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Internal Transport Barrier Physics for Steady-state Operation in Tokamaks

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Acknowlegement for members of ITER Physics R&D Group on Internal Transport Barrier Physics

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1. Properties of ITB based on International ITB Database

2. Theoratical study of ITG turbulence for reversed (negative) shear configuration

3. Zonal flow generation due to ETG turbulence

4. Quasi-steady state and steady state ITBs

5. Eextrapolation to ITER

6. Summary

1. Introduction: International ITB [Internal Transport Barrier] database activity

Internal transport barrier
- Improved confinement
- High bootstrap fraction

→ Advanced steady-state operation in ITER

1-1. Objectives of THE INTERNATIONAL ITB DATABASE WORKING GROUP

(1) address the necessary conditions to form ITBs, with an emphasis on the critical heating power required for the ITB formation

(2) establish the confinement scaling for plasmas with ITBs for extrapolation to future devices

(3) explore the underlying physics of ITB formation from the compiled database, aiming at further extension of the physics understandings through validation of the theoretical models , such as Newman, PoP 5 (1998) 938, Fukuyama, NF 37 (1995) 611 and Horton, PoP 7 (2000) 4534 as well as the active control and sustainment of ITBs.

1-2. Structure and status of the ITB DATABASE

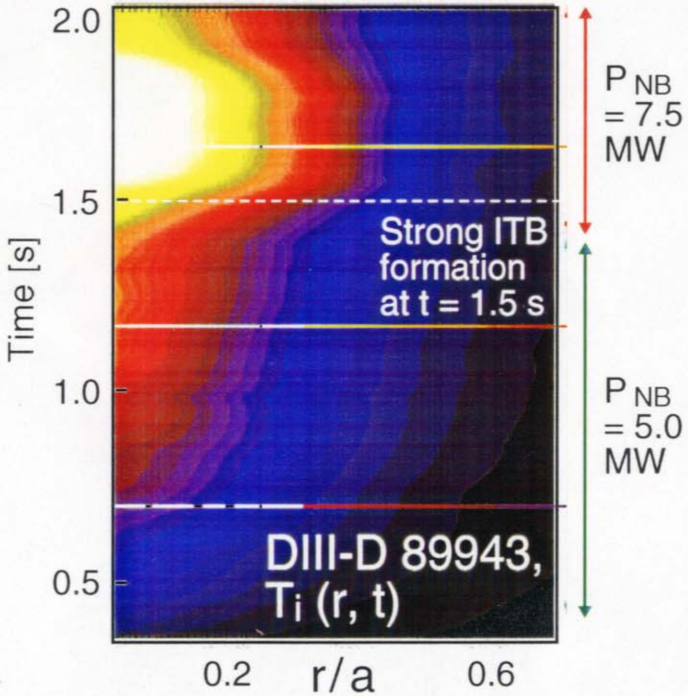
- More than 800 contributions from the ITB experiment in 9 tokamaks in the world have been so far accumulated, namely ASDEX-U, DIII-D, FTU, JET, JT-60U, RTP, T-10, TFTR, TORE SUPRA.
- The database is composed of 0-D global database with 126 variables and 6 kinds of 2-D profile database
  - Emphasis on variables which reflect the profile information for 0-D database
  - Multiple time slices across the ITB formation for 2-D database

2. The observed ion ITB formation in ASDEX Upgrade, DIII-D, JET, JT-60U

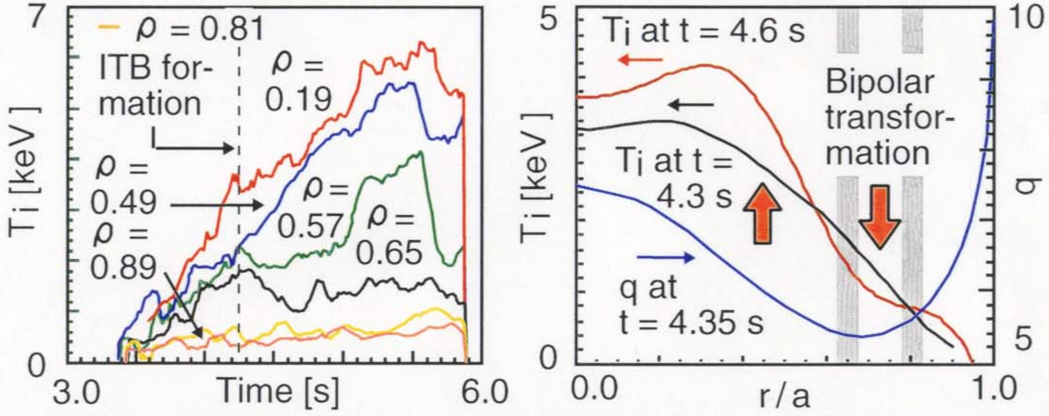
- The ITB formation is defined at a time when signals in two neighboring channels of T_i measurement start to separate from each other [DIII-D, JET, JT-60U]

⇨ Bipolar transformation of the T_i profile across the barrier is often observed, indicates the reduction of heat flux across the barrier and drop of T_i outside ITB

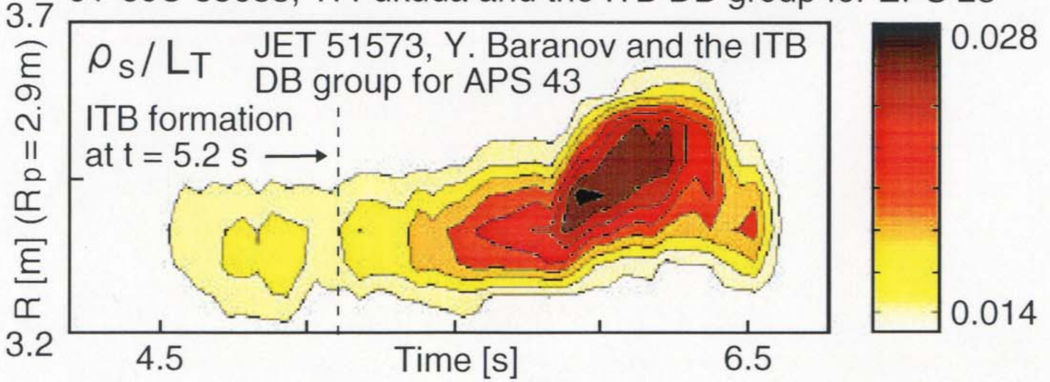
- $\rho_s / L_T > 1.4 \times 10^{-2}$ [G. Tresset, CEA Cadarache report FC1700 (2000)] in JET (ρ_s: ion Larmor radius, $L_T^{-1} = T^{-1} \nabla T$)
- The STIFFNESS in the T_i profile is often referred to in ASDEX-Upgrade



A. Sips and the ITB DB group for 8 th H mode and transport barrier physics workshop



JT-60U 35683, T. Fukuda and the ITB DB group for EPS 28

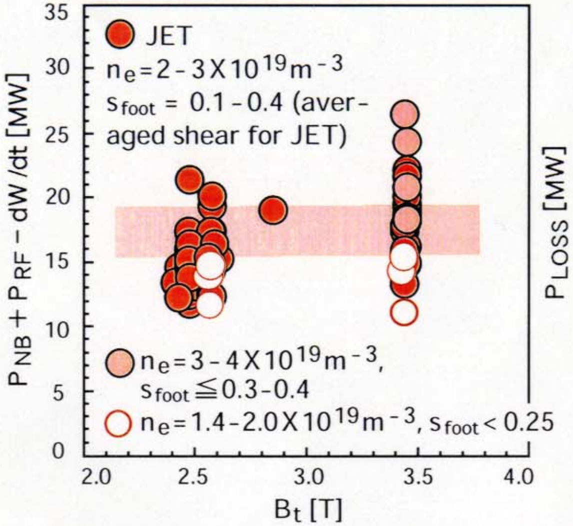


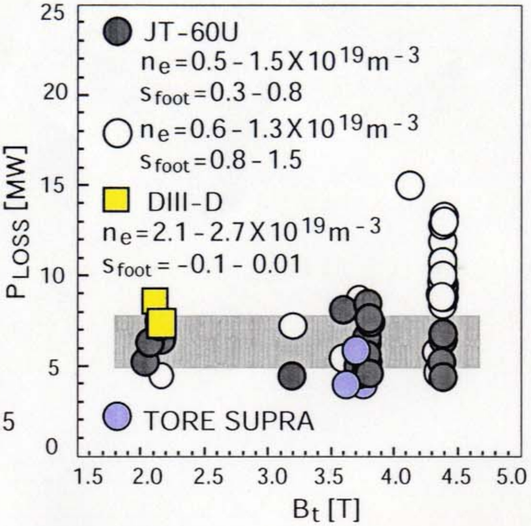
JET 51573, Y. Baranov and the ITB DB group for APS 43

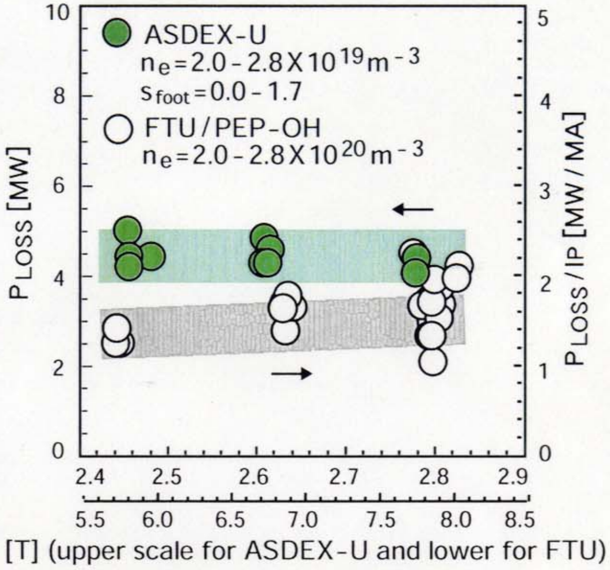
Parameter dependence of the ITB formation power threshold observed in the ITB database

1. B_t dependence of the ITB power threshold

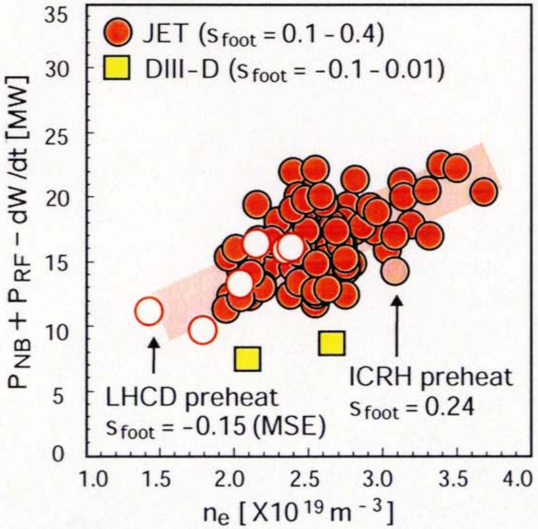
T. Fukuda and the ITB DB group for EPS 28

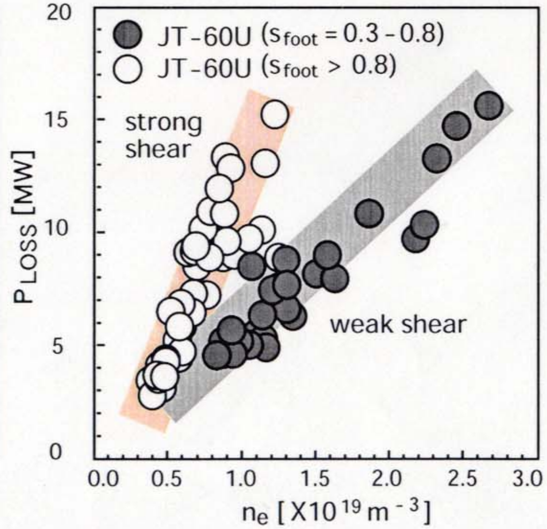


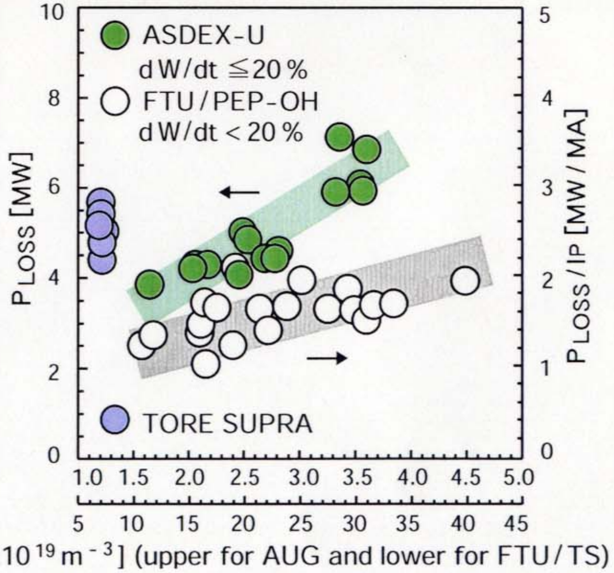




2. n_e dependence of the ITB power threshold

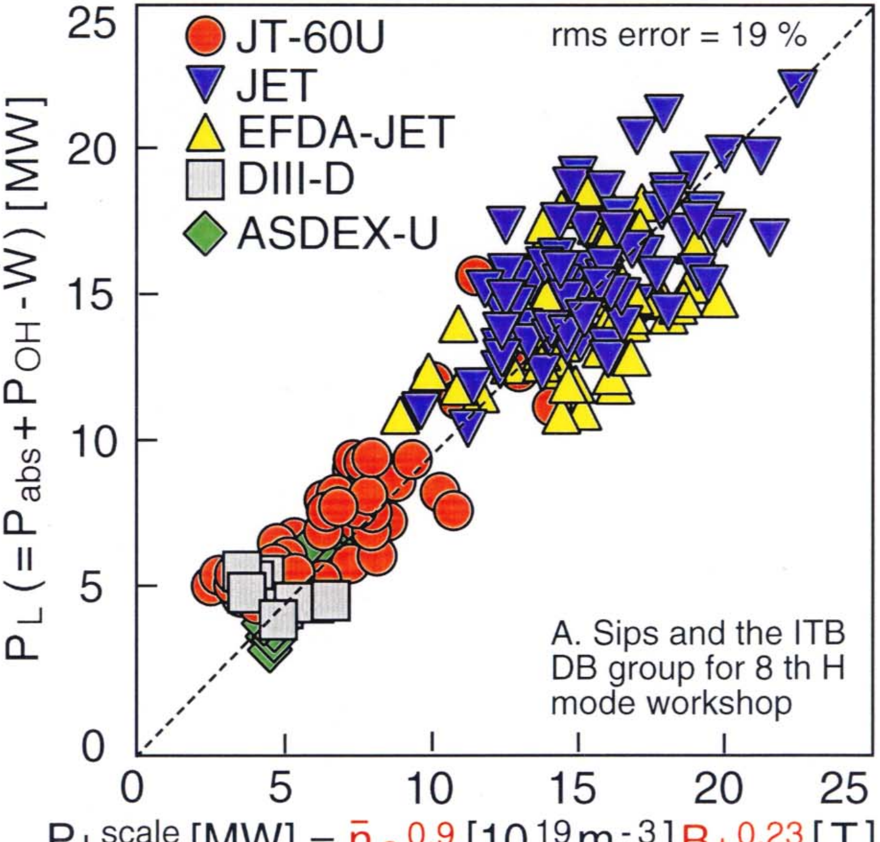






Global scaling for the ITB formation power threshold, derived without local variables, has strong density but weak magnetic field dependence

Contrary to the result of scaling, the paradigm of sheared EXB flow stabilization predicts strong B_t dependence, indicating that the sheared flow effect may be significant only for the reduction of core transport but not for the ITB formation



A. Sips and the ITB DB group for 8 th H mode workshop

P_L^{scale} [MW] = $\bar{n}_e^{0.9}$ [10^{19} m^{-3}] $B_t^{0.23}$ [T] $f(\kappa,\delta)$ $R^{2.13}$ [m]

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

Dimensional analysis of the criteria yields

$$\frac{\omega_{EXB}}{\gamma_L} = \frac{v_i\rho_i/L^2}{k_\theta\rho_s c_s/L} \sim \frac{\rho_i}{L} = \mathrm{const}, T_i \propto B_t^2/m_i$$

Assuming the gyro-Bohm transport

$P_{th} \propto n_e B_t^3 S$

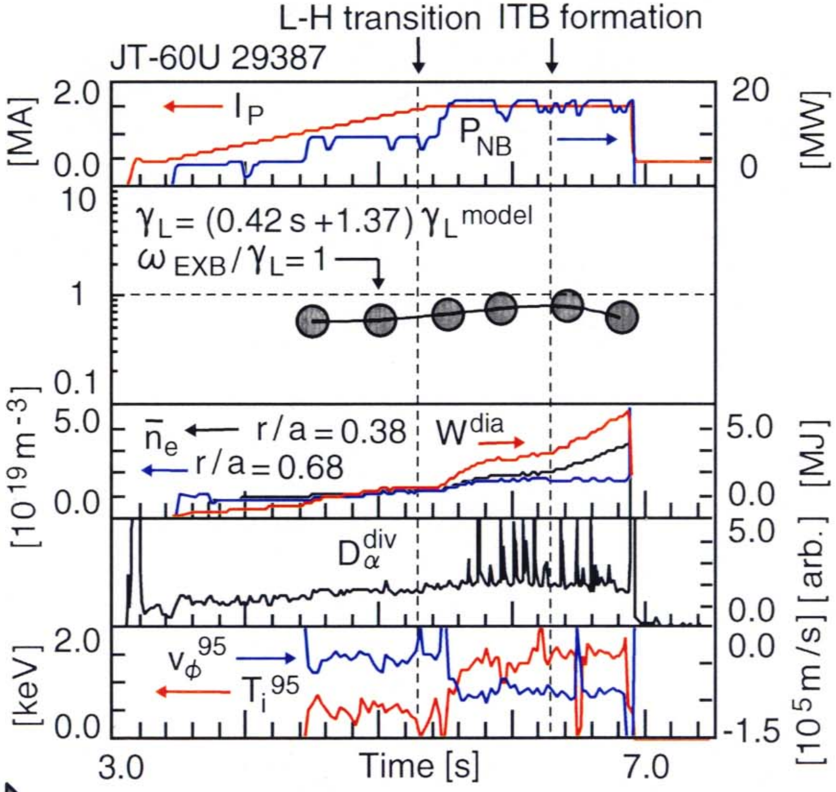
- $P_{th} \sim n_e B_t m_i^{-1} S$
  [Newman, PoP 5 (1998) 938]
- $P_{th} \sim c\, n_e a^3 B_t T_e f(d/a, s/q)$
  Bohm-like transport, where "d" is the power deposition radius
- $P_{th} \sim \frac{n_e S a^2}{R}\frac{c_s T_e}{R} f(d/a, s/q)$:
  gyro-Bohm [Horton, PoP 7 (2000) 4534]
- $P_{th} \sim n_e a^2 R^{0.5} B_t^{0.5} T_i^{1.25}$
  [Connor, to be submitted to NF]

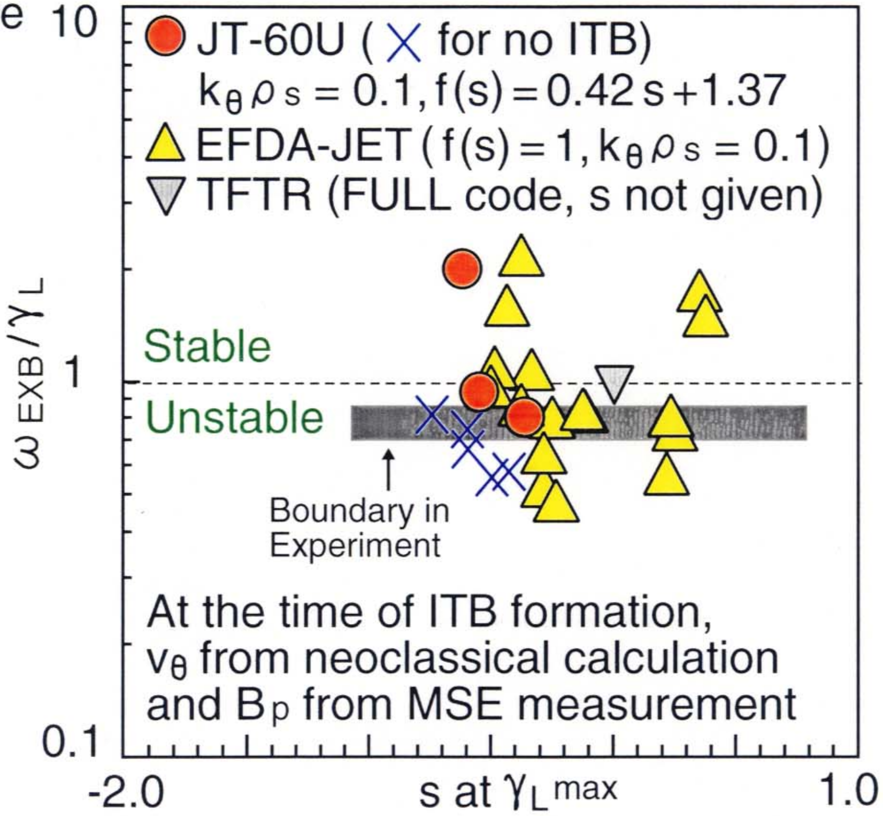
T. Fukuda and the ITB DB group JSPF 18

Influence of the sheared EXB flow on the ITB formation in terms of ω_{EXB}/γ_L

The ratio of EXB shearing rate and the ITG linear growth rate is around unity at the time of ITB formation, corroborating the theoretical model on local criteria

- Although the local ITB formation criteria of $\omega_{EXB}/\gamma_L = 1$ may be plausible with uncertainty in resolution, the intrinsic B_t dependence is weakened in converting into the heating power via transport in the core





At the time of ITB formation, v_θ from neoclassical calculation and B_p from MSE measurement

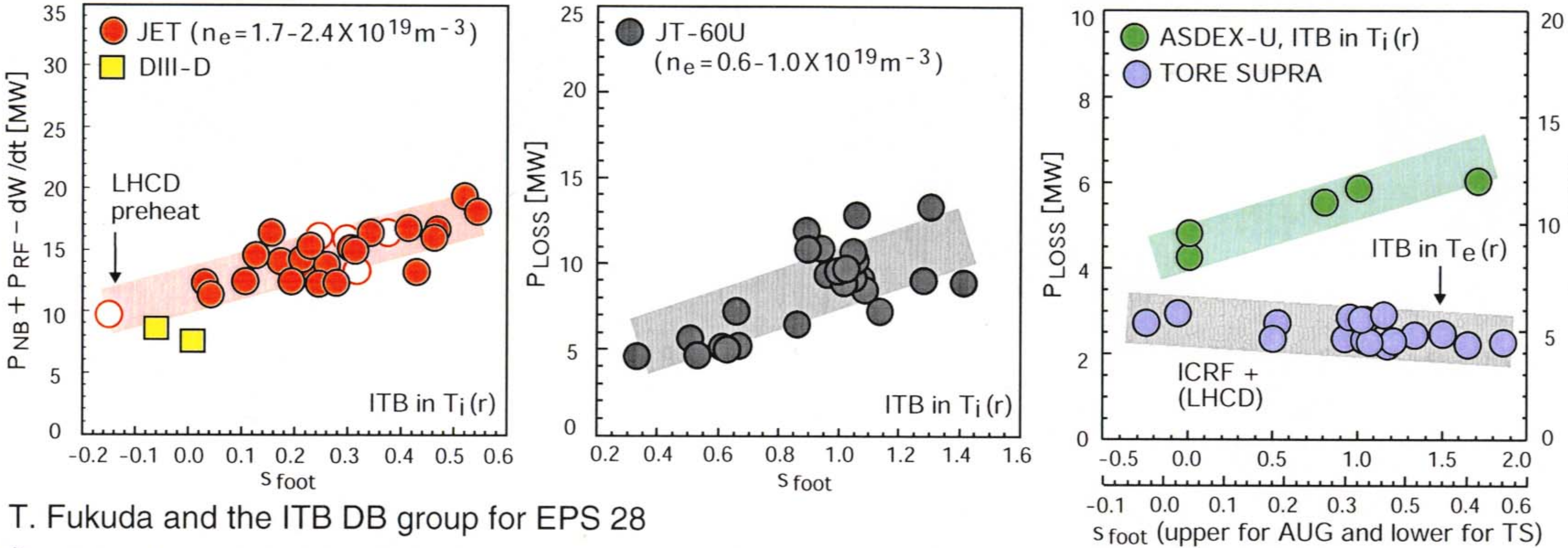
➡ FULL and GS2 analyses performed in JET, DIII-D and TFTR also indicate $\omega_{EXB}/\gamma_L \sim 1$ when ITB is formed [Budny/APS 43, Gohil/H mode workshop and Bell/EPS 23]

T. Fukuda and the ITB DB group JSPF 18

Influence of local quantities which modifies the scaling of ITB formation power threshold

The ITB database indicates the influence of (1) magnetic shear at the location of ITB, (2) heating profile and (3) momentum input on the ITB formation power threshold

(1) The reduction in the ITB formation power threshold was observed as the magnetic shear at the location of ITB is decreased towards the negative direction



T. Fukuda and the ITB DB group for EPS 28

➡ ITB threshold power may have a form under dimensionless constraint :
$n_e a^{1.2} f(d/a, s/q^{ITB}) \sim n_e a^{1.2} f(\alpha \text{ or } L_P^{ITB}, L_s^{ITB})$, $\alpha = -q^2 R d\beta/dr$

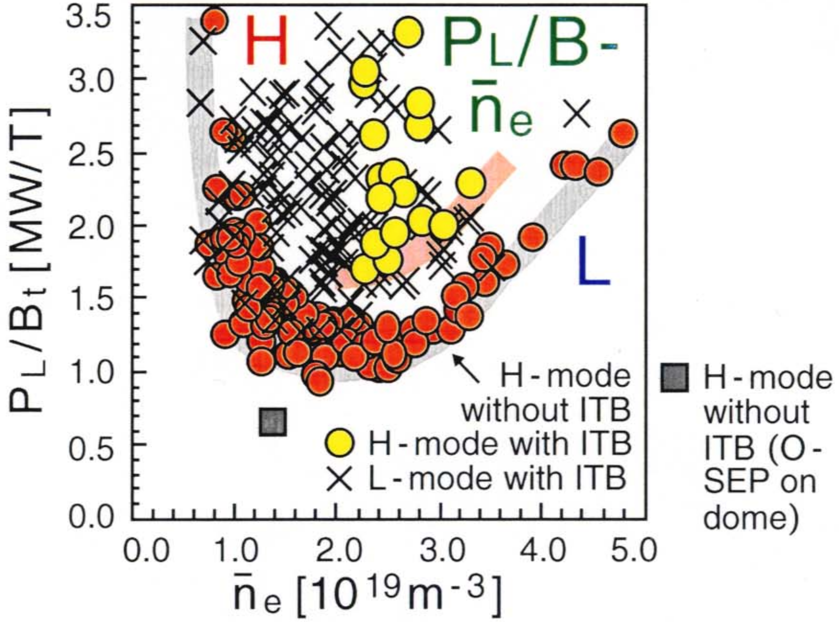
- No power threshold for the ITB formation in JET negative shear plasmas [Becoulet, EPS28] which is consistent with the result of gyro-fluid simulation [Garbet, to be published in Theory of Fusion Plasmas] ➡ Type I and type II ERS in TFTR
- No power threshold for T_e ITB in FTU ECH negative shear plasmas [Barbato, EPS28]

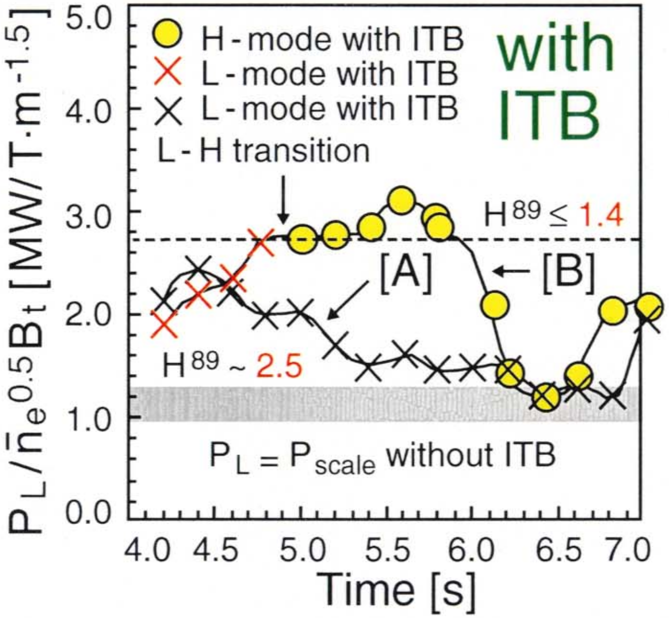
➡ Conditions to form ITB in T_i(r) and T_e(r) are different, possibly by the suppression of ITG and either TEM or ballooning mode respectively

2. L-H TRANSITION conditions in Internal Transport Barrier plasmas [1]

● Modification of the threshold power scaling by the ITBs in RS plasmas

In very high performance RS plasmas with strong ITB, a large amount of heating power exceeding the threshold scaling is required to induce the L-H transition





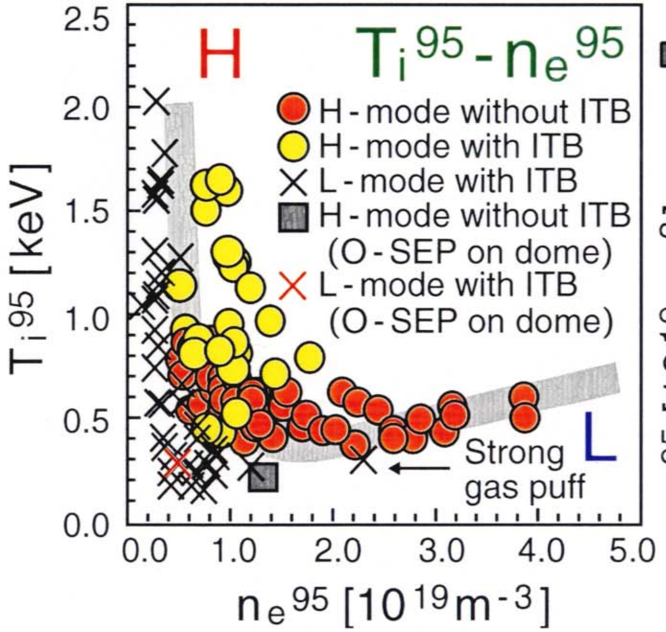
● The L-H transition threshold power scaling is NOT directly applicable to ITB plasmas, as it is a mixture of core transport and transition physics

➡ Comparison of EDGE parameters in plasmas with and without ITBs

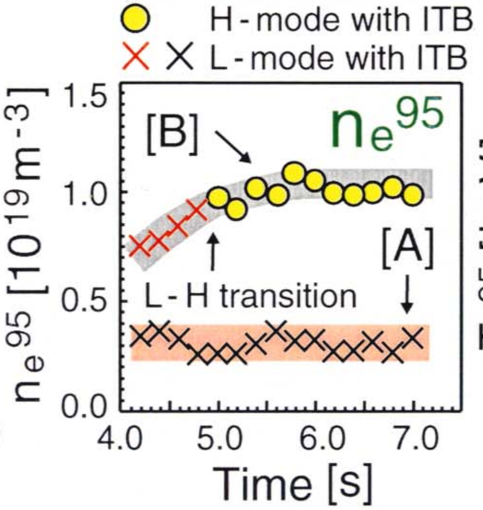
- Comparison of EDGE parameters in RS plasmas with and without ITBs

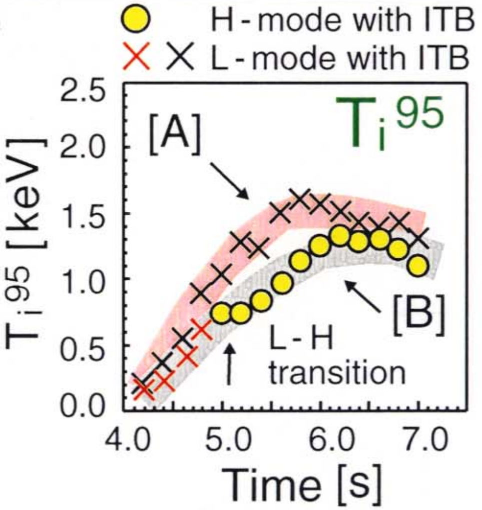
L-H transition boundary for the edge electron density and edge ion temperature space is the SAME between the plasmas with and without ITB

- In high performance plasmas with strong ITB, edge density is lower, and an increase of heating power does not effectively contribute to the L-H transition



Similar to the increased threshold power in LOW density plasmas without ITB





- Compatibility of the L to H mode transition and ITBs

An INCREASE of the edge electron DENSITY is above all crucial

The International ITB Database Activity

(1) address the necessary conditions to form ITBs, with an emphasis on the critical heating power required for the ITB formation

(2) establish the confinement scaling for ITB plasmas for extrapolation to future devices

(3) explore the underlying physics of ITB formation from the compiled database, aiming at further extension of the physics understandings through validation of the theoretical models, as well as the active control and sustainment of ITBs.

OBJECTIVES : Improvement in the predictive capability and controlability of plasmas with ITB for application in the ITER advanced steady state scenario

- Dependencies of ITB power threshold on s^{ITB}, n_e, B_t, q_{95} (q_o), T_e / T_i, and V_ϕ : very low power threshld in JET, JT-60U, TFTR ERS-II and Gyro fluid results by X. Garbet
- Very low power threshold for T_e-ITB : sheared EXB flow shear or magnetic shear
- Size scaling of the ITB power threshold

$$P_L^{scale} = \bar{n}_e^{0.9}\,[10^{19} m^{-3}]\, B_t^{0.23}\,[T]\, f(\kappa, \delta)\, R^{2.13}\,[MW]$$

- Systematic comparison of the conditions for ITB formation with predictions of transport models to be discussed with the Modelling Group
- ➡ Evaluation of the accessibility of ITBs in burning plasmas, namely at low toroidal rotation, $T_i / T_e \sim 1$, and flat density profiles
- Compatibility of ITBs with ELMs and impurity exhaust to be discussed with the Edge and Pedestal Physics Group

Introduction

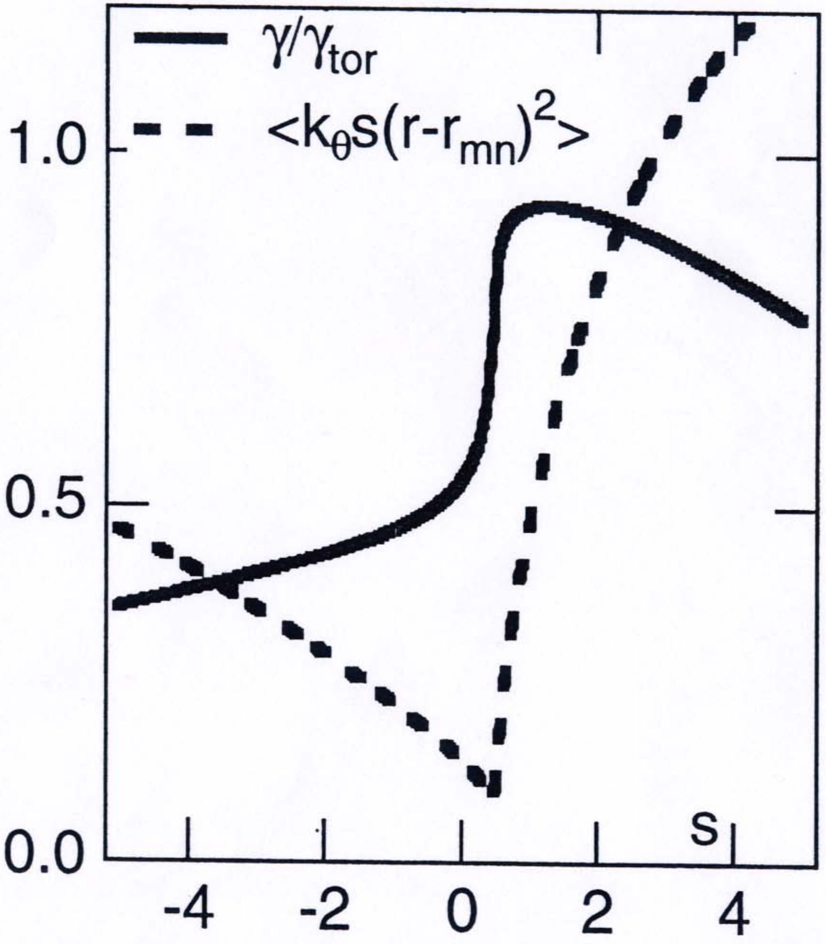
- Open questions concerning ITB 's
  - Magnetic shear versus ExB shear
  - Power threshold
  - Role of rational q_{min}
  - Role of toroidal velocity
  - Hysteresis

Magnetic Shear

Low shear : increases the distance between resonant surfaces (Romanelli and Zonca 93)

Negative shear

- trapped particles: curvature drift reversal.
- passing particles: interchange drive decreases Drake et al. 96



ITG, Ballooning representation

Magnetic Shear (cont.)

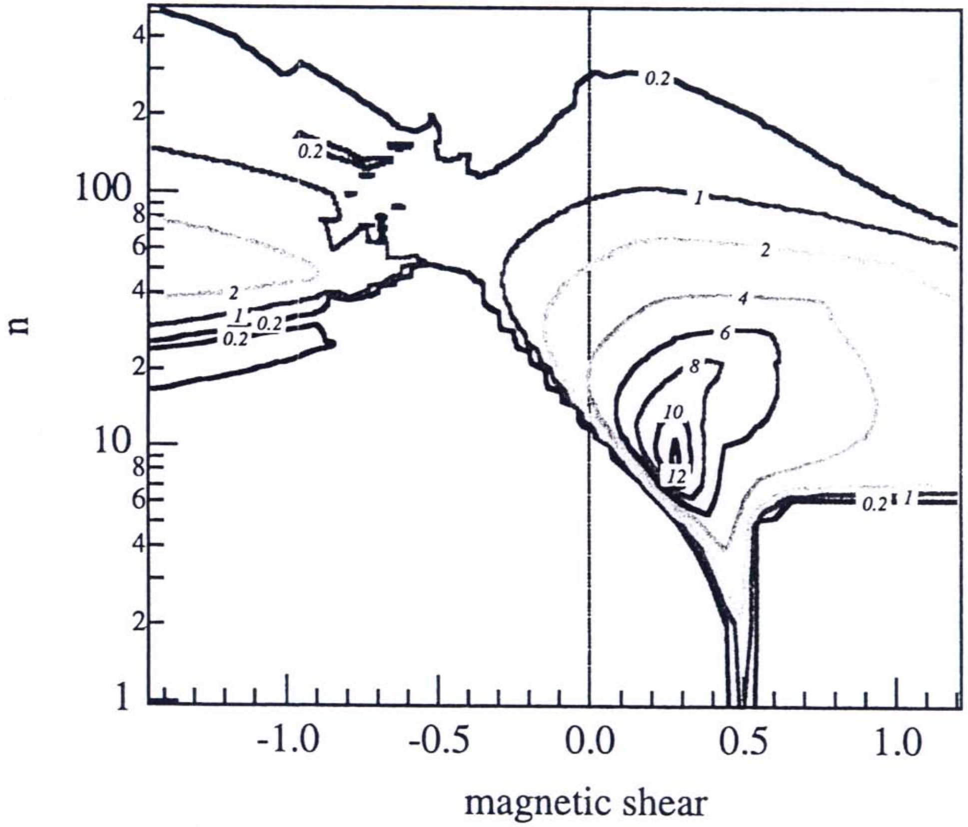
Maget et al. 99

- Slab branch

optimum at s=0.

- Ion mode slab branch persists for s<0. Brunner 00, Jenko 00

- Optimum close to s=-0.5.



$\gamma_n \lambda_n^2$ versus (s,n)

Fluid Equations

¥ Ion fluid equations

$$d_t n_i = -n_i \nabla_{//} V_{//} - n_i \nabla . \mathbf{v}_\perp$$

$$n_i m_i d_t V_{//} = -n_i e_i \nabla_{//} \phi - \nabla_{//} p_i$$

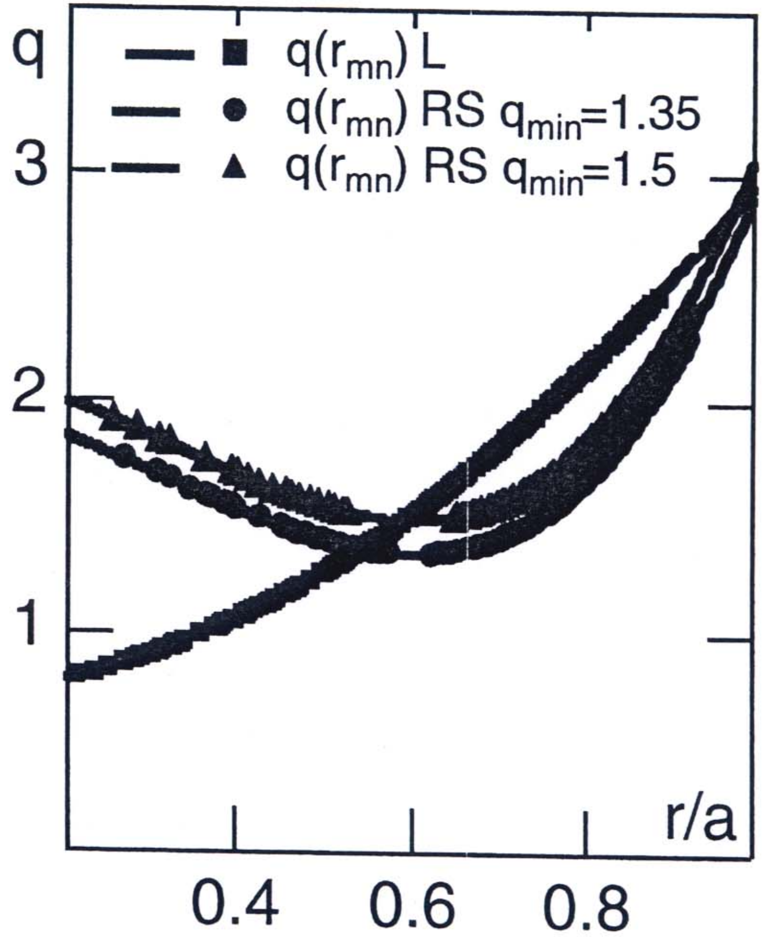
$$\frac{3}{2} d_t p_i = -\frac{5}{2} p_i \nabla_{//} V_{//} - \frac{5}{2} p_i \nabla . \mathbf{v}_\perp - \nabla . \mathbf{q}_\perp + S$$

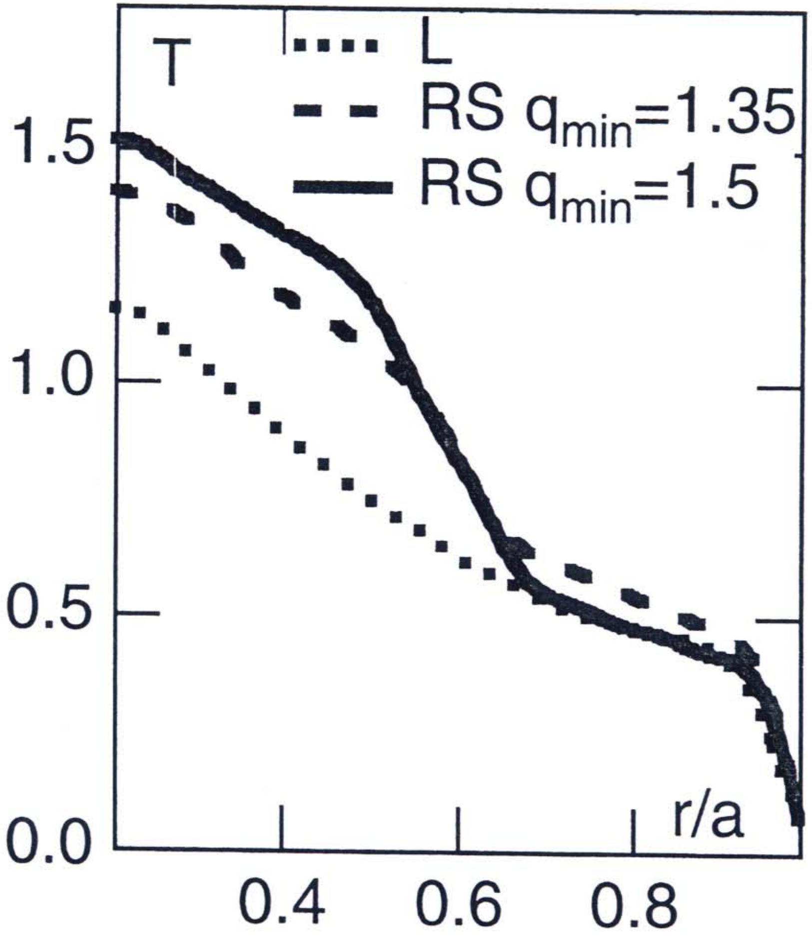
$$d_t = \partial_t + v_\perp . \nabla - D \nabla_\perp^2$$

Landau fluid dissipation in heat equation

¥ Electron adiabatic response

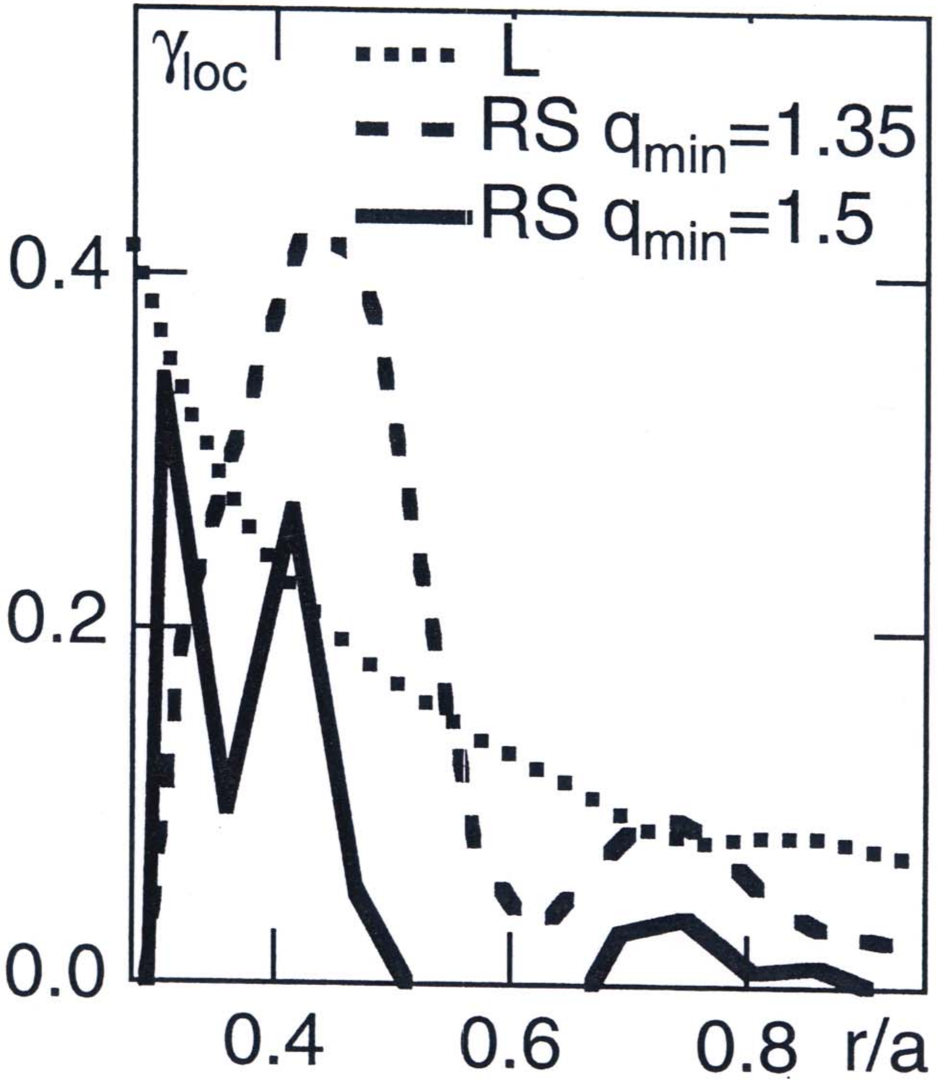
q and Temperature Profiles





Linear Stability

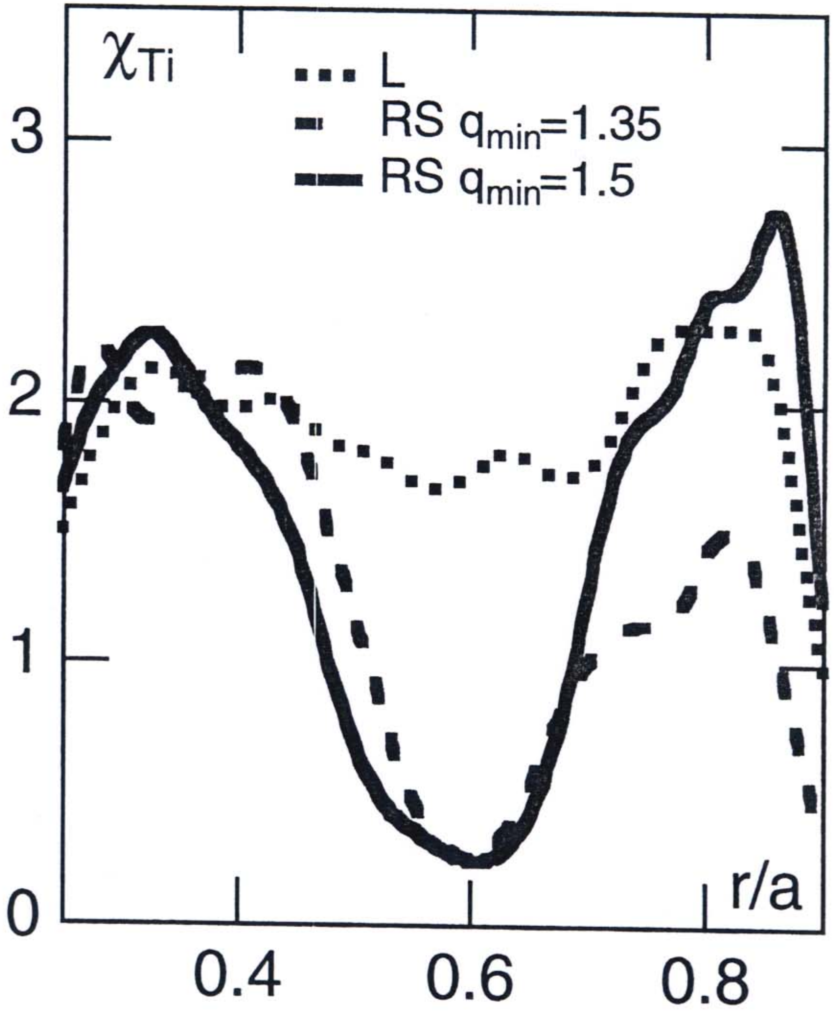
- Local growth rate (ballooning representation)
- Minimum at s=0



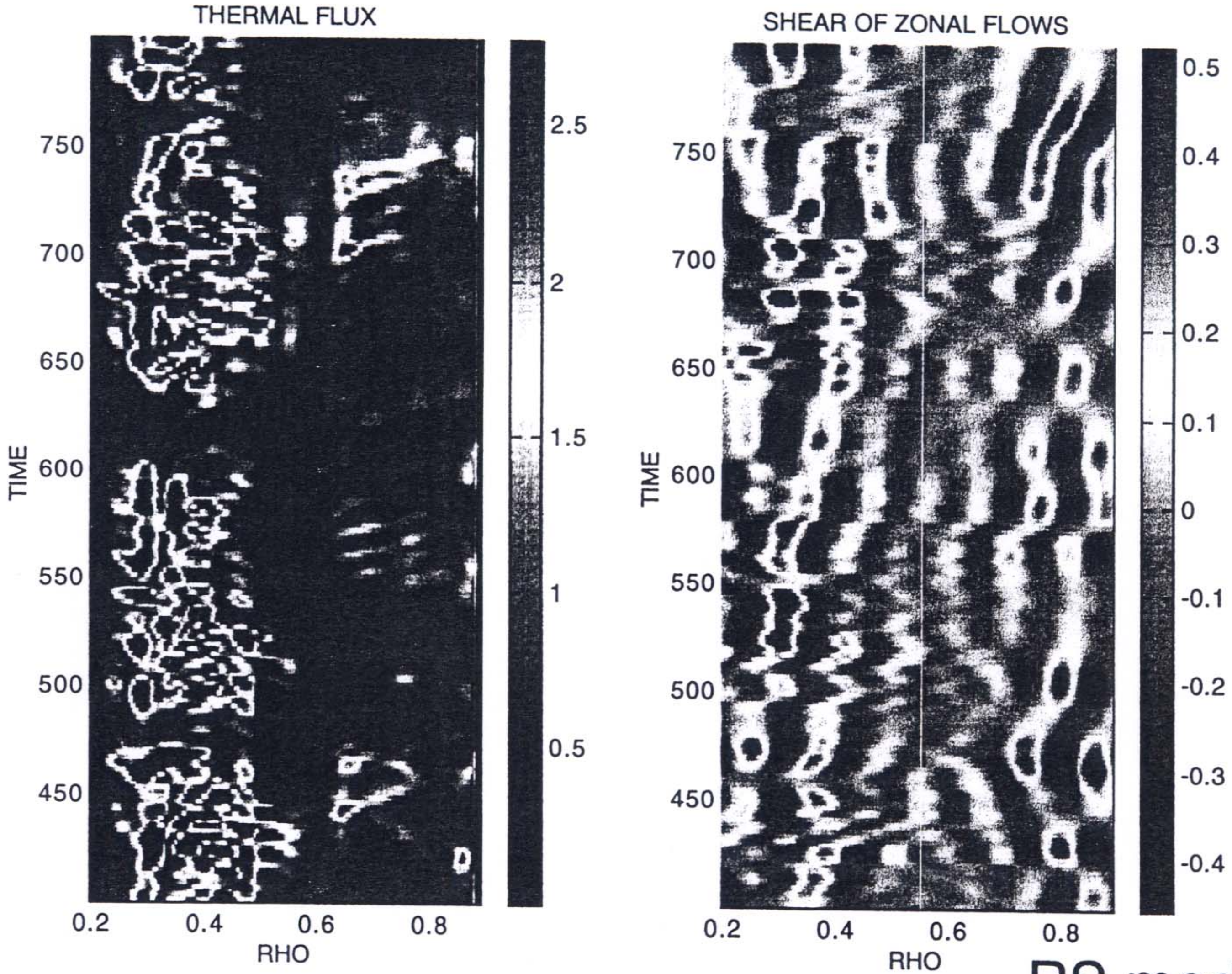
Thermal Diffusivity

- Minimum at $q=q_{min}=m_0/n_0$.
- Gap in the density of rational surfaces

$$d_{gap} \approx \left[\frac{2q_{min}\rho_i}{n_0 r_{min} q''_{min}}\right]^{1/2}$$



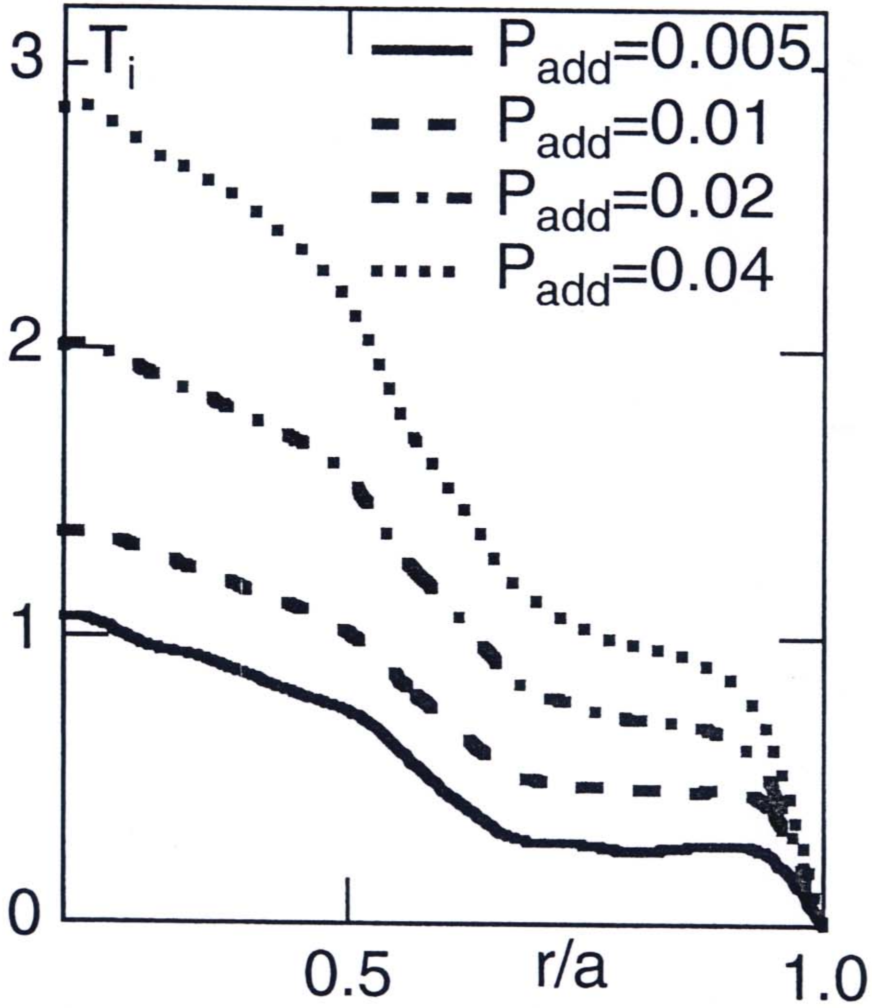
Flux and Zonal Flows



RS mode

Power Scan

- No evidence of a threshold for the barrier onset .
- Fast increase of the barrier height above a critical value.



ExB Shear

- Not a pure s<0 mechanism: the width is controlled by ExB shear.
- Flat density profile, no external source of parallel momentum.

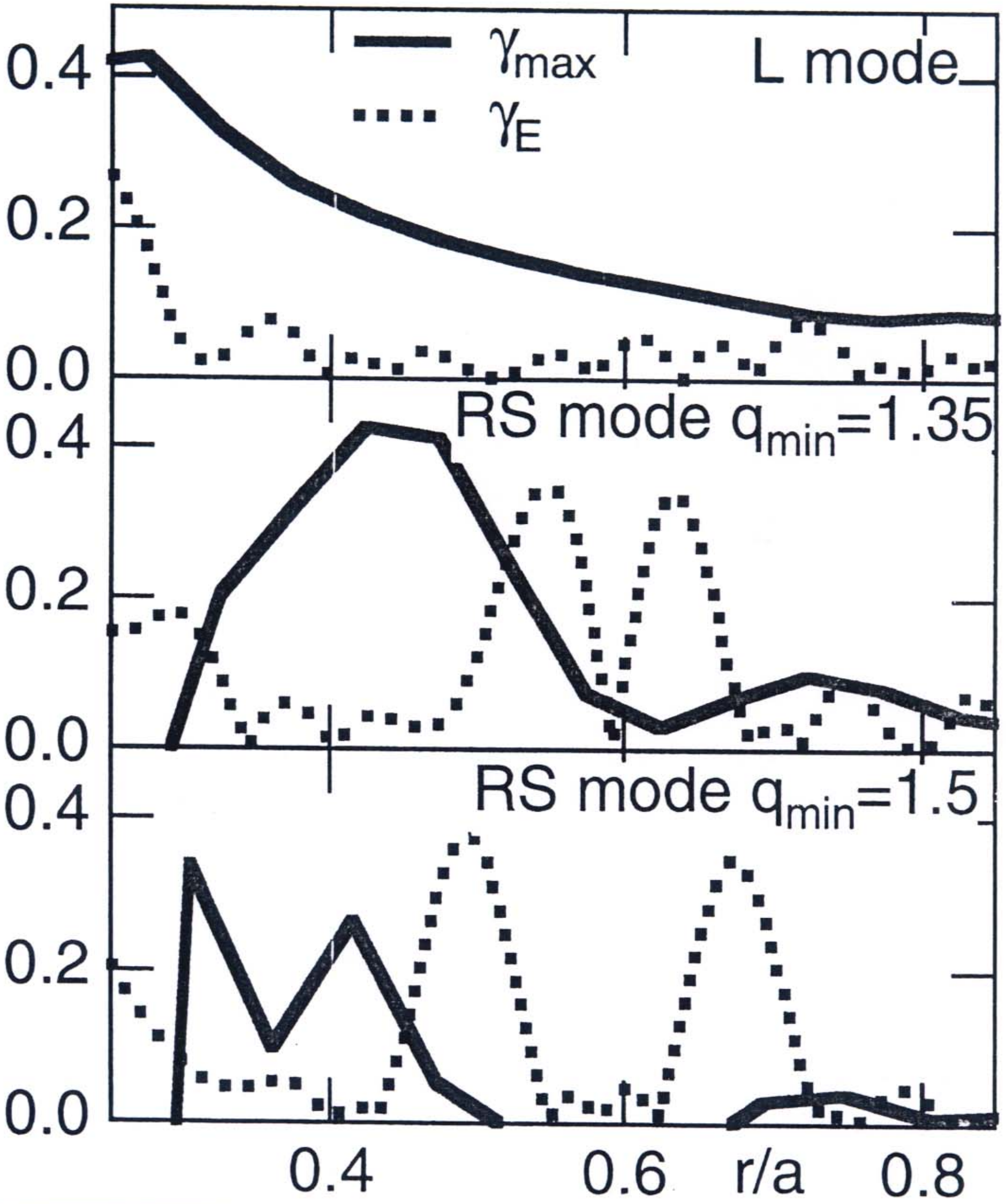
→ dipole structure

$$\gamma_E = \frac{d}{dr}\left(\frac{E_r}{B}\right) = \frac{1}{e_i B}\frac{d^2 T_i}{dr^2}$$

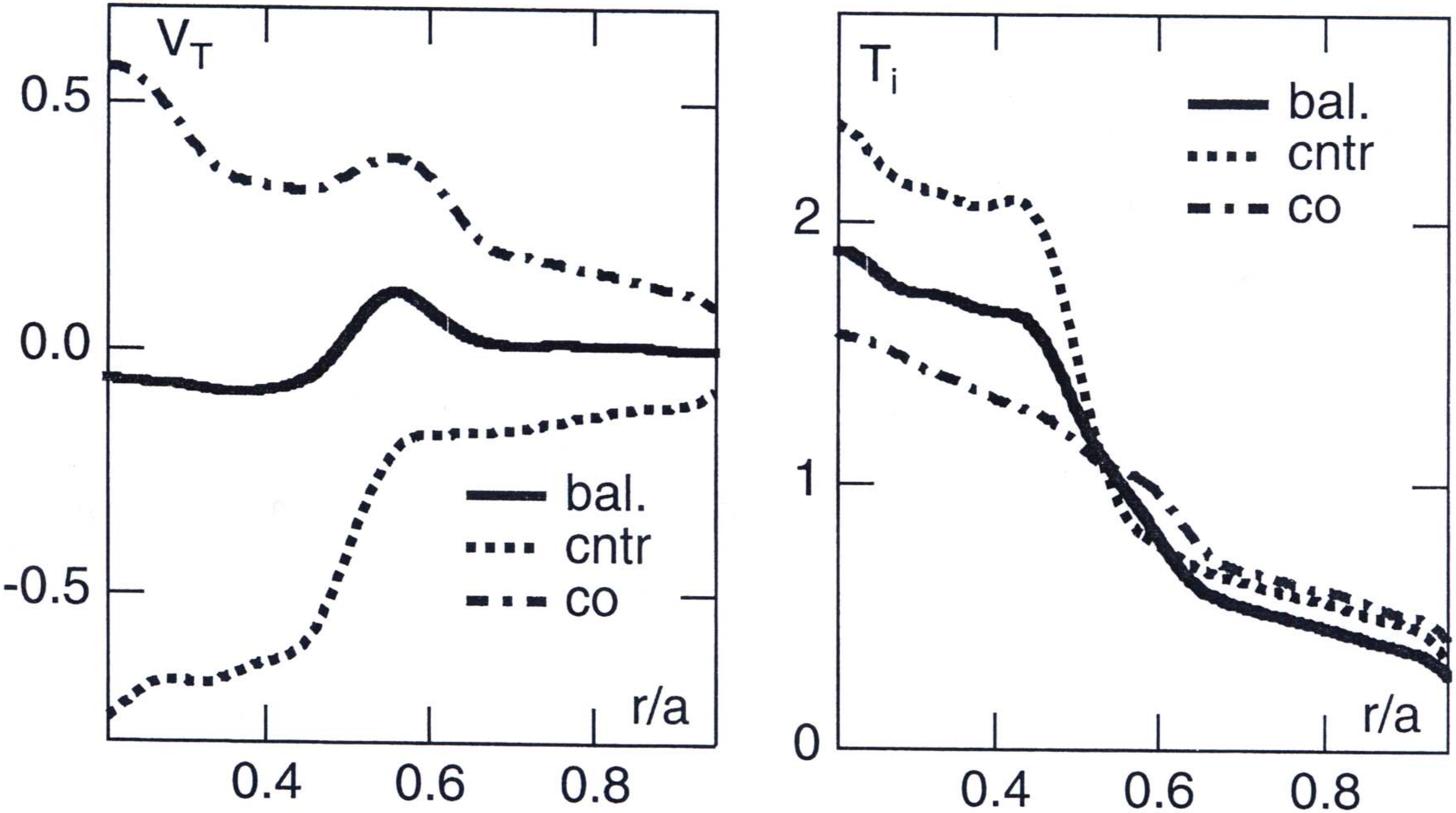
→ the barrier does not move (consistent with Lebedev and Diamond 97, Newman et al. 98.)

ExB Shear vs Linear Growth Rates

- Dipole structure of the ExB shear rate.
- Barrier broader than the $\gamma<0$ region.

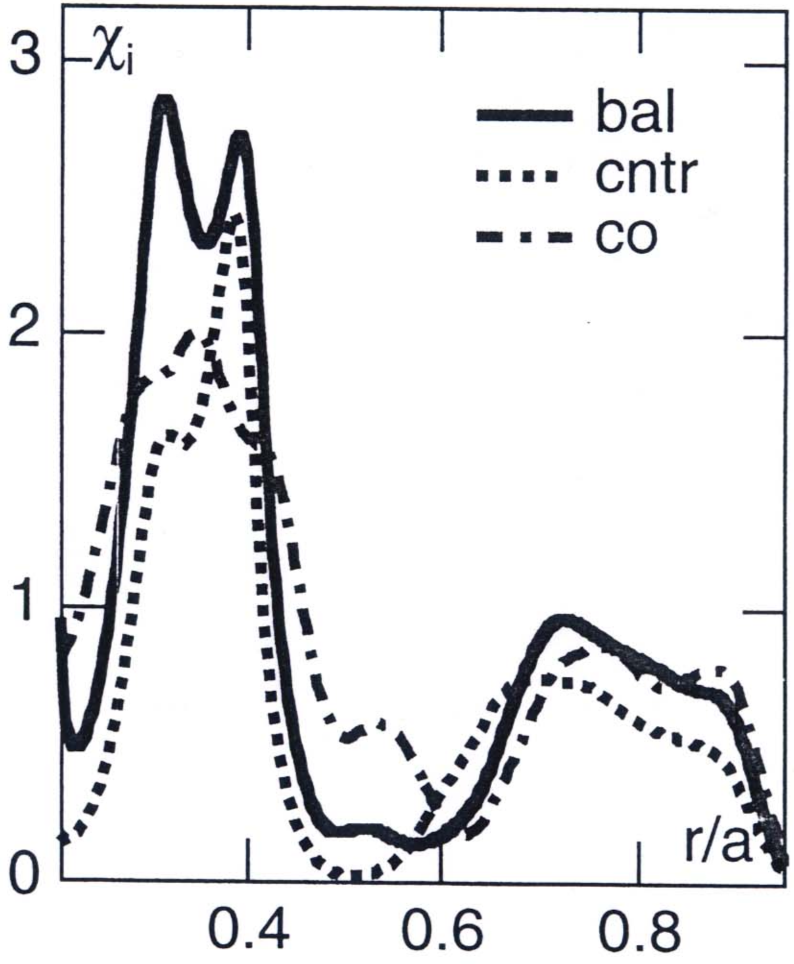


Simulations with Toroidal Momentum



Diffusivity

- Neoclassical diffusivity inside the ITB with counter-rotation.
- Balanced momentum as good as counter-rotation.



Conclusion

- Stable because of rarefaction of resonant surfaces → ITB localised at s=0 without toroidal rotation.
- Explains why rational q_{min} is more efficient.
- No power threshold.
- Not a pure s=0 mechanism: the barrier width is controlled by ExB shear.
- Counter or balanced rotation seems to be more favorable than co-rotation.

Steady State Operation

- A large contribution of bootsrap curret (>50% of Ip) and an additional current drive makes a steady state operation possible.

- Since BS current becomes hollow, negative (reverse) shear configuration is a natural configuration for steady state tokamak operation. However, current profile alignment is required with a current drive.

- Physical and techological time scale:
  (i) MHD time scale (μ sec or msec)
  (ii) Transport and confinement time scale (~sec)
  (iii) current diffusive time scale (~100sec)
  (iv) plasma wall equilibrium time scale (>a few min.)

Practical Definition:

Quasi-steady state >less than or comparable to 100sec

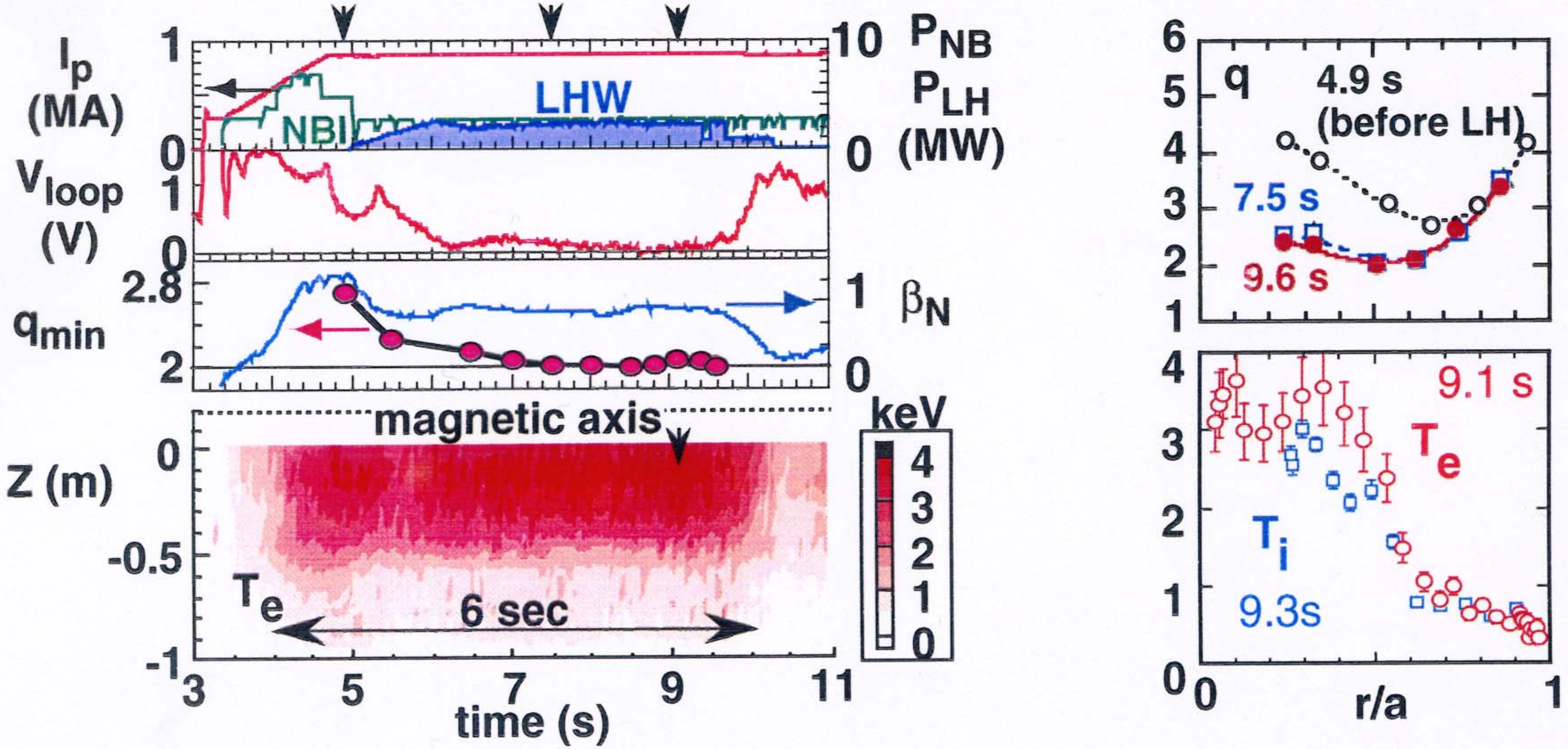
Steady state > a few min.

Steady sustainment of RS discharge with ITB by full non-inductive current drive (LHCD)

JT-60U

- LHCD at off-axis controls a RS configuration
- ITB sustained for ~5 s at ~constant location non inductively
- Full non-inductive CD with LH (77%)+BS (23%).
- $T_e \sim 1.2\ T_i$ (core)

Ip=0.85 MA,Bt=2.0 T, PLH~2.3 MW, PNB=2.5 MW



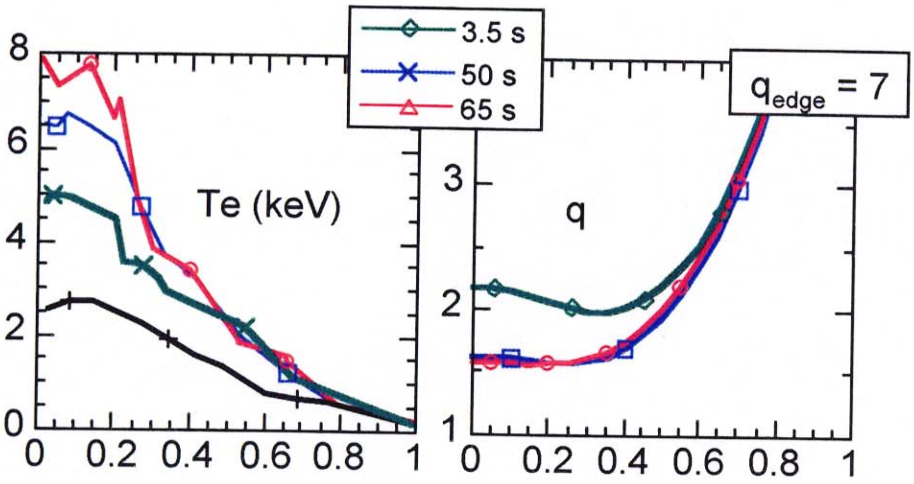


Figure 11 *Profiles of the electron temperature and safety factor in a 2min discharge in Tore Supra at three times: t=3.5s (beginning of the pulse), t=50s (LHEP phase) and t=65s (after the hot core transition).*

Quasi-steady ITBs

- Since high bootstrap current is required, the plasma beta should be high enough($\beta_N \sim 3$). Thus the MHD stabilities become crucial in negative (reverse) shear configurations.

Example: kink-ballooning modes,
resistive interchange modes,
double tearing modes.

⇒ Which is optimum q profile with negative shear ?

Sustainment of high Q_{DT}^{eq}

JT-60U

Transient:

Q_{DT}^{eq}=1.25 (RS 2.6MA)

0.6 (High-βpH 2.0MA)

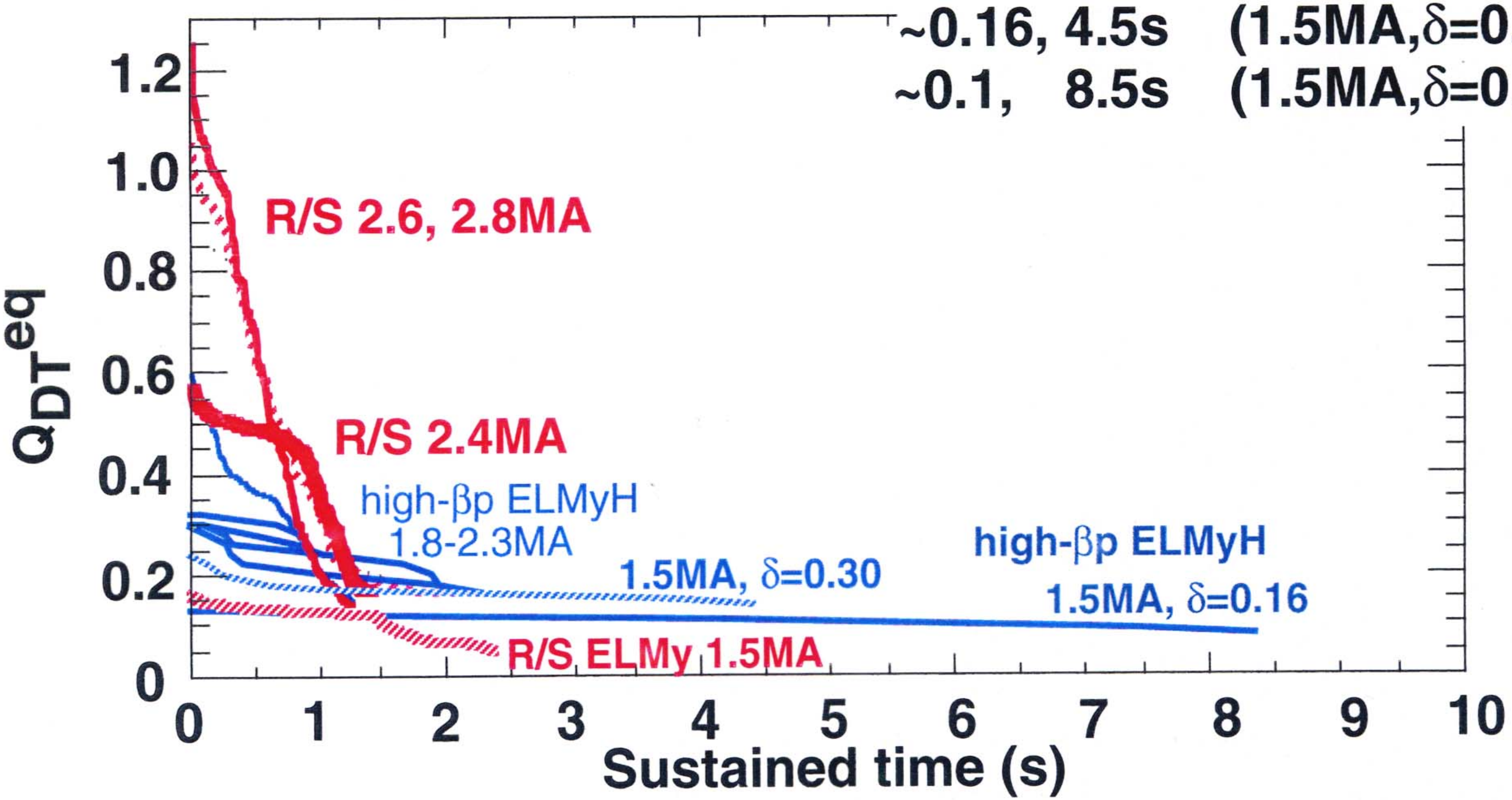
quasi-steady:

RS ~0.4- 0.5, 1s (2.4MA)

High-βp ELMyH

~0.16, 4.5s (1.5MA,δ=0.3)

~0.1, 8.5s (1.5MA,δ=0.16)



Extrapolation to ITER

Two types discharges will be realized in ITER:

(1) $Q>10$ with ELMy H-mode
(2) $Q>5$ with ITB formation

Extrapolations:

(i) size scaling for ITB formation conditions,
(ii) possibility to sustain ITBs at high density ($n>0.8\ n_G$)
(iii) prevention of impurity accumulation inside ITB
(iv) possibility to control ITBs

ITB formation in ITER

(I) From the scaling of threshold power to obtain ITBs, capability to form ITB in ITER with 100MW is shown for low density regime ($n < 0.5\ n_G$).

However, ITER must be operated at the high density regime ($n > 0.8\ n_G$).

⇒ First ITB is formed at the low density regime, then the density is increased up to $n \fallingdotseq 0.8\ n_G$.

(II) For improved confinement with ITB, $\omega_{EXB} > \gamma$ is necessary.

Questions:

(1) What *Er* will be expected in ITER ?
(2) Diamagnetically driven *EXB* flow shear has unfavorable scaling with ρ^*.
(3) Contribution to *EXB* flows from toroidal plasma rotation in large macine is expected to be lower than in present experiments.
(4) Reliability of scaling law of power threshold to obtain ITBs.

Favorable points:

The stabilizing effect of Shafranov shift and the effects of negative and low shear are independent of mascine size and should be as effective in ITER as in present day tokamaks.

Summary

1. International ITB Database is evolving and analyses using this Database are progressed.

2. Theoretical studies for ITB physics based on gyrofluid and gyrokinetic simulations are progressed.

3. Experimental and theoretical efforts for realzing quais-steady ITBs are on going.

4. Probability to realize ITB in ITER for obtaining $Q>5$ seems high.