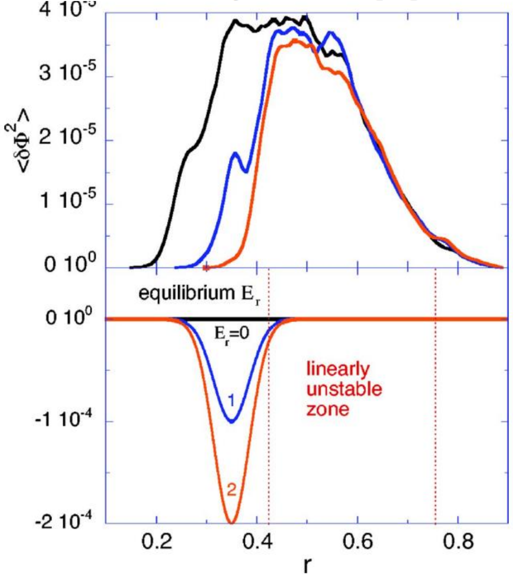
Experimental Evidence of Turbulence Spreading

- Often, transport is anomalous where pressure gradient is weak and linear instabilities are absent.
  e.g., NSTX [Kaye *et al*., NF '07]

- Non-zero fluctuations and anomalous transport observed in linearly stable zone of JT-60U reversed shear plasma.
  [Nazikian *et al*., PRL '05]

- From GTS simulation [W. Wang *et al*., PoP '07] and simple analytic theory, effects of E×B flow shear on turbulence spreading has been studied by placing E×B shear layer next to linearly unstable zone as a barrier.


FULL code without (purple) and with (green) E×B shear



Outline

- Radially Elongated Eddies
- E×B Shear Reduction of Turbulence
- Physics of Zonal Flows
- Turbulence Spreading
- Self-Organized-Criticality
- Avalanches and E×B Staircase

Review: [Hahm and Diamond, JKPS **73**, 747 (2018)]

Self-Organized-Criticality Model of Tokamak Transport

- Construction of Heat Flux Expression
  from consideration of symmetry and conservation law

  \- rather than conventional quasi-linear paradigm from
  specific linear instabilities (ITG, TEM, ETG, …).

- Early work for MFE [Diamond and Hahm, PoP ‘95] adopted from
  Sand Pile Model by [Hwa and Kadar, PRA ‘92].

  \- related to “Profile Consistency”, but, “scale invariance” and “1/f spectrum”
  (familiar from many other physical systems) play crucial roles.

Joint Reflection Symmetry

[Diamond and Hahm, PoP ‘95]

Flux: $Q[\delta T] = \frac{\lambda}{2}(\delta T)^2 - \chi_{\mathrm{Neo}}\partial_x \delta T + \text{higher order terms}$

Invariant under $\left[\begin{array}{l} x \to -x \\ \delta T \to -\delta T \end{array}\right.$

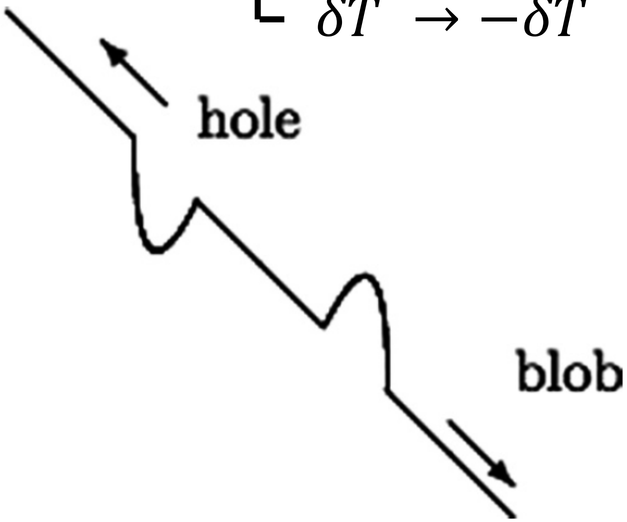
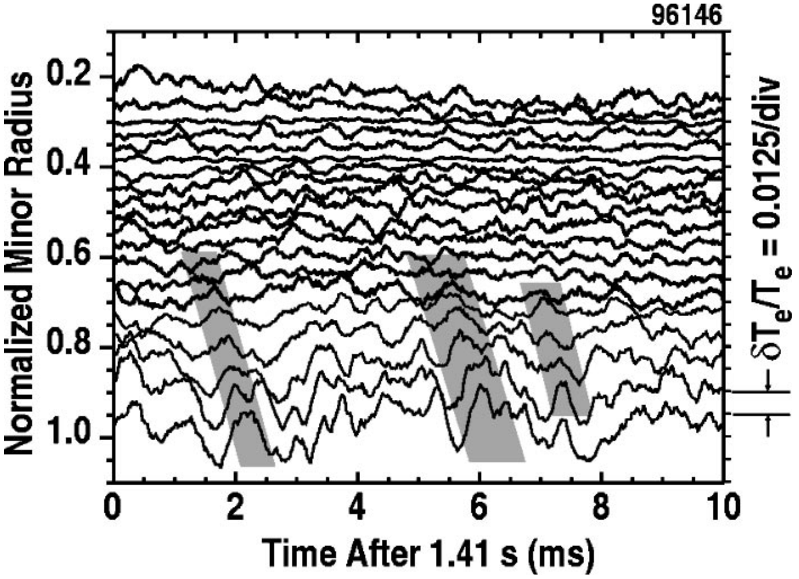
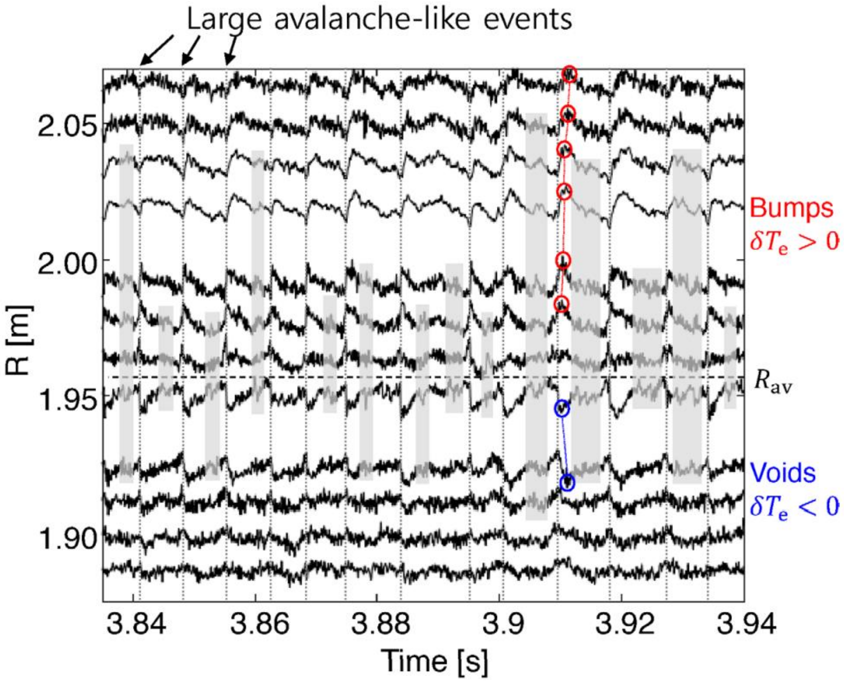


FIG. 4. Schematics for blobs propagating outward and holes propagating inward. These are allowed to have net transport down the gradient. To have both solutions, equation must be invariant under the simultaneous transformation of $x \to -x$ and $\delta T \to -\delta T$.

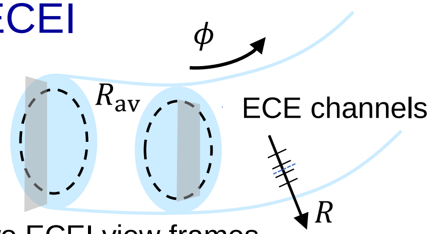
Electron Heat Avalanches exhibit “JRS”.



[P.A. Politzer *et al*., PoP (2002)]
from DIII-D ECE



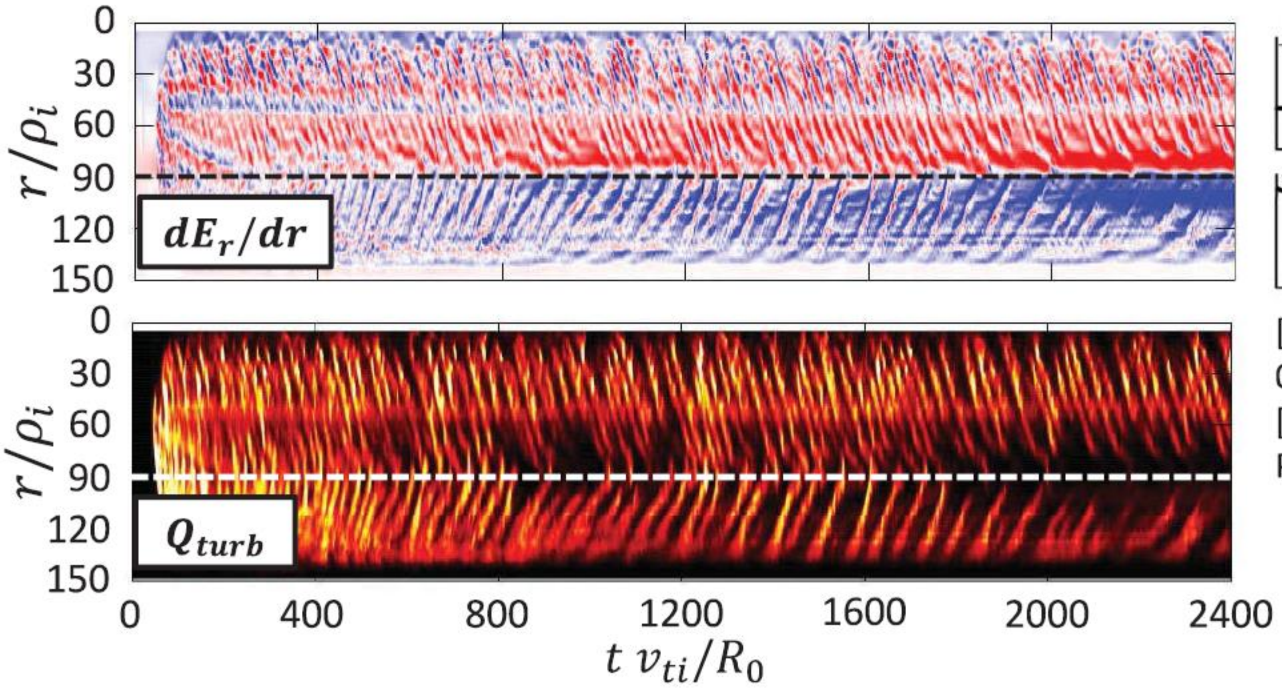
[M.J. Choi *et al*., NF (2019)]
from KSTAR ECEI

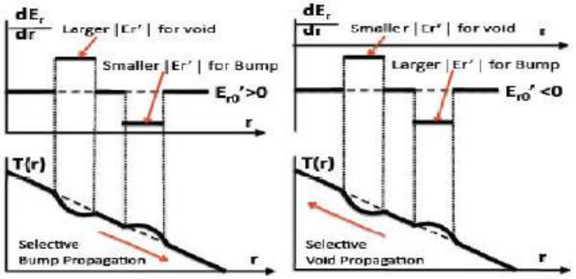


Two ECEI view frames
on (R, z) space

- More experimental evidences of nonlocal transport from [K. Ida *et al*., NF **55**, 013022 (2015)]

Avalanches exhibit Joint Reflection Symmetry

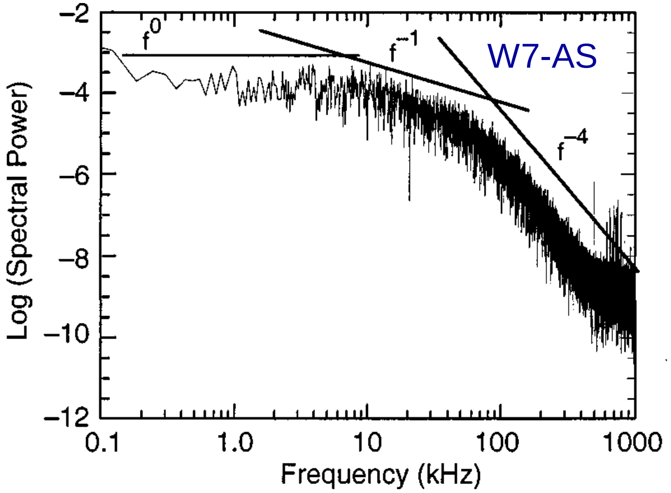




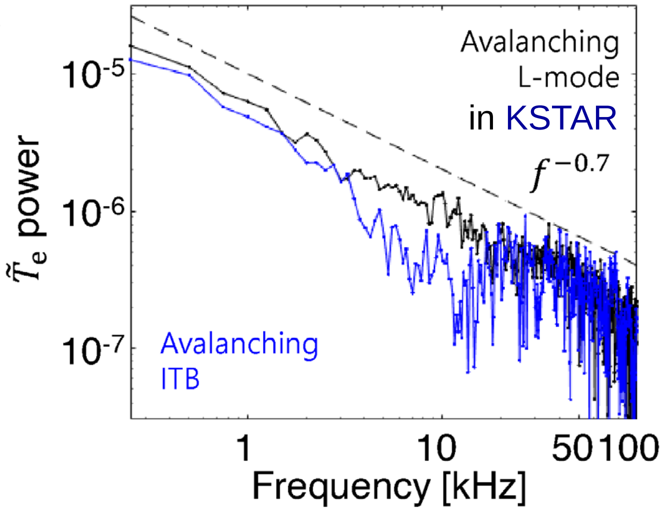
[Y. Idomura, *et al*. Nucl. Fusion, **49,** 065029 (2009).]
[M. Kikuchi and M. Azumi, Rev. Mod. Phys. **84**, 1807 (2012).]

✓ Clear correlation between the sign of E_r shear and the direction of avalanches can be observed.

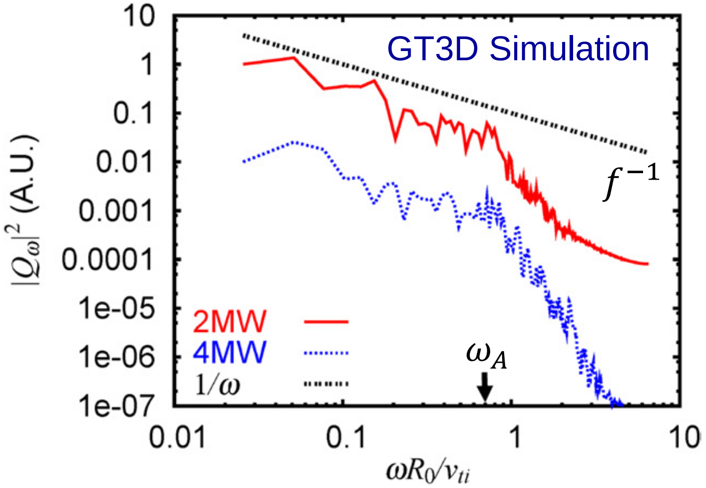
Frequency Spectra from Experiments and Simulations

- 

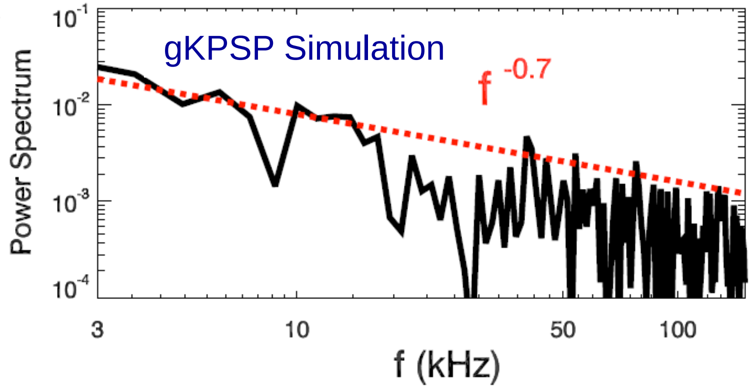
[B.A. Carreras *et al*., PoP '98]

- 

[M.J. Choi *et al*., NF '19]

- 

[Y. Idomura *et al*., NF '09]

- 

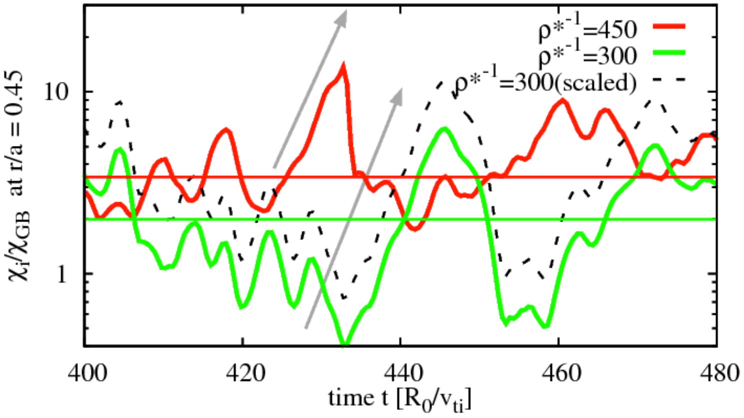
[L. Qi *et al*., NF '21]

Outline

- Radially Elongated Eddies
- E×B Shear Reduction of Turbulence
- Physics of Zonal Flows
- Turbulence Spreading
- Self-Organized-Criticality
- Avalanches and E×B Staircase

active on-going research

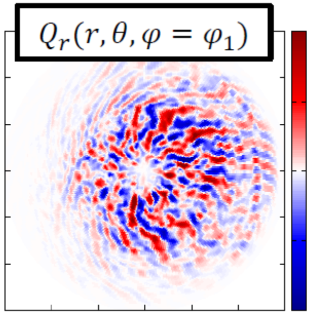
Bursty Avalanche Events prevail in Flux-driven Simulations

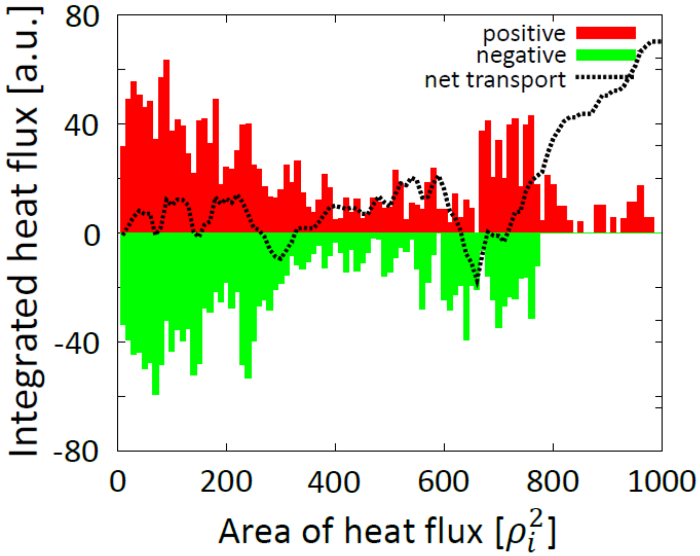


[Nakata and Idomura, IAEA-FEC ‘12]

- Transport shows intermittent behavior between bursty phase and relatively quiescent phase.
- Bohm-like transport persists even at large a/ρ_i.

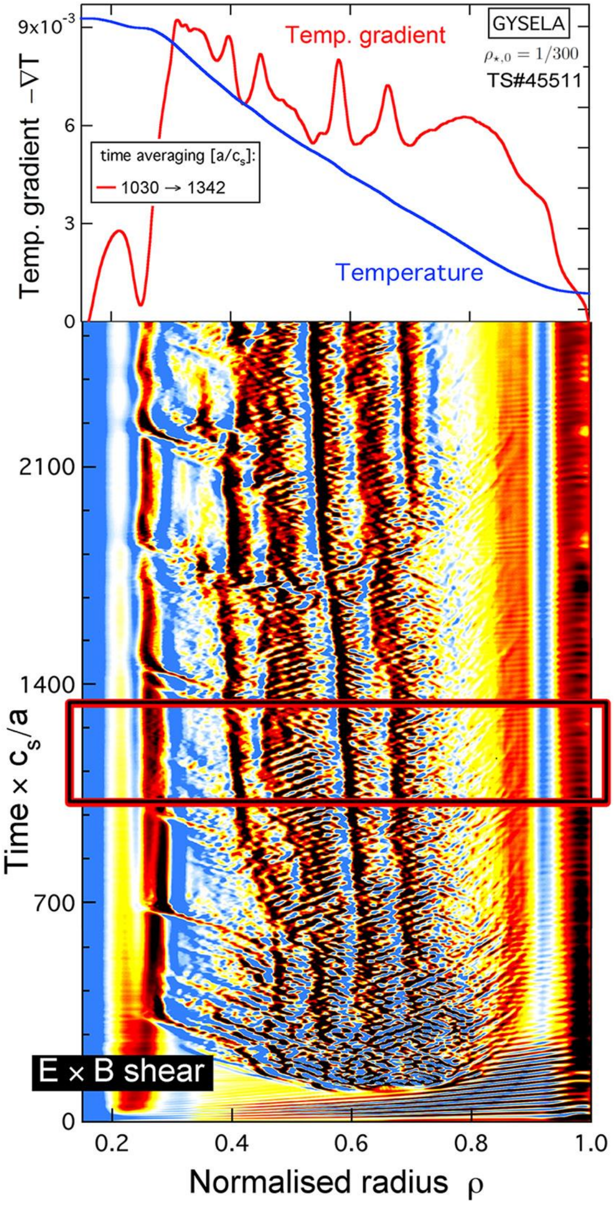
Burst phase





[Kishimoto, Imadera *et al*., IAEA-FEC ‘16]

E×B Staircase from Flux-driven ITG Simulations



[G. Dif-Pradalier *et al*.,
Nucl. Fusion **57**, 066026 (2017)]

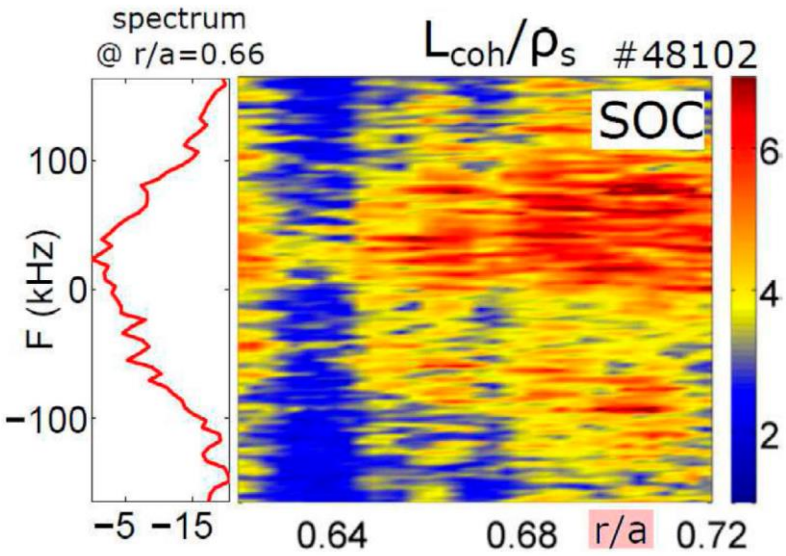
(i) The mean profile corrugations here displayed on the temperature gradient.

(ii) The strong, long-lived and coherent shear flows defining ‘valleys’ of hindered transport – the mean radial E×B shear profile is evident.

(iii) The radial transport dominated by avalanche-like events in-between the staircase steps.

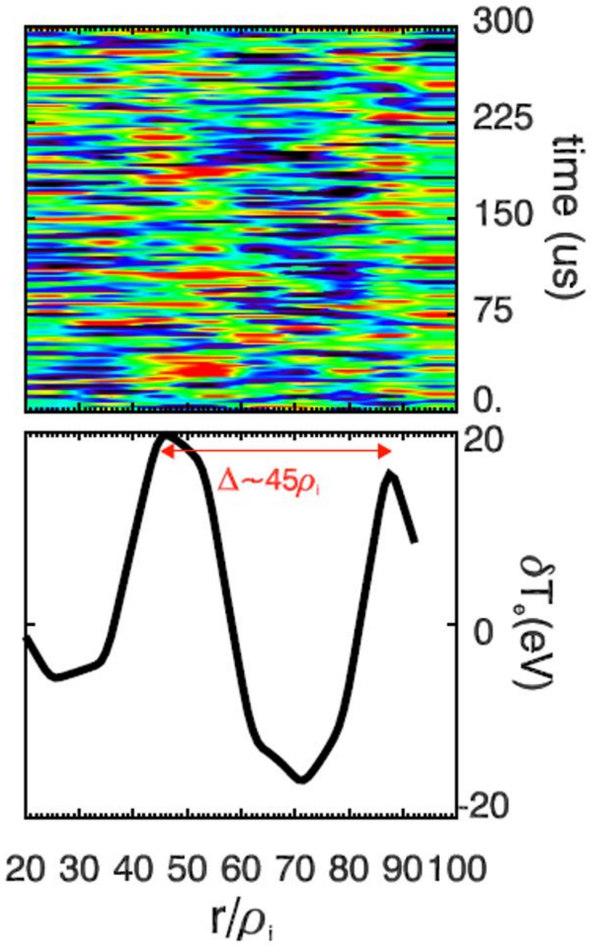
Staircases from Experiments

From Reflecto-measurements of SOC Plasma of Tore Supra



[G. Hornung *et al*., NF ‘17]

From ECE measurements of L-mode Plasma of KSTAR



[L. Qi, **M.J. Choi**, J.M. Kwon *et al*., NF ‘21]

An important conundrum: scaling of turb. transport to change with system size?

- BAD $\ell \sim a \Rightarrow D \sim D_B$
- GOOD $\ell \sim \rho \Rightarrow D_{gB} \sim \rho_\star D_B$
- Actual $\ell \sim \Delta \sim 40\rho \Rightarrow D \sim \rho_\star^\alpha D_B$

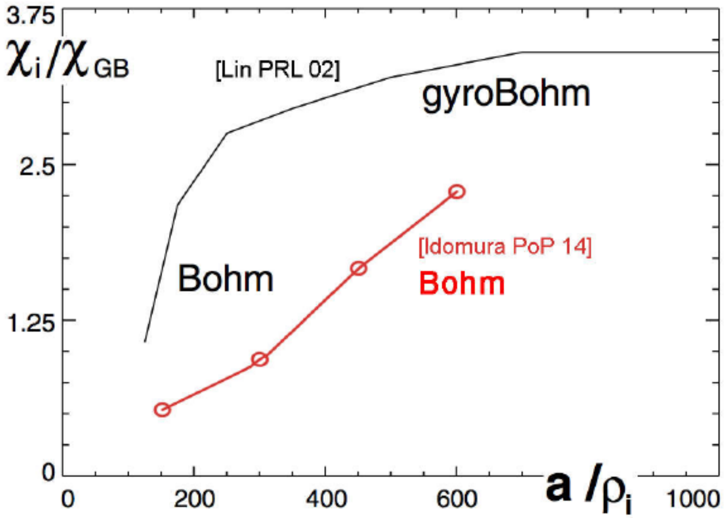
near-marginal w/ staircase

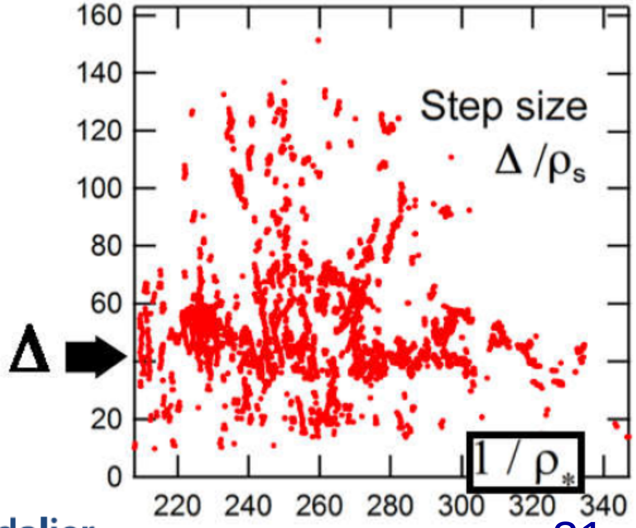
- $\Delta \equiv$ 'avalanche' scale $\propto \rho$, NOT $\sim a$
- more shear layers per unit volume with $1/\rho$
- caveat: $\alpha \sim 0.7$, but is really a distribution

Avalanches break gyro-Bohm scaling;
staircase statistically restores part of it

far from marginality w/o staircase

- avalanches take over → Bohm-like

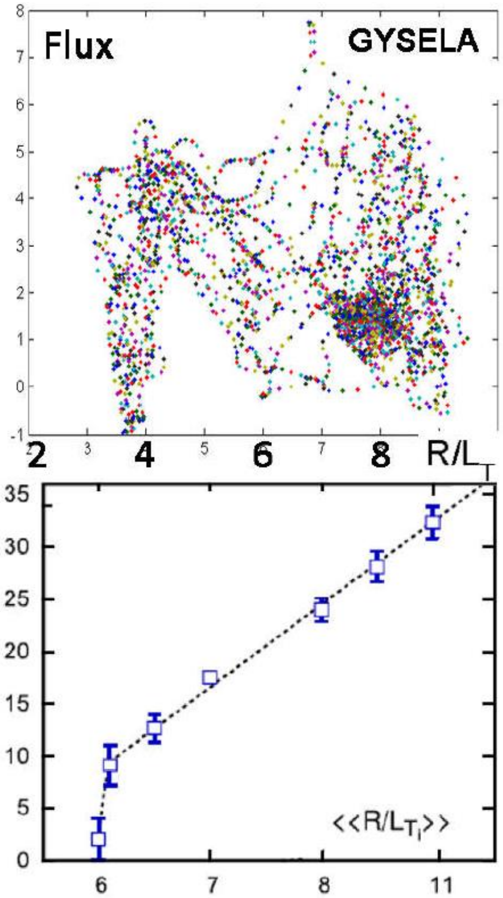


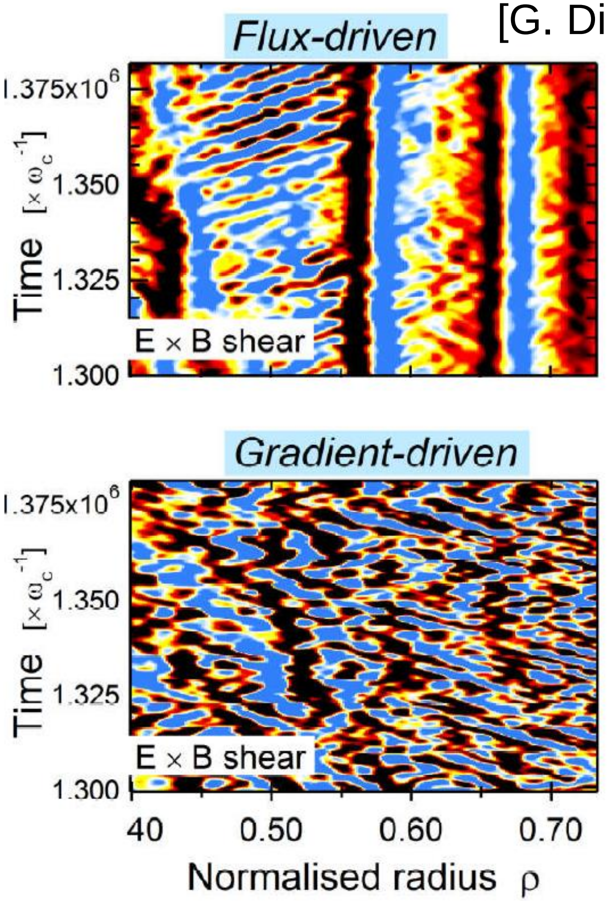


Courtesy: G. Dif-Pradalier

Characterization of Flux-Gradient Relation

[G. Dif-Pradalier, NF ‘17]





- Non-monotonic trend appear in Flux statistics.
- Bistability might be a key in understanding staircase. [Ashourvan and Diamond, PRE ‘16]

EP Avalanches driven by Energetic Particle Modes

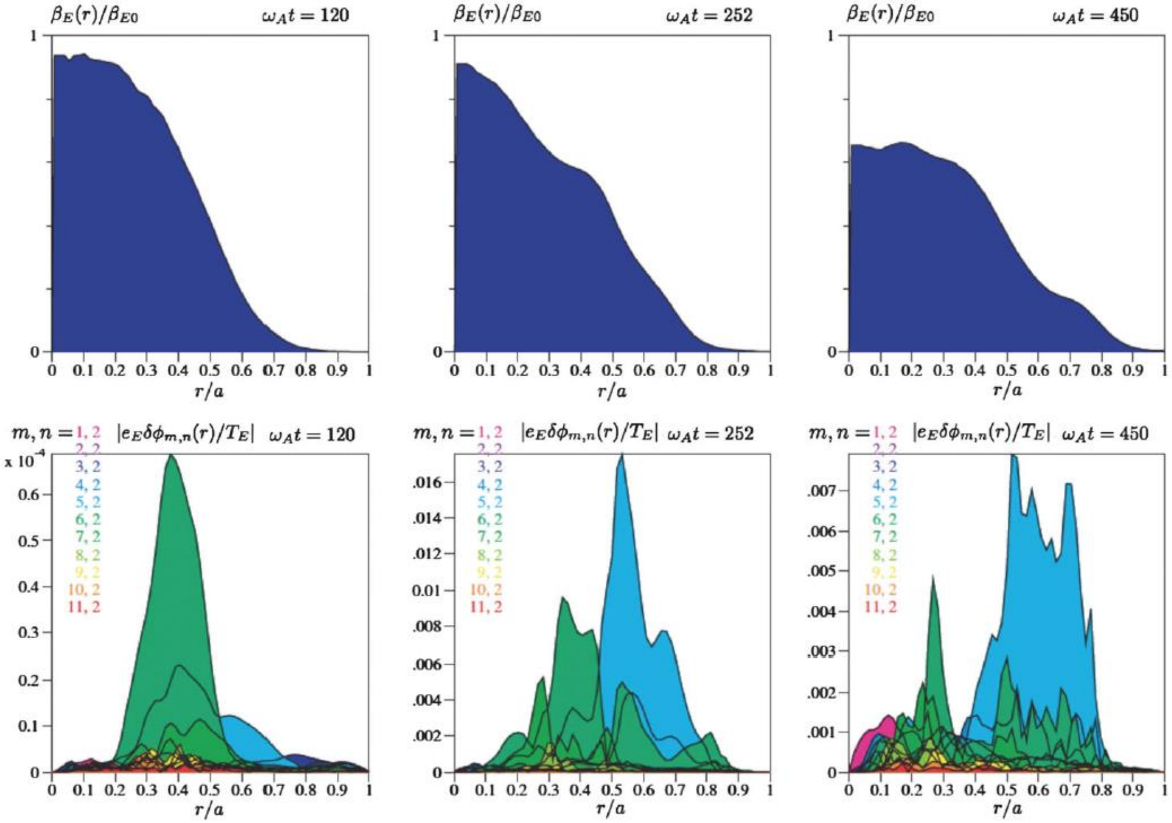


FIG. 3. Radial profiles of β_E and $(m, n = 2)$ Fourier components of the EPM scalar potential fluctuations during the linear growth (left), the end of the EPM avalanche (middle), and saturation phase (right). Time normalization is $\omega_A t$, with $\omega_A = v_A/R_0$ computed at the magnetic axis. From Vlad *et al.*, 2004.

[G. Vlad *et al*., PPCF 46, S81 (2004)]
[L. Chen and F. Zonca, RMP 88, 015008 (2016)]

Partial Conclusions

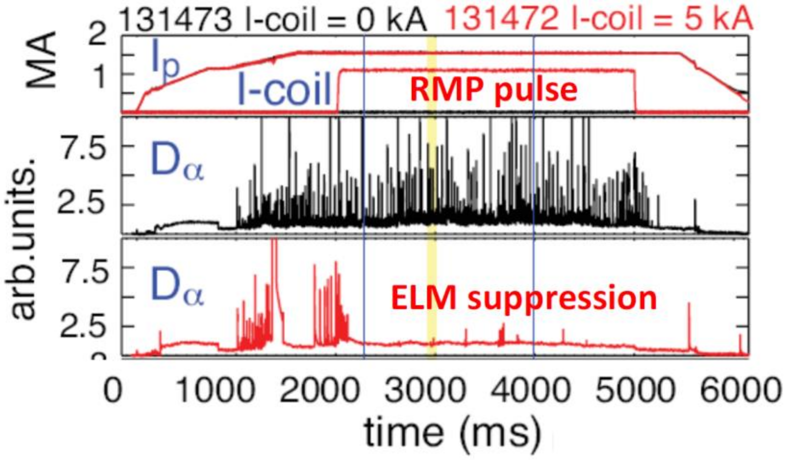
- Self-organized Structures play key roles in determining confinement of turbulent plasmas.
- Considerable Progress has been made possible by advances in theory, simulations, and experiment as higher level of Primacy Hierarchy in Validation gets achieved:

$$\begin{tikzcd} \tau_E \arrow[r] & \begin{array}{c} \chi_i \\ T_i(r) \end{array} \arrow[r] & \begin{array}{c} \delta n \\ \Delta r \end{array} \arrow[r] & \begin{array}{c} \delta n^2(\omega, \mathbf{k}) \\ \delta T_e^2(\omega, \mathbf{k}) \\ u_{\mathrm{E\times B}} \end{array} \arrow[r] & Q[\delta T] \arrow[r, dashed] & \mathrm{PDF}[Q] \end{tikzcd}$$

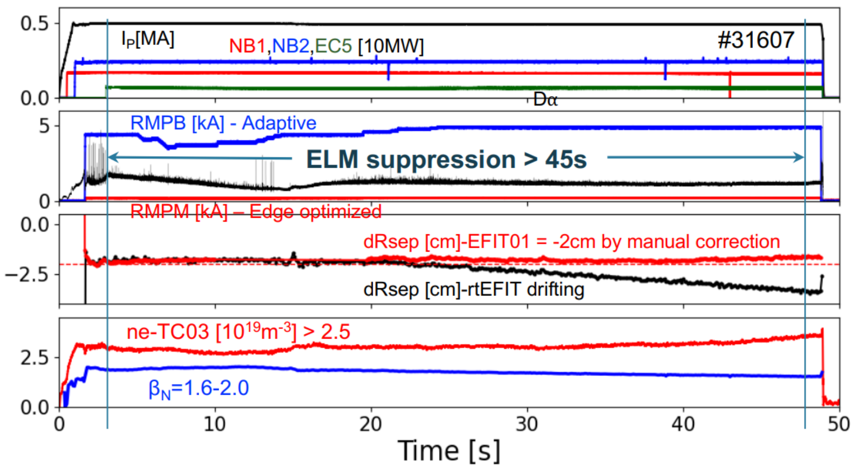
Outline

- Radially Elongated Eddies
- E×B Shear Reduction of Turbulence
- Physics of Zonal Flows
- Turbulence Spreading
- Self-Organized-Criticality
- Avalanches and E×B Staircase
- Recent Progress in Experiments

ELM-suppressed H-mode is a leading candidate for ITER operation



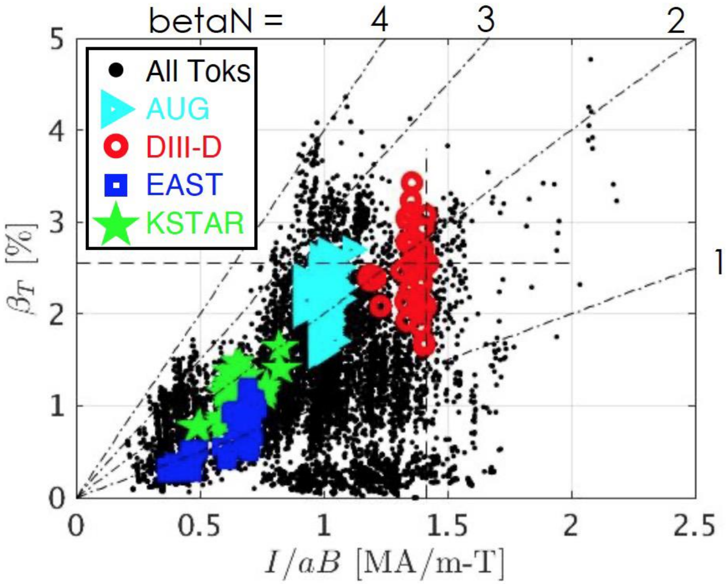
[T.E. Evans *et al.*, PRL (2004)]
also demonstrated in
JET [Liang *et al.*, PRL (2010)]
KSTAR [Jeon *et al.*, PRL (2012)]
EAST [Sun *et al.*, PRL (2016)]
ASDEX-U [Suttrop *et al.*, PPCF (2017)]



“ELM suppressed for 45 seconds”
[J.K. Park, C. Paz-Soldan, Y. Liu, Z. Lin *et al.*, Private communication (2022)]

Considerable Progress has been made in suppressing ELMs using RMP, but there are accessibility issues.

- ELM suppression is never achieved for
  - Pedestal density exceeding $n/n_G > 0.5$
  - $\beta_N > 2.7$
  - Up-down symmetric plasmas (e.g. DND)
  - Spherical Torus geometry
  - Shaping is too high or too low
  - When rotation is too low

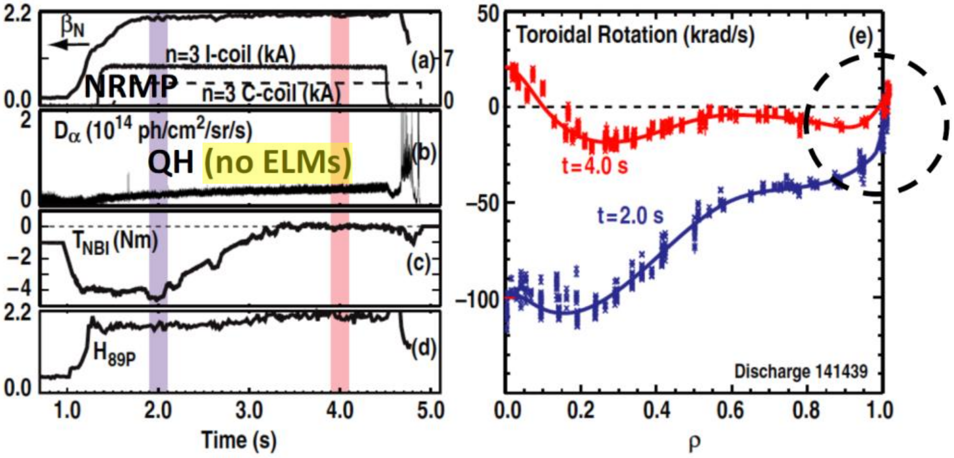


[C. Paz-Soldan, PPCF (2021)]

- Unclear if RMP ELM control scenario is compatible with Q=10 ITER Baseline (IBS)

Courtesy: J.K. Park

Non-resonant RMP can be used for ELM-free Quiescent H-mode for near-zero NBI torque



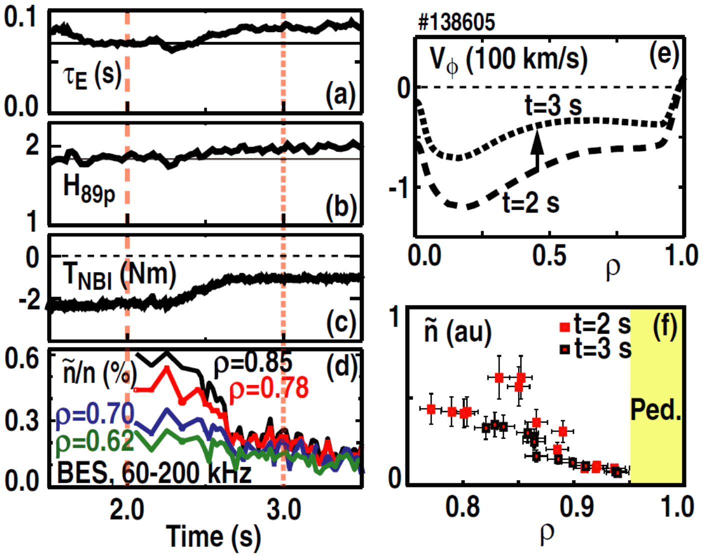


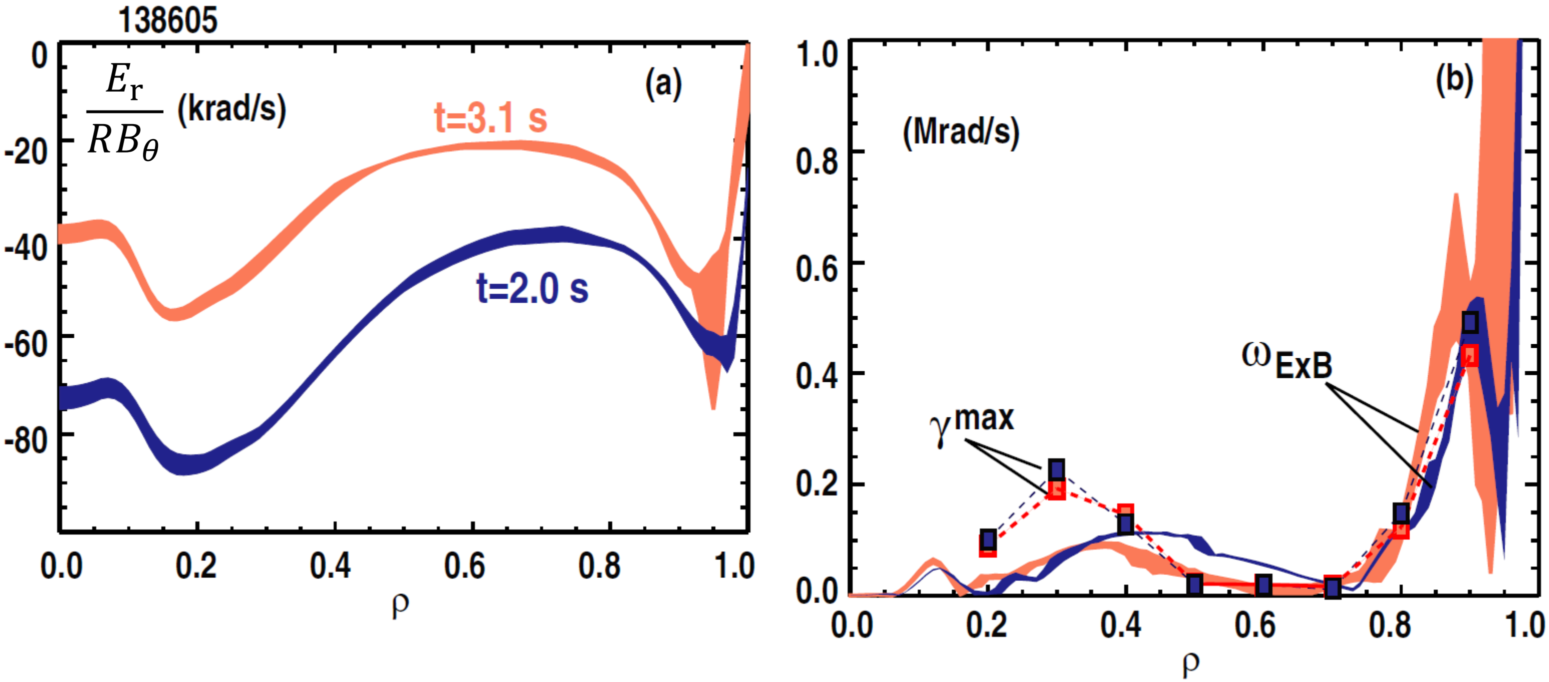
Figure 5. Confinement effects of NBI torque ramp-down. Discharge is terminated early by a fault of the plasma control system. Time histories of (*a*) thermal energy confinement time; (*b*) confinement quality; (*c*) NBI torque; (*d*) relative density fluctuation levels measured by BES at different normalized minor radii. Shaded vertical bands indicate time ranges relevant to the next panels: (*e*) radial profiles of toroidal plasma rotation; (*f*) radial profiles of relative density fluctuation level measured by DBS at high and low rotation.

- Edge Harmonic Oscillations cause density pump-out.
- QH-mode also achieved in JT-60U, ASDEX-U, JET, KSTAR, EAST, ⋯

[A.M. Garofalo, W.M. Solomon, J.K. Park, K.H. Burrell *et al.*, NF 51, 083018 (2011)]

E×B Shearing Rate in QH-mode can be higher for Low rotation and exceeds $\gamma^{\max}$

[A.M. Garofalo et al., NF 51, 083018 (2011)]



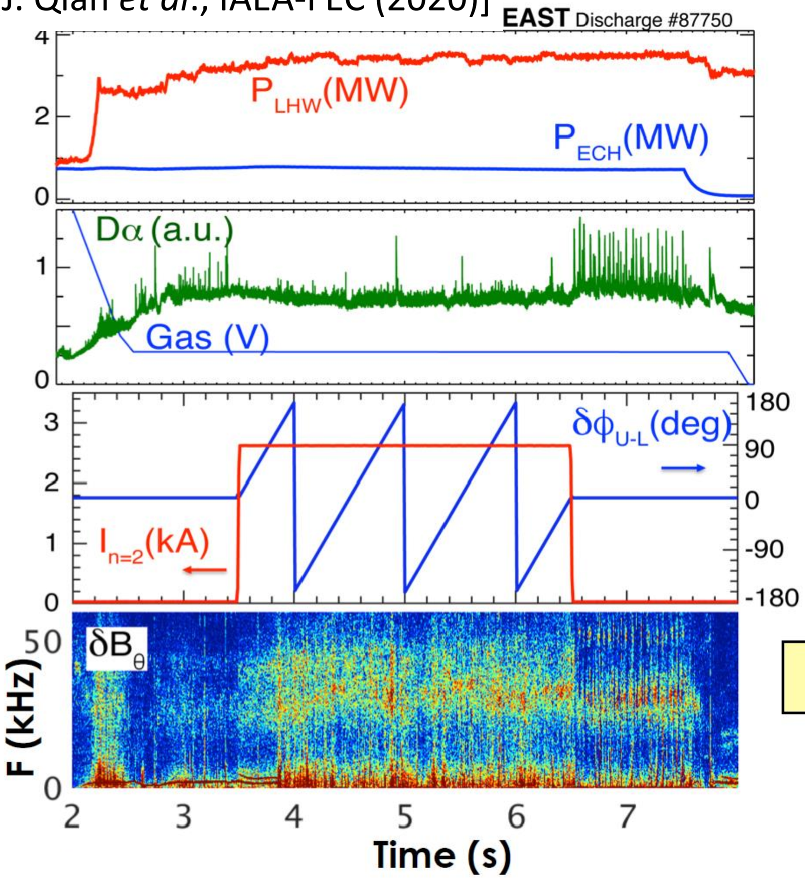
$$\omega_{E\times B} = \frac{(RB_\theta)^2}{B}\frac{\partial}{\partial\psi}\left(\frac{E_r}{RB_\theta}\right)$$

[Hahm-Burrell, PoP (1995)]

Figure 6. Comparison of radial profiles evaluated at high (blue) and low (red) rotation of (*a*) toroidal $E \times B$ rotation (ω_E); (*b*) absolute magnitude of the $E \times B$ shearing rate ($\omega_{E\times B}$) and calculated maximum growth rate for turbulence modes in the BES wavelength range ($\gamma^{\max}$). The vertical width of the curves indicates the uncertainty.

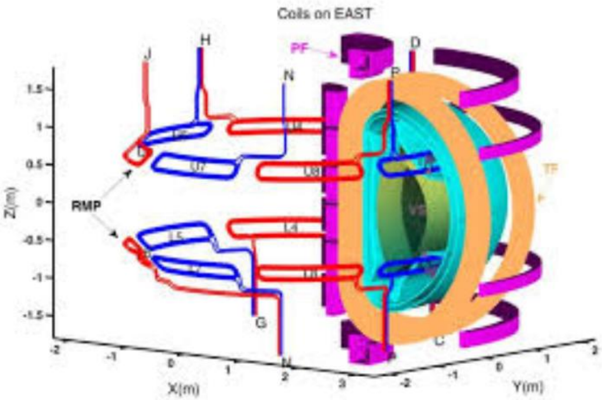
QH-mode Obtained in EAST Using RF-only Heating, Tungsten Divertor, and 3D Fields

[J. Qian *et al*., IAEA-FEC (2020)]



- **ELMs replaced by quasi-coherent/broadband MHD fluctuations**
  - Similar to high density QH-mode on DIII-D
- **Rotating phase of upper coil row (helicity scan) shows effect is nonresonant**

3D coil in EAST:



q_{95} ~5

Courtesy: A. Garofalo

ECH-only LH transition at low density

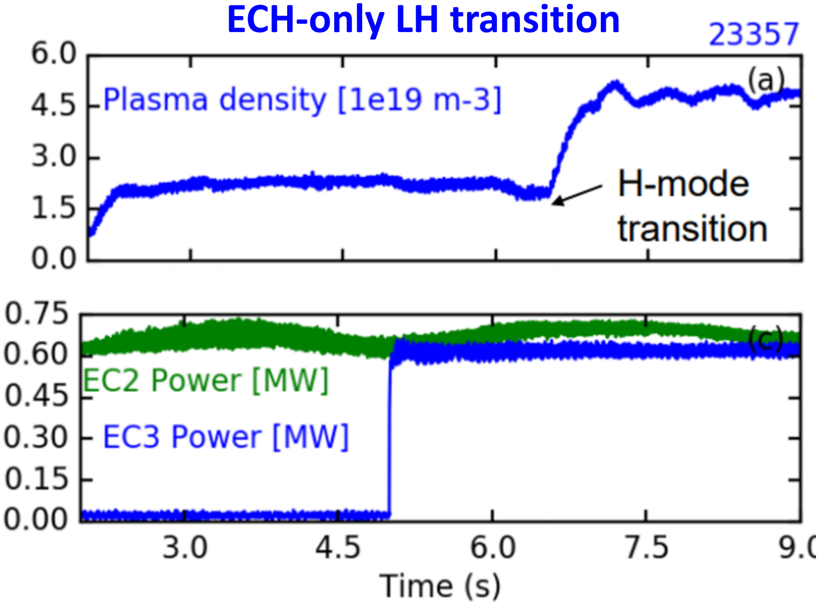
- **LH transition happens with** Courtesy: H.G. Jhang [ITPA (2022)]
  - ➢ **ECH only (with characteristic U-shaped curve in P_{LH} vs <n>)**
- **n_{crit} ~ $2.0*10^{19}/m^3$ < n_{Ryter} ~ $2.73*10^{19}/m^3$ (~27% lower)**

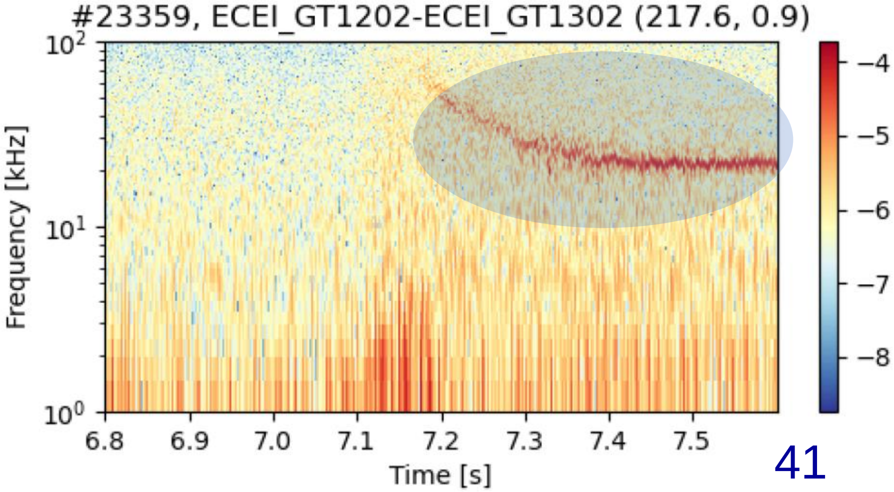
(Empirical Scaling of Low-Density Limit)

→ Conventional Explanation inapplicable!

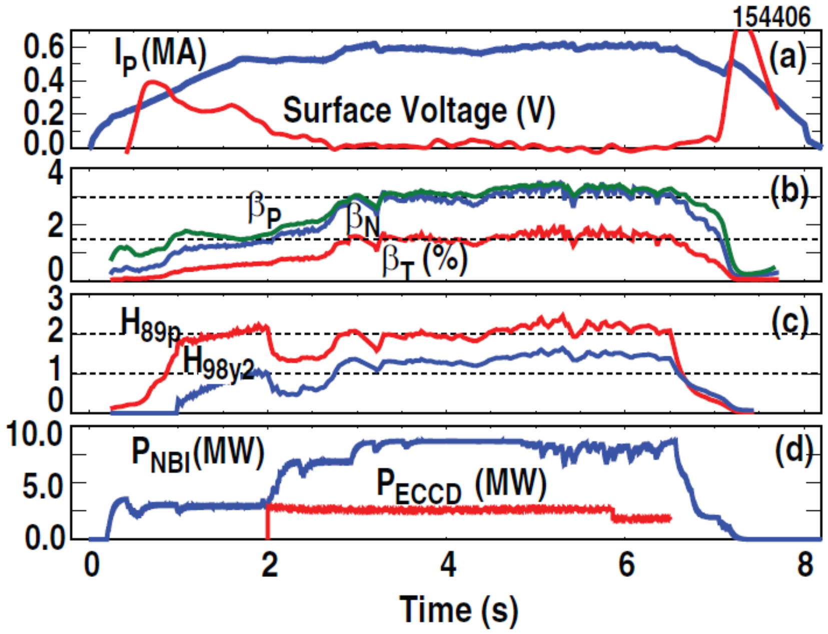
- **Weak/No ELMs.**
- **Coherent mode emerges during LH transition, instead.**

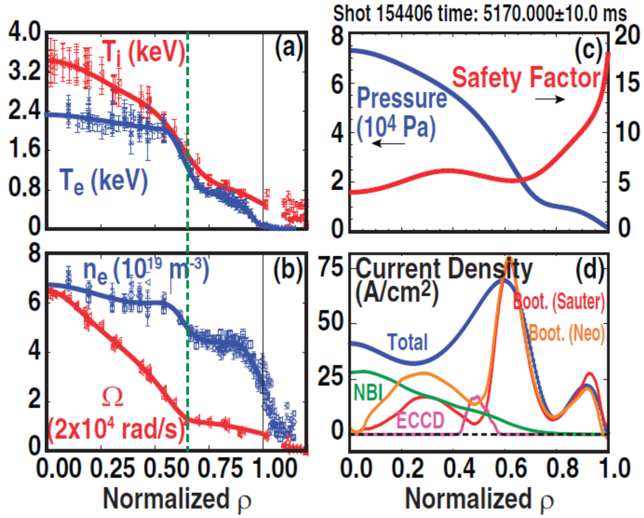
ECH-only LH transition





Recent Results on High β_P mode 1.

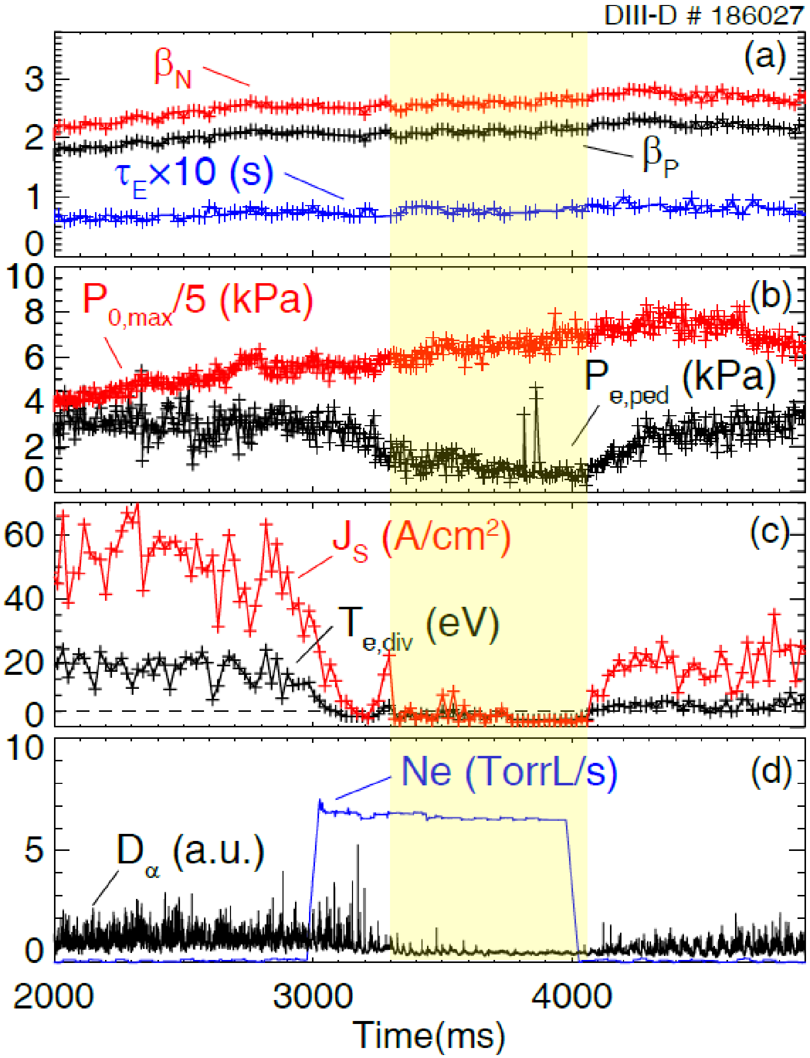




- High β_P Mode has been found while ago [Koide, Kikuchi, Mori *et al*., PRL (1994)].
- $q_{min} > 2.0$ with q_{95} ~7.0-12.0.
- **Broad ITBs (ρ~0.7) at f_{GW}~1.0-1.1, low NB torque < 2 Nm:**
  - low ω_{ExB} effect
  - high Shafranov shift effect
  - **No strong impurity accumulation** [A.M. Garofalo et al, NF **55** 123025 (2015)]
- $H_{98} \geq 1.5$, $\beta_p \sim 3$, $\beta_N \sim 3$, $f_{BS} > 0.8$.
- Higher performance **if AE activity and fast ion transport reduced** (below $\nabla\beta_{fast,crit}$).

Courtesy: A. Garofalo

Recent Results on High β_P mode 2.



- **Full divertor detachment** with good energy confinement, H_{98} ~1.5. **(for the first time in a tokamak)**
- Pedestal pressure degraded due to detachment.
- **The growing ITB** compensated the degradation of pedestal.

[L. Wang *et al*., Nat. Commun. **12** 1365 (2021)]

Courtesy: A. Garofalo

Lessons from Last Century

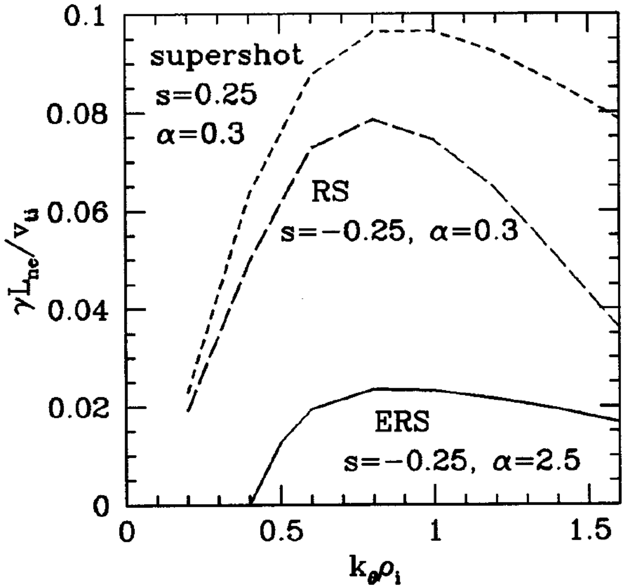
承先啓後

Courtesy 陳騮

Role of Shafranov shift and E×B Shear

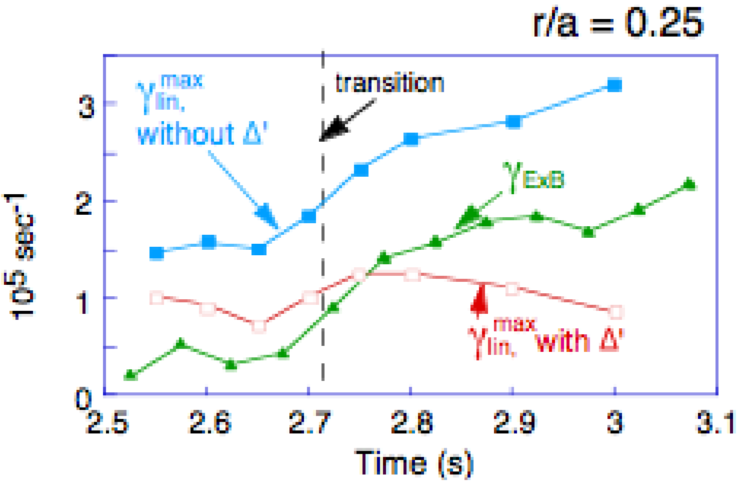
$$\gamma_{E\times B} = \frac{RB_\theta}{B}\frac{\partial}{\partial r}\left(\frac{E_r}{RB_\theta}\right)$$

[Beer *et al*., PoP '97] TFTR ERS vs RS and supershot



[Synakowski *et al*., PoP '97]

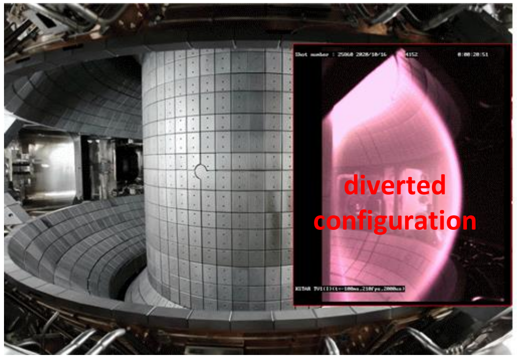
TFTR ERS transition

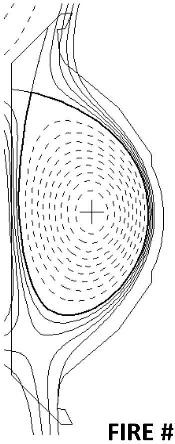


FIRE (Fast Ion Regulated Enhancement) mode

- **Stationary ITB discharges** have been established in a diverted configuration at $q_{95} \sim 4–5$ on KSTAR.
- L-H transition was avoided by keeping **low density and unfavorable ∇B single null configuration.**
- **Fast ions** have significant roles in this new regime, so it is coined to "Fast-Ion-Regulated Enhancement."

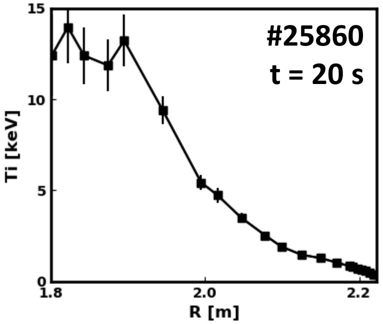
<Camera Image of KSTAR FIRE mode >

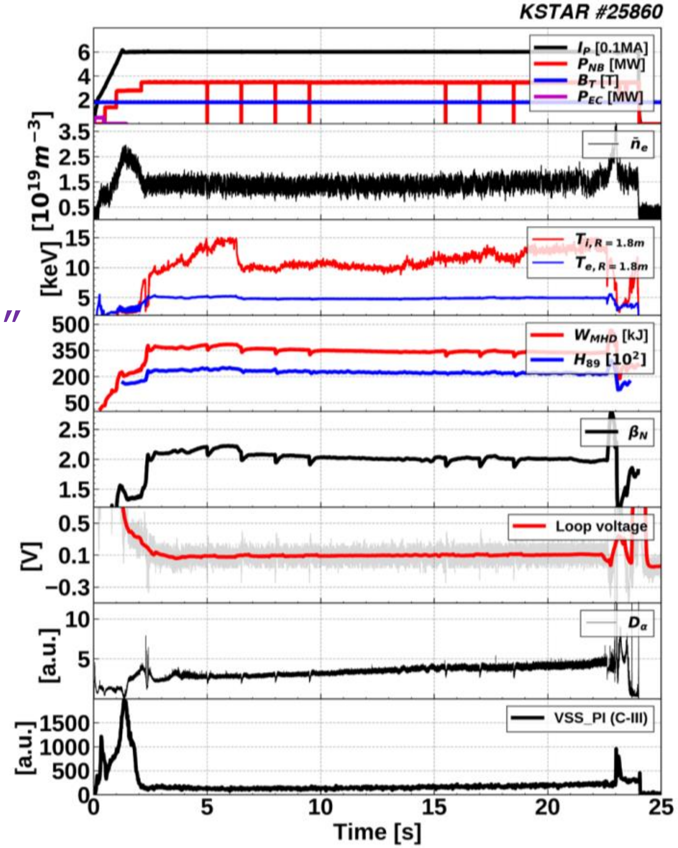




FIRE #25860
EFIT construction at 20 s

<Ion Temperature Profile of FIRE mode>



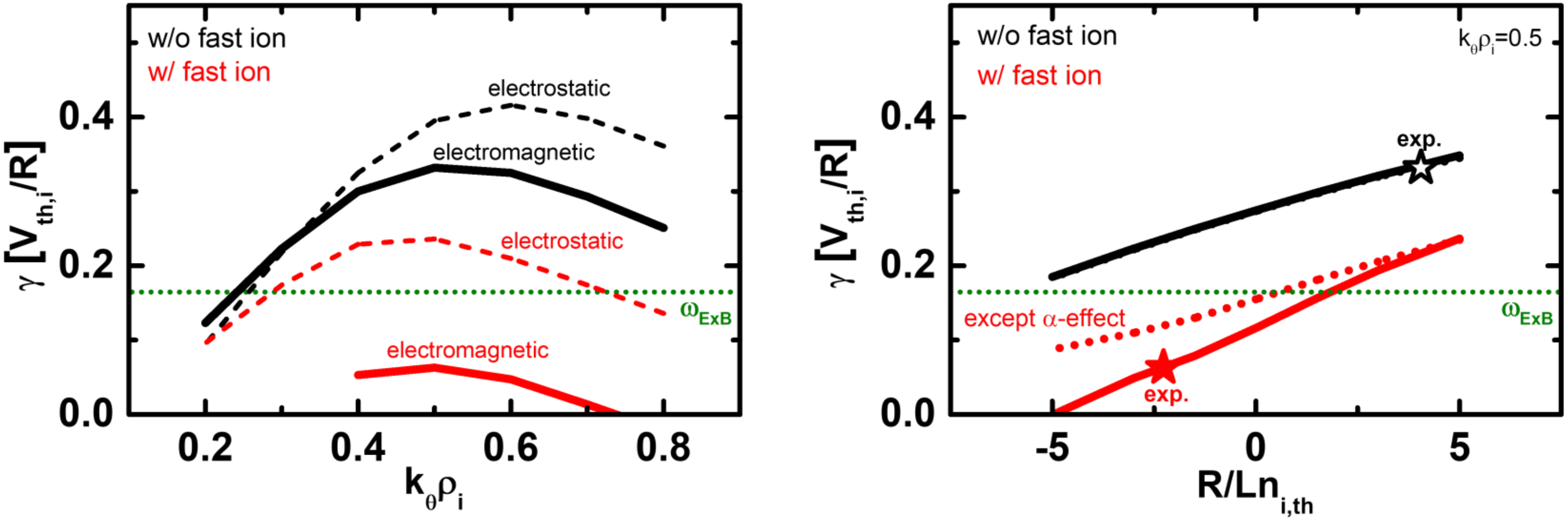


*H. Han, S.J. Park and Y.-S. Na et al. Nature **609** 269 (2022)*

Courtesy: Y.-S. Na

FIRE (Fast Ion Regulated Enhancement) mode

- **GKW Linear simulations for evaluating fast ion effects**



- **$R/L_{ni} < 0$ due to dilution by centrally peaked fast ions $R/L_{nf} \gg 1$**

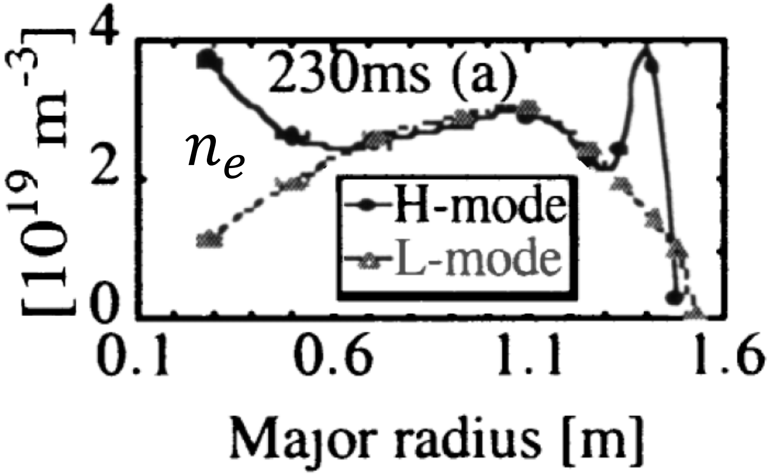
  ⇒ Strong ITG stabilization.
- ExB shear stabilization is also substantial.

  (But even in its absence, significant reduction of turbulence expected.)
- Shafranov shift and electromagnetic effects contribute to further stabilization.

*H. Han, S.J. Park and Y.-S. Na et al. Nature **609** 269 (2022)*

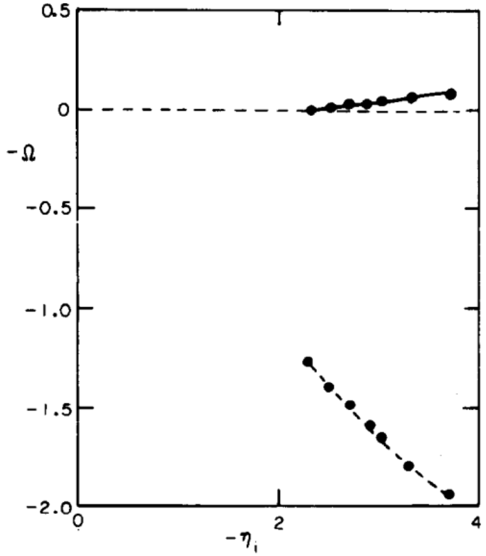
Courtesy: S.J. Park

Ion Temperature Gradient Mode becomes weaker for hollow density profiles



Experimental data from NSTX
[R. Maingi *et al.*, PRL (2004)]

- n_e sometimes gets hollow in core of H-mode plasma during ELM-free period.

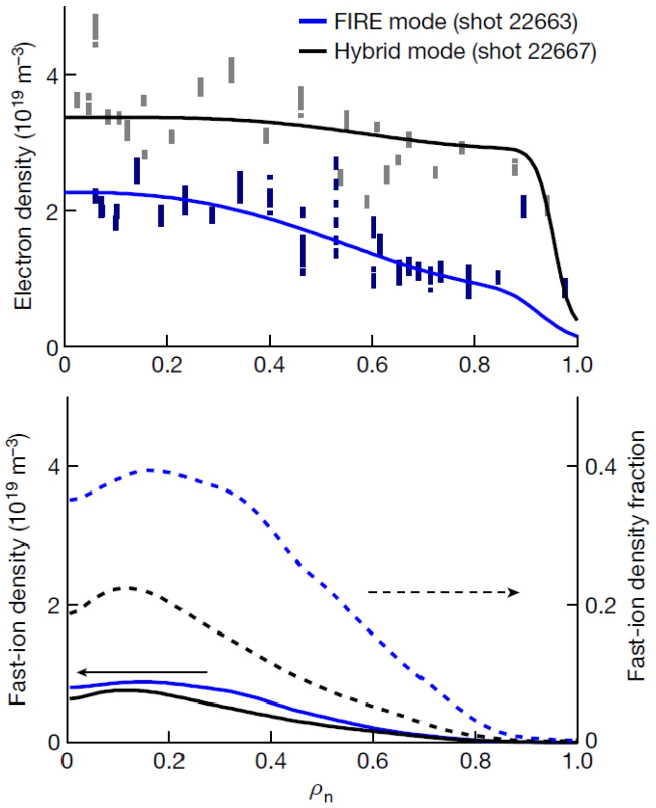


[Hahm-Tang, PFB (1989)]

FIG. 2. Plot of numerically computed Ω vs η_i for $L_n/L_s = -1$, $b_i = 0.1$, and $\tau = 1$. The solid and dashed lines correspond, respectively, to $\mathrm{Im}(-\Omega)$ and $\mathrm{Re}(-\Omega)$. Note that $\Omega = \omega/\omega_{*e} \propto -\omega$ since $L_n < 0$.

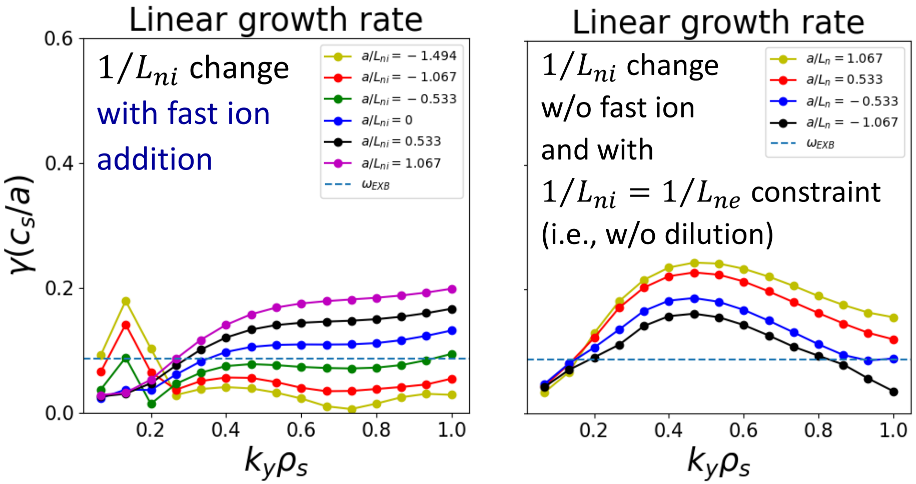
- "A particularly interesting new feature for the inverted density profile cases is that $\gamma \ll |\omega_r|$ is satisfied for η_i modes over a wide range of negative η_i values."
- More detailed toroidal analyses in
  - [Baiocchi *et al*., NF (2015)]
  - [Du, Jhang, Hahm *et al*., PoP (2017)]

Hollow Density ITG becomes significantly weaker with fast ion induced dilution



[H. Han, S.J. Park *et al*., Nature (2022)]

- Main ion density profile becomes hollow with centrally peaked fast ion density profile.

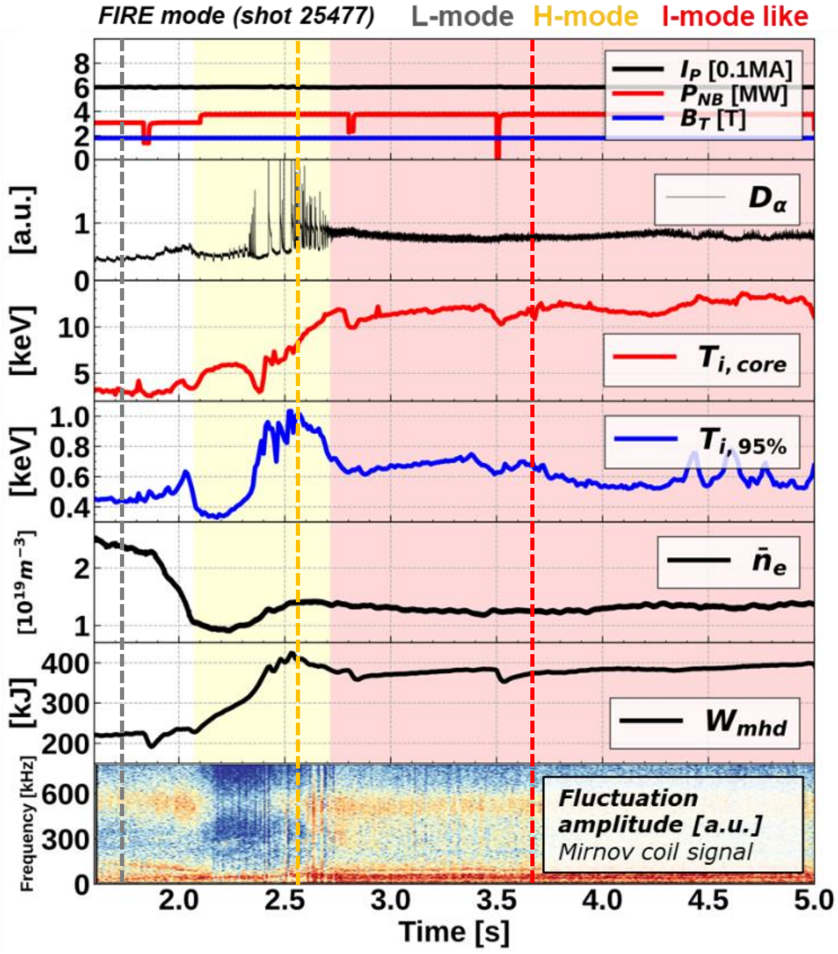


from CGYRO linear simulations
[D.U. Kim, C.K. Sung, S.J. Park *et al*.,
Private Communication (2022)]

- "$1/L_{ni}$" is the key quantity determining ITG stability with fast ion induced dilution.

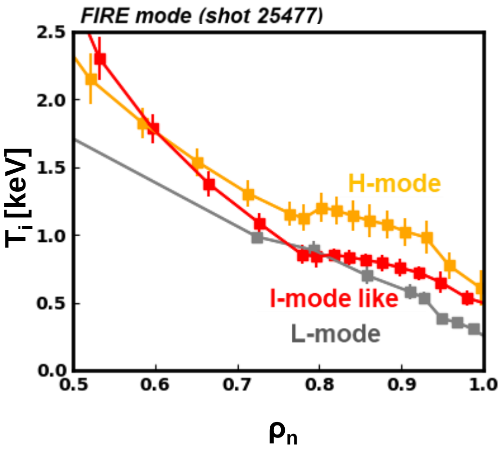
FIRE mode with I-mode like Edge

<Time Evolution of 0d Parameters >



- Some of FIRE modes have ETB is formed only in the energy channel not in the particle channel like **I-mode.**
- They shows a high ion temperature gradient at the edge region and **no clear barrier in the density profile.**

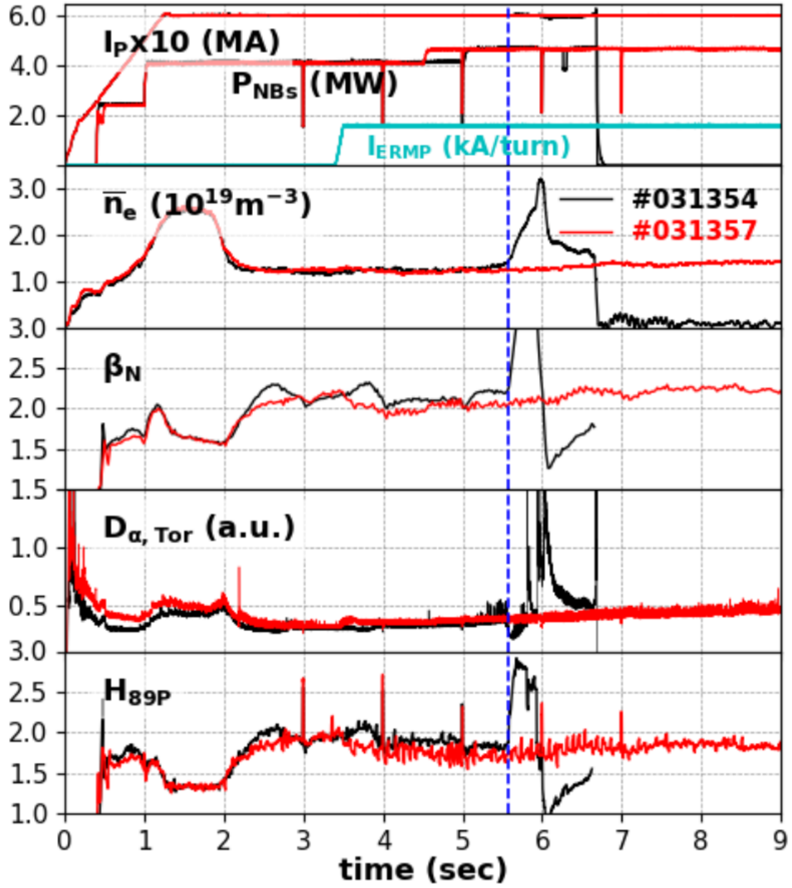
<Ion Temperature profile>



The absence of the particle transport barrier can enhance the fraction of fast ions by reducing thermalization of fast ions with a low density.

Courtesy: Y.-S. Na

I-mode access & sustainment can be improved by E-RMP
: By using E-RMP (Edge-localized RMP)



- **#31354: P_{NBs}>6.0MW made I/H transition eventually**

→ How to make I-mode sustained with more power?

- **RMP can do …**
  - **Reduce edge density (pumping-out) further**
  - **Increase P_{th} for H-mode transition**
  - **Reduce the impact of ST crash**

  → Useful for both I-mode access and sustainment

(3) By applying E-RMP fields (#31357)

- **E-RMP made I-mode resistant to H-mode transition**
- **Similar high-Ti still obtained (thanks to edge-localization of RMP)**

KSTAR

Courtesy: Y.M. Jeon and S.M. Yang [ITPA (2022)]

Conclusions
(on Progress in Enhanced Confinement Regimes)

- E×B shear suppression remains effective in many examples (H, QH, ⋯)
- Other mechanisms (at near-zero external torque) are actively being analyzed with gyrokinetic simulations.
  → Understanding mostly linear stabilization mechanisms
  (fast-ion-induced main ion density profile inversion, Shafranov shift, ⋯)
  → More insight on nonlinear mechanisms (e.g., zonal flows) would guide further progress more effectively.
- Encouraging results from experiments:
  - FIRE (ITB with I-mode edge)
  - QH (at near-zero external torque, high density, and with RF only)
  - ⋯
- But high β_N, high n/n_G, zero external torque and low q have NOT been achieved simultaneously.
- International Collaborations found to be very effective.

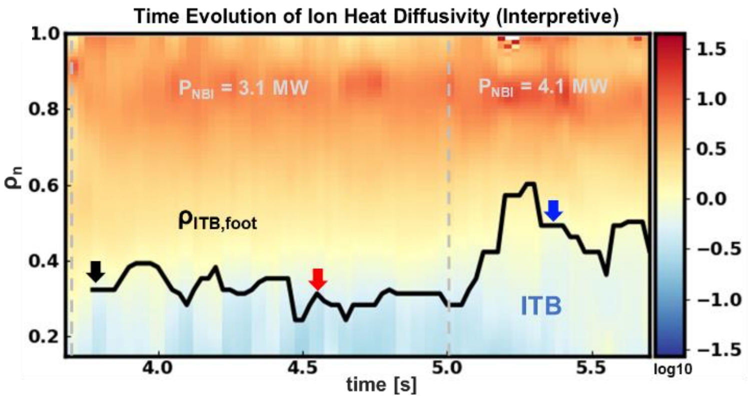
Back-up Slides

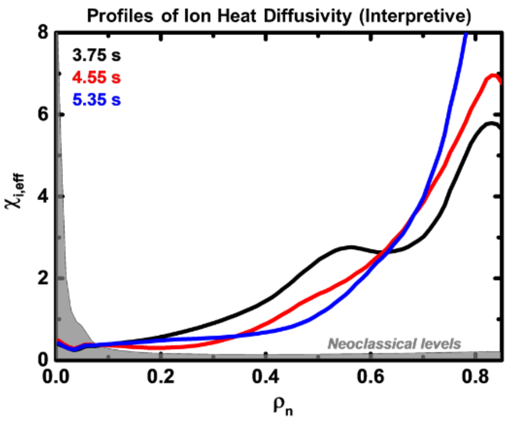
ITB characteristics – heat diffusivity and S-curve

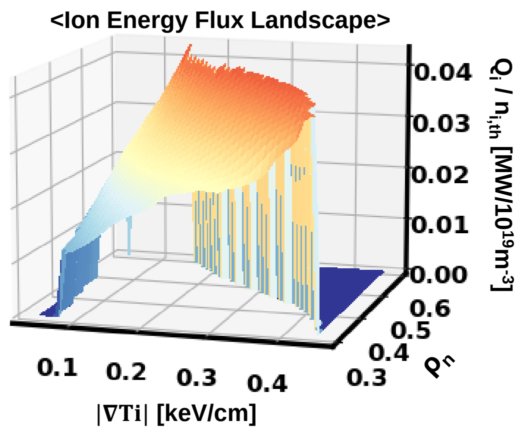
KSTAR

- **Thermal Ion Heat Diffusivity and S-curve**

- The time evolution of the ion heat diffusivity was calculated from the power balance analysis.
- The **thermal ion heat diffusivity reduces** in time correlated **with the expansion of ITB** though it is still above the neoclassical level.
- The relation between the **ion energy flux** and the **ion temperature gradient** shows that there is a “S-curve” in the 3-D landscape of the flux-gradient space.
- The reduction of the energy flux while the gradient increases implies a transport bifurcation.

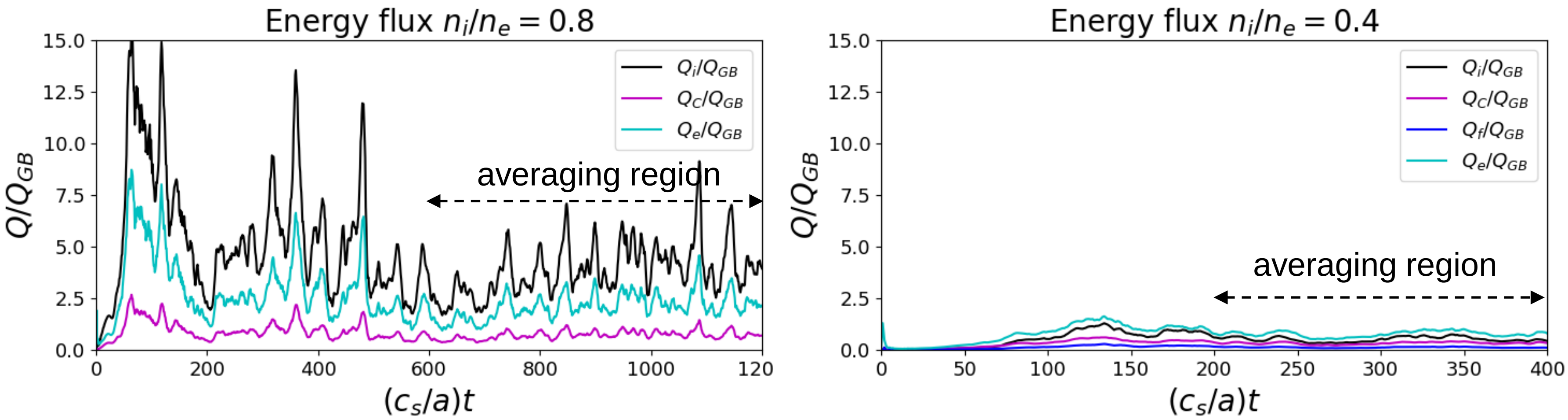

Time Evolution of Ion Heat Diffusivity (Interpretive)


Profiles of Ion Heat Diffusivity (Interpretive)


<Ion Energy Flux Landscape>

Courtesy: Y.-S. Na

Dilution effect



- Energy flux level predicted by CGYRO nonlinear gyrokinetic simulation shows the reduction when effect of dilution is included.

  - $Q_i[Q_{GB}] \sim 4.567 \rightarrow 0.836, Q_e[Q_{GB}] \sim 2.102 \rightarrow 0.769$

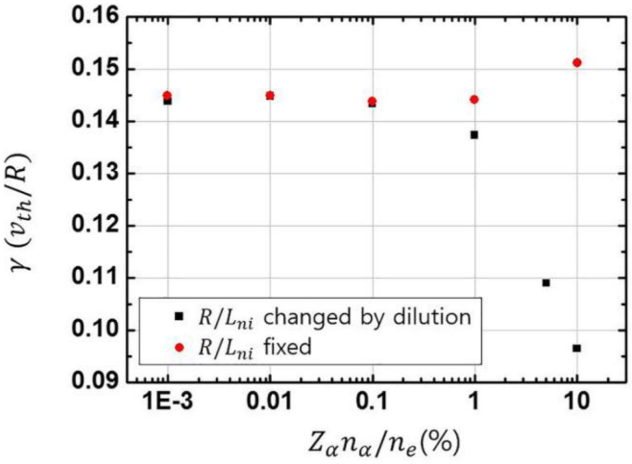
  - But, energy flux is still higher than nonlinear run with fast ion ($Q_i[Q_{GB}] \sim 0.001, Q_e[Q_{GB}] \sim 0.067$).

- Dilution contribute reduction of energy flux, but not sufficient to explain the reduction of energy flux due to fast ion.

Courtesy: D.U. Kim

TEM-driven EP Transport

[S.M. Yang *et al*., PoP 25, 122305 (2018)]



- It can be significantly lower than thermal particle transport, due to Orbit averaging and Frequency detuning.
- Similar conclusions on ITG-driven EP Transport: [Estrada *et al*., PoP (2006)], [Zhang *et al*., PRL (2008)], [Angioni *et al*., NF (2009)], [Di Siena *et al*., PCS (2016)].

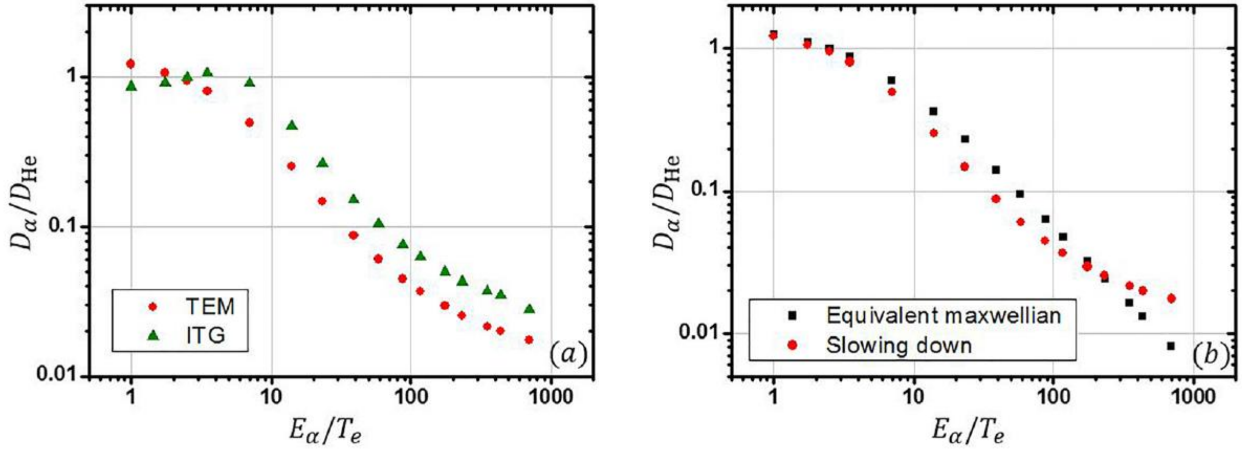
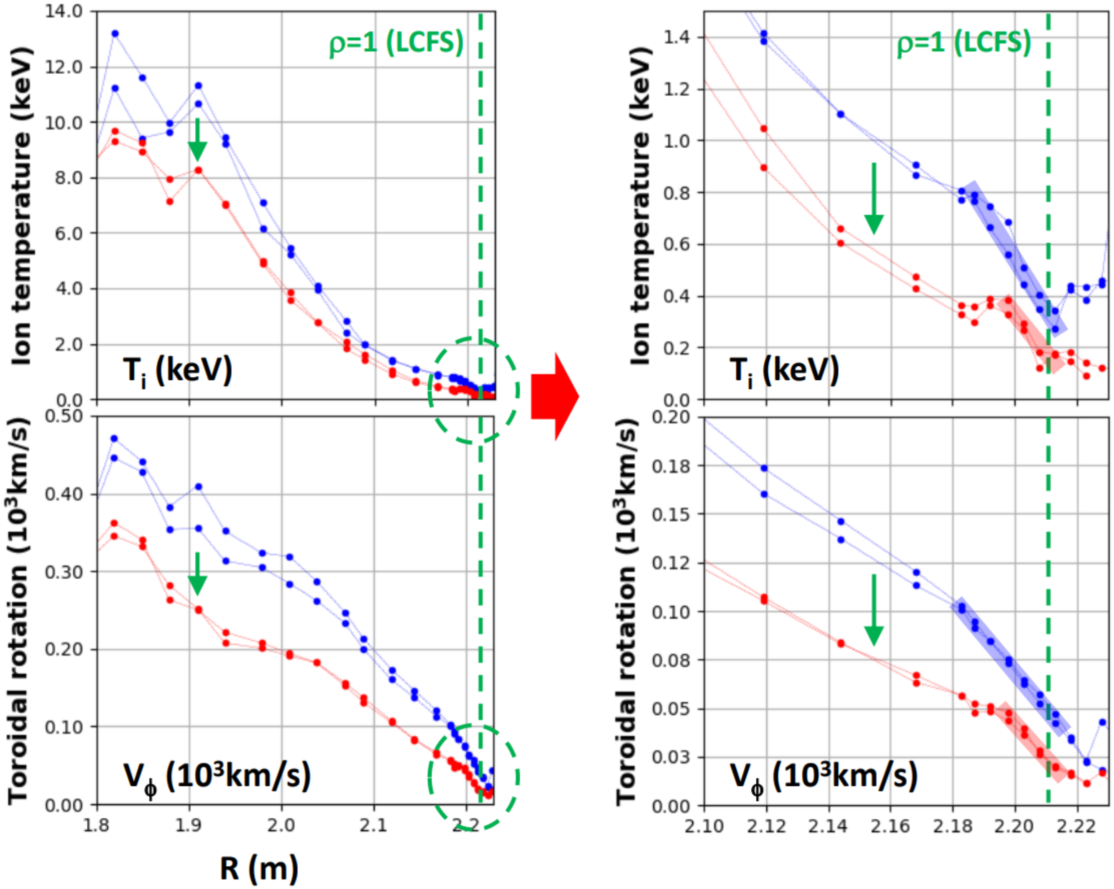


FIG. 3. The normalized diffusivity D_α/D_{He} of the α particles from linear GKW calculations for (a) the TEM (circles, red) and the ITG (triangles, green) case and (b) the equivalent Maxwellian (squares, black) and the slowing down (circles, red) distribution as a function of E_α/T_e.

E-RMP made pedestal weakened but didn't destroy it



- **Before** vs **After** **E-RMP in #31357**

- **Highly peaked Ti profile remained**
  - **high-Ti condition not broken**
  - **→ Weak effect on plasma core**

- **Weakened ETB/pedestal (still existed)**
  - **Narrowed pedestal width**
  - **Reduced pedestal height**
  - **→ Effectively increase P_{th}**

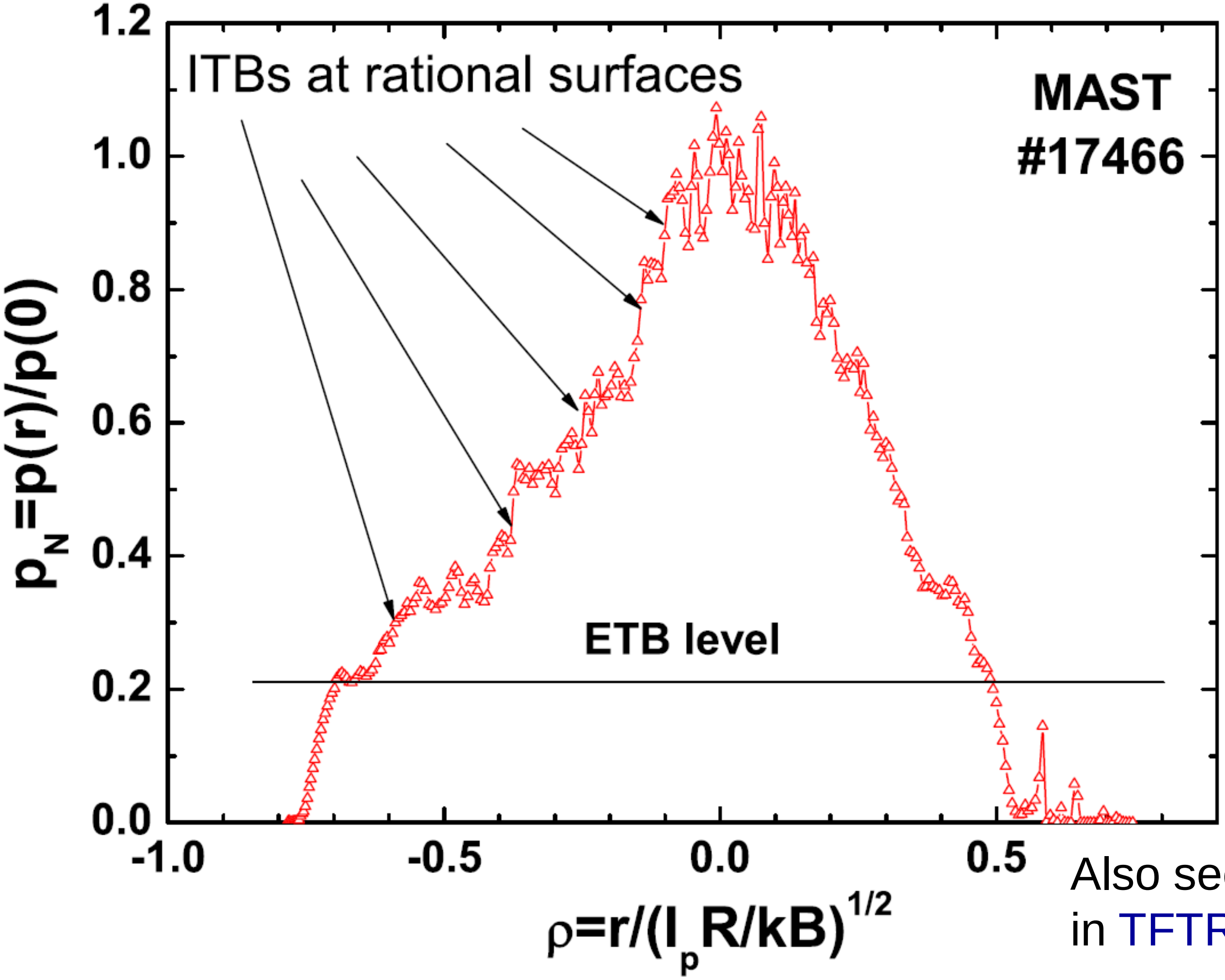
Courtesy: Y.M. Jeon [ITPA (2022)]

FUSION without Transport Barriers?

“Think differently” M. Kikuchi, [Kikuchi-Fest (2022)]

- L-mode edge with high density compatible with divertor detachment.
- Core confinement improvement with Negative Triangularity.
- Some Encouraging Initial Results from TCV, DIII-D, AUG, ···

Corrugations in Electron Temperature Profiles

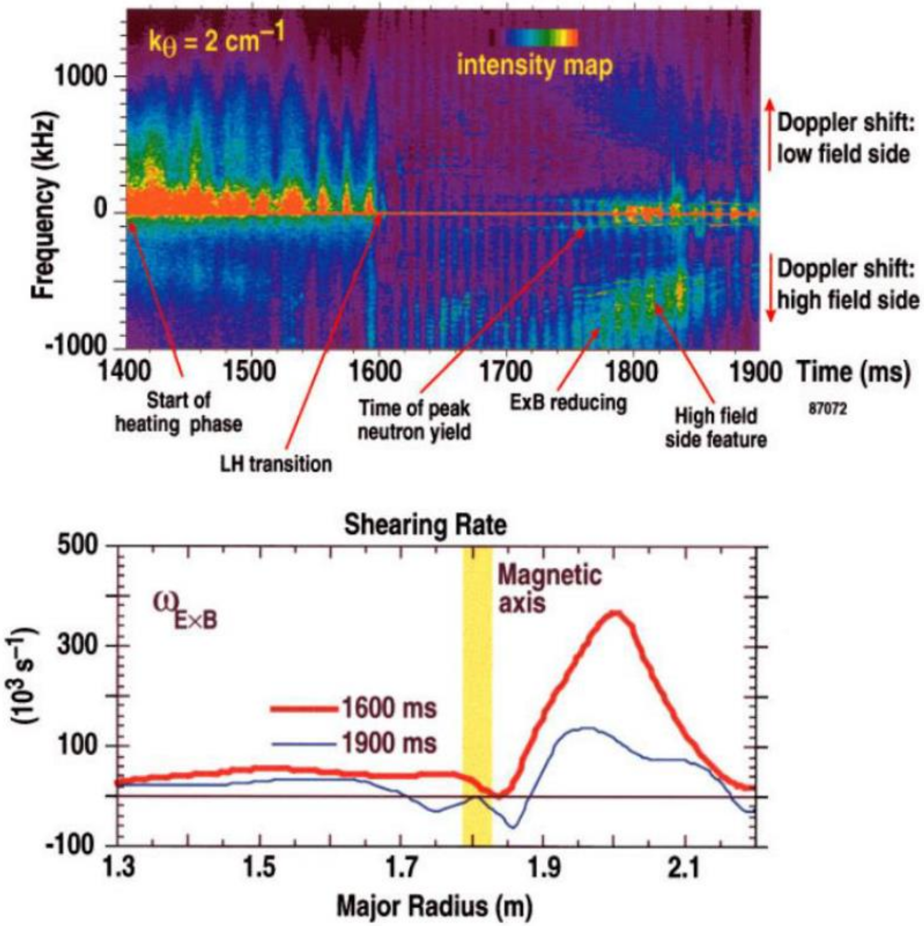


Also seen before in TFTR and RTP.

[K.A. Razumova *et al*., Nucl. Fusion **51**, 083024 (2011)]

In-out Asymmetry of Turbulence

- Frequently observed from experiments
  (Fujisawa on TEXT, on Tore-Supra, DIII-D and pronounced in ST …)



An example from DIII-D [K.H. Burrell, PoP ‘97].

q dependence of transport from Zonal Flow behavior

I_p scaling of confinement:
one of the remaining puzzles of ion thermal transport

Zonal flow characteristics depend on q values:

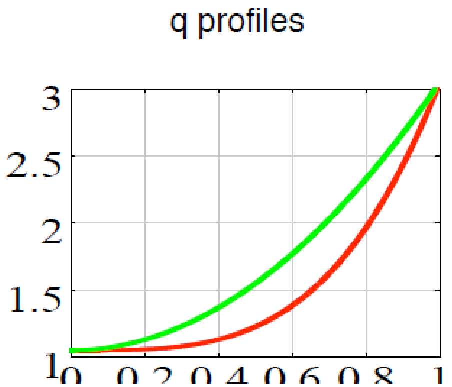
GAMs can exist only in high q region.
In low q region, Stationary Zonal Flows persists.

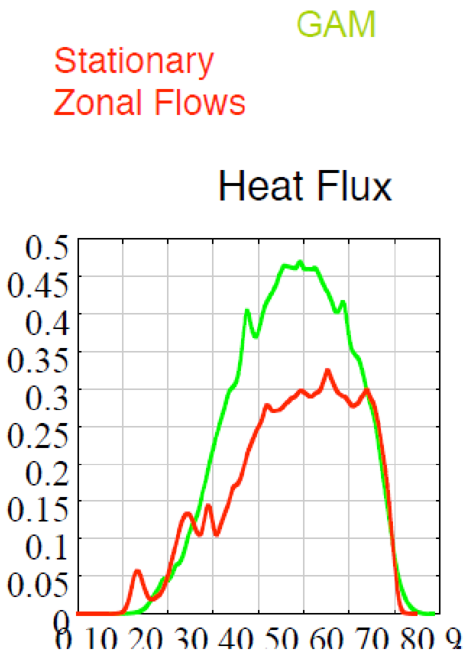
GAMs are less effective in reducing turbulence and transport than Stationary ZFs, due to its high frequency [Hahm et al., PoP '99]

Transport is consequently lower for lower q value from gyrofluid simulations [Miyato et al., IAEA '04]

Similar results from GK simulations
[Angelino et al., PPCF '06]

Experimental Relevance?





Turbulence Spreading into Magnetic Island

- Another clear example where turbulence exists in the absence of ∇P to drive linear instability.
  [K. Ida *et al*., Phys. Rev. Lett. (2018)]
  [M.J. Choi *et al*., Nat. Comm. (2021)]
  [T.S. Hahm *et al*., PoP (2021)]

- Turbulence outside MI spreads into inside MI through X-point.

- More recent progress by G.J. Choi
  PRL 128, 225001 (2022) and Nov 29, 3:40pm ICPP (2022)

Traffic Jam Model of Staircase

Heat Flux | Profile evolution

Usual SOC

$$Q = Q_0[\delta T]$$

$$\partial_t T = \chi \partial_x^2 T$$ Diffusion

$$\partial_t \delta T + \lambda \delta T \partial_x \delta T = \chi_2 \partial_x^2 \delta T$$ Burgers

~ Sand Pile

[Diamond-Hahm, PoP ‘95]

↓

Extended:

$$\partial_t Q = -\boxed{\frac{1}{\tau}}(Q - Q_0)$$

$$\partial_t \delta T + \lambda \delta T \partial_x \delta T = \chi_2 \partial_x^2 \delta T - \boxed{\tau \partial_t^2 \delta T}$$

Nonlinear Telegraph

finite response time

[Kosuga *et al*., PRL ‘14]

~ Traffic Jam

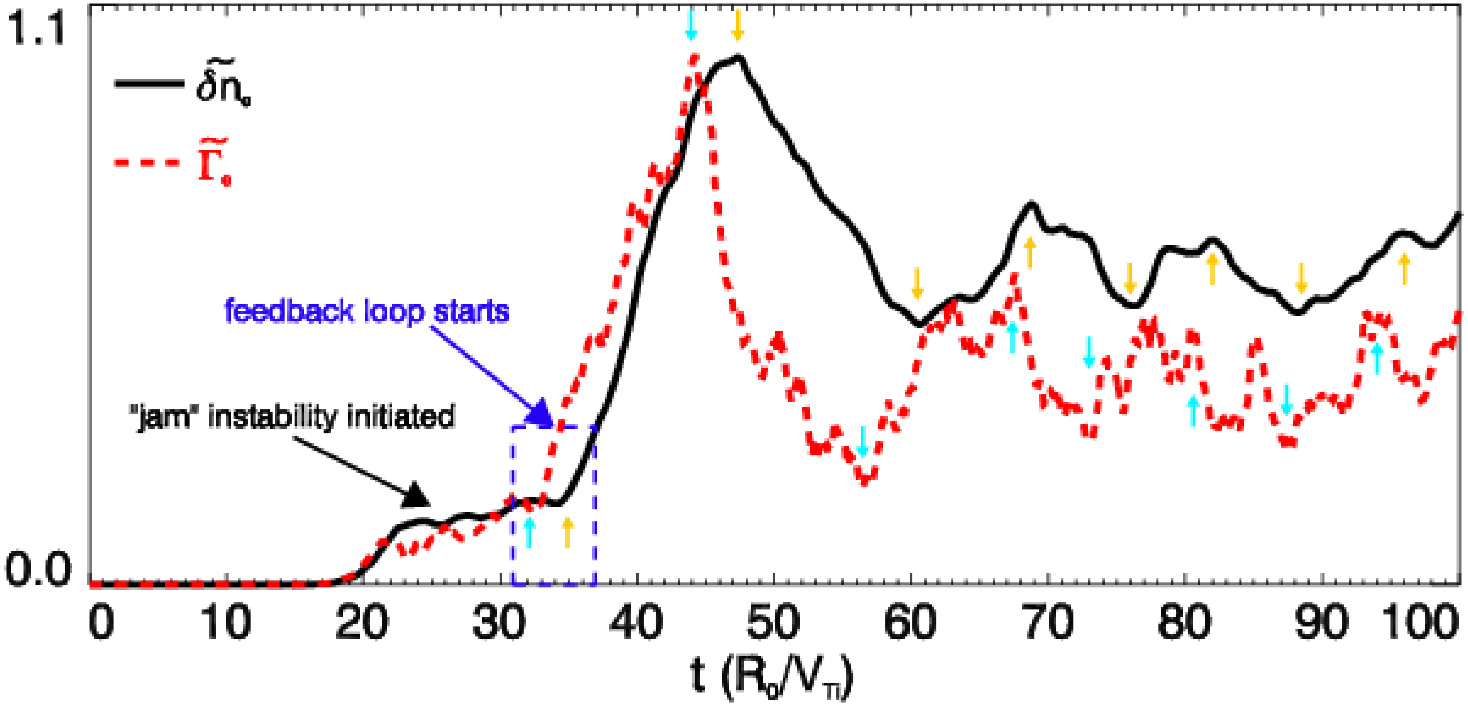
[Y. Kosuga *et al*., Phys. Plasmas **21**, 055701 (2014)]

~ derivation from GK equations for a simple system

[O. Gurcan *et al*., Phys. Plasmas **20**, 022307 (2013)]

Particle Flux reaches a mean level after a time-delay

- $\tilde{\Gamma}_e$ growth leads $\widetilde{\delta n_e}$ with a finite time τ,
  from gKPSP simulation of TEM turbulence using KSTAR-like parameters.



Time evolution of the staircase intensity of $\widetilde{\delta n_e}$(black solid line) and $\tilde{\Gamma}_e$(red dash line)