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# Physics of Edge Transport Barriers and Importance for Fusion Experiments

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# Physics of Edge Transport Barriers and Importance for Fusion Experiments

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Alcator C-Mod

Material from many colleagues is gratefully acknowledged!

**J. W Hughes, R. MacDermott, J. Snipes (MIT), A. Loarte (ITER), S. Kaye, E. Synakowski (PPPL), B. Carreras (ORNL), P. Diamond (UCSD), Phil Snyder, T. Evans, K. Burrell R. Waltz (GA), E. Doyle (UCLA), G. Saibene, P. Nave (JET), P. Lang, F. Ryter, F. Wagner, T. Eich (IPP), N. Oyama, Y. Kamada (JAEA) , G. Bateman (Lehigh), K. Thomsen (EFDA)**

*International Centre for Theoretical Physics*
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# Physics of Edge Transport Barriers and Importance for Fusion Experiments

- **Introduction**: *What is an edge transport barrier or "pedestal"? How is it obtained?*

- **Importance for fusion experiments:** *Why should we care?*
  - Impact of barrier parameters on global performance.
  - Impact of barrier instabilities (ELMs) on the divertor.

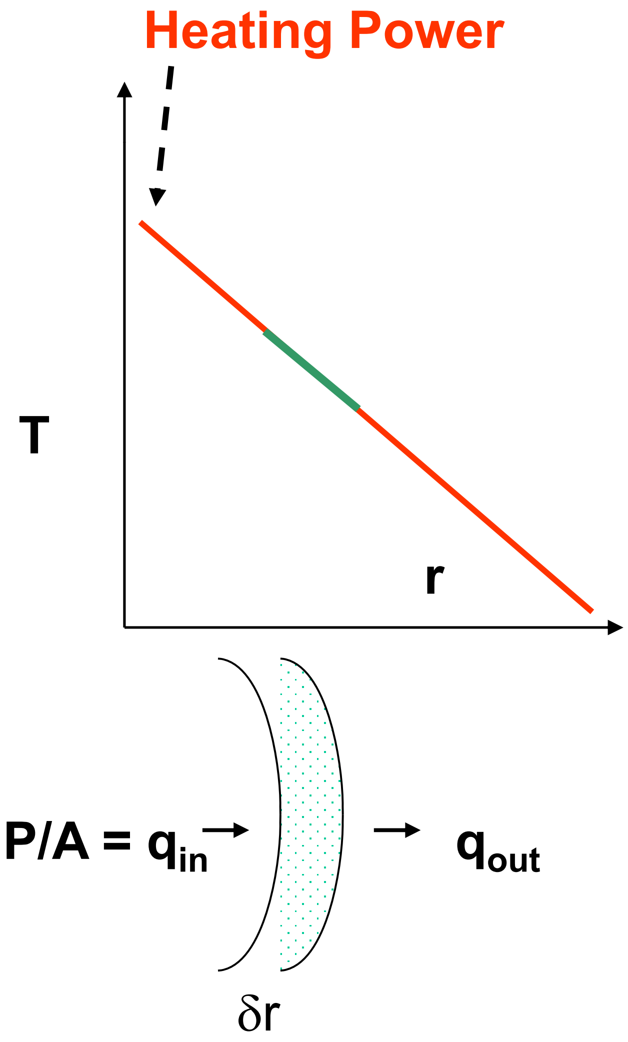
- **Overview of key physics**. *What is the present understanding, and what are open scientific issues for current research?*
  - L-H transition and thresholds
  - Pedestal width, gradient and height.
  - ELM physics, avoidance and control.

**This talk will be a *tutorial*, not a comprehensive review!**

Will focus on tokamaks – but barriers also occur in other configurations.

Mainly from an experimental perspective. Other speakers cover modeling.

# Introduction : *What is a ‘transport barrier’?*



**Measures of plasma transport:**

- Global’ Energy Confinement time:

$$\tau_E \equiv \frac{\text{Energy Content (J)}}{\text{Input Power (W)}} = \frac{\int 3nkT\,dV}{P_{tot}}$$

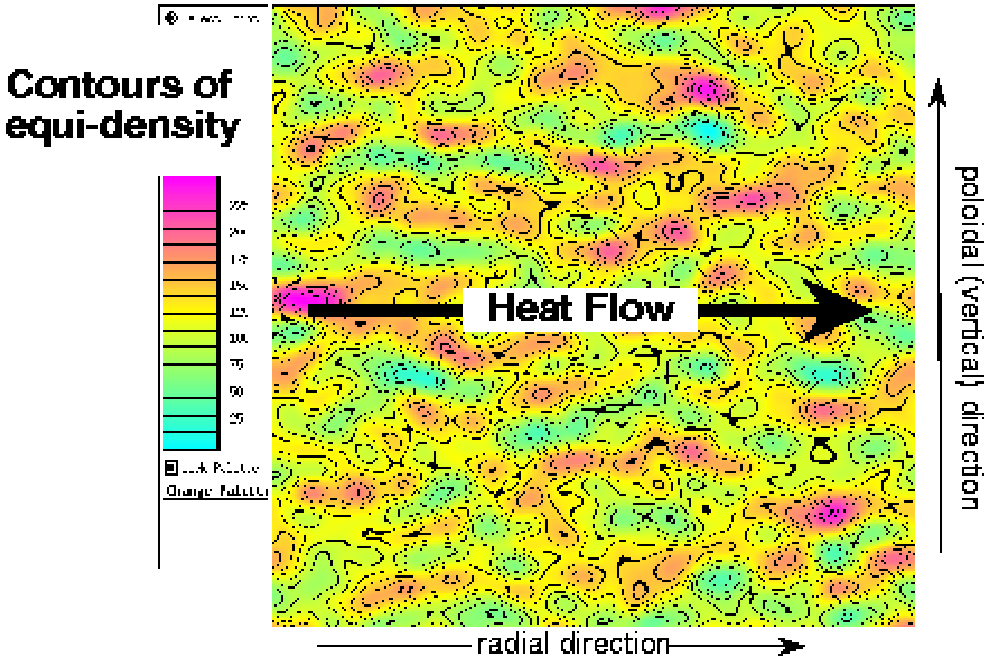
- ‘Local’ thermal diffusivity $\chi$ ($m^2/s$):

$$q = \chi nk\nabla T$$

heat flux= conductivity x gradient

(for *diffusive* flux, in steady state)

# Most transport in fusion plasmas is due to TURBULENCE



Reconstruction of Spectral Data Showing Turbulent Eddies in TFTR

Dale Meade, PPPL

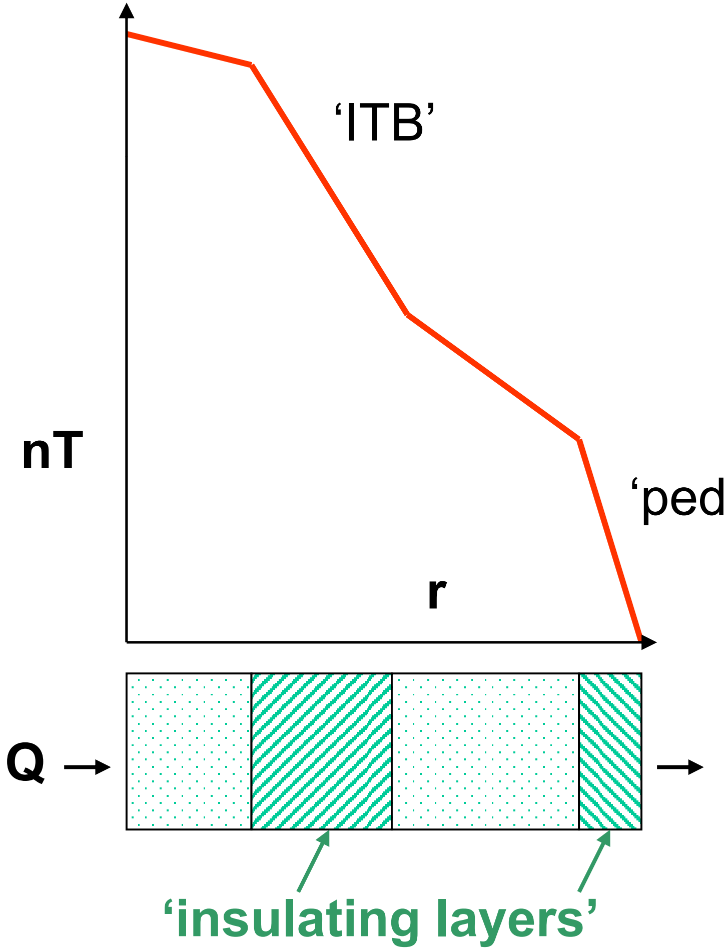
$\delta n/n \sim 0.1\%$

$\delta T/T \sim 0.3\%$

$\lambda >> \rho_i$

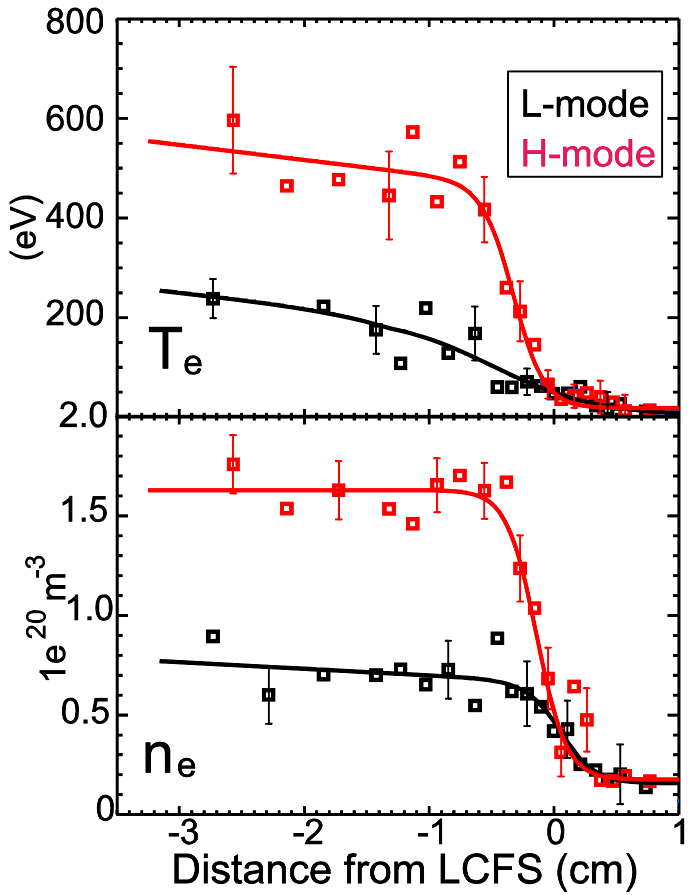
Well reviewed in talks by F. Wagner, S. Cowley, F. Jenko, and others to come in this Programme (eg T.S. Hahm, G. Tynan, J. Weiland).

# Regions of much reduced $\chi$, D, ‘transport barriers’ can occur!



- With constant heat flux, reduced $\chi$ is seen by steeper gradients.
- Can occur in either edge or core. Also in particle transport.
  - **Edge barrier**, or ‘pedestal’ in T, n first seen on ASDEX in 1982.
    F. Wagner *et al*, Phys. Rev. Lett **49** 1408 (1982).
  - Called ‘High Confinement’, or **‘H-mode’**.
- **Core ‘internal’ barriers (‘ITB’s)** first produced with pellets, now many different methods, names.

# Edge barriers can be very narrow and steep

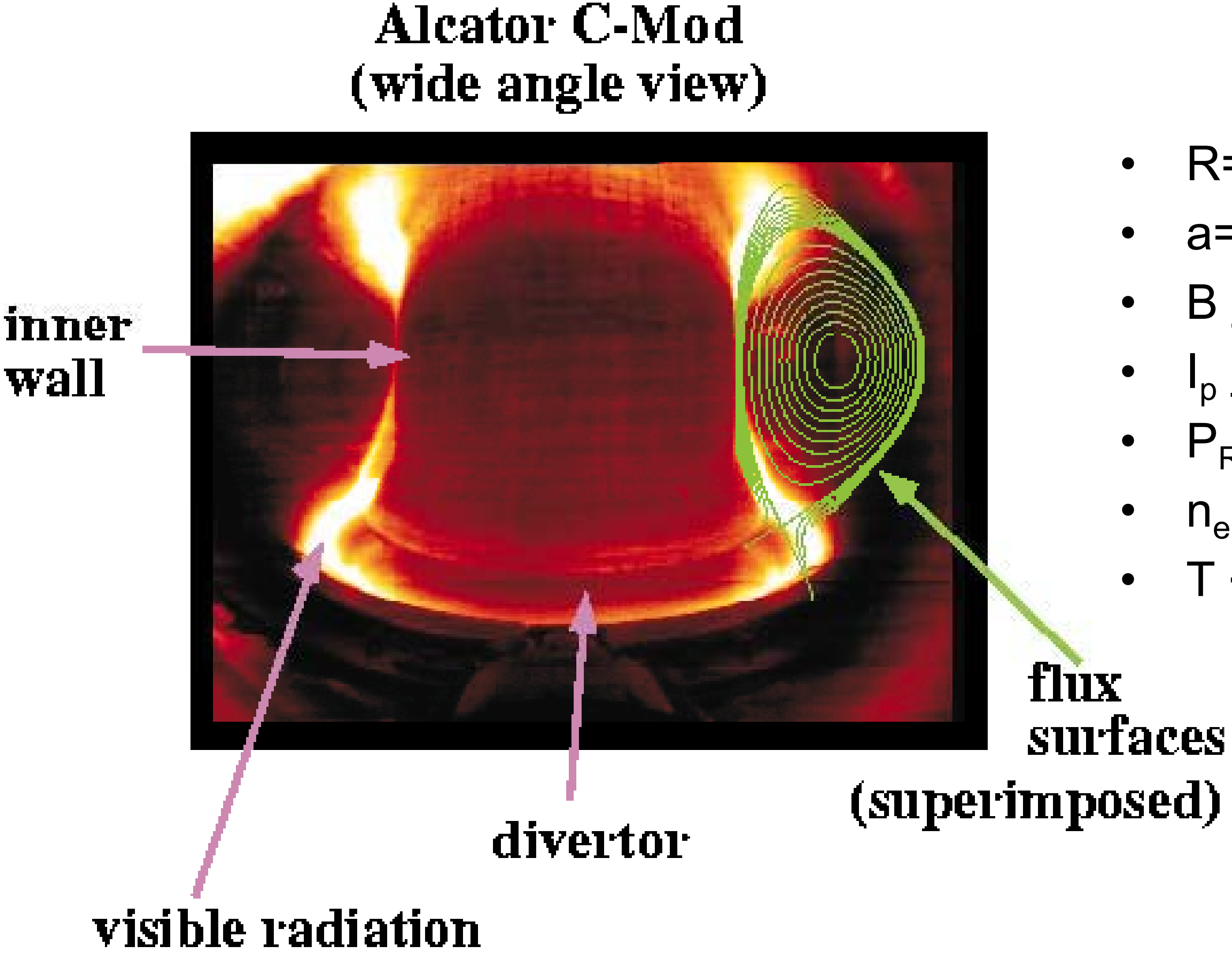


- **Barrier seen in electron and ion density, electron and ion temperatures, impurities**.
- *Width < 5 mm* on C-Mod, few cm on most other tokamaks
- Gradients ~ 50-100 keV/m.

**C-Mod Thomson scattering**

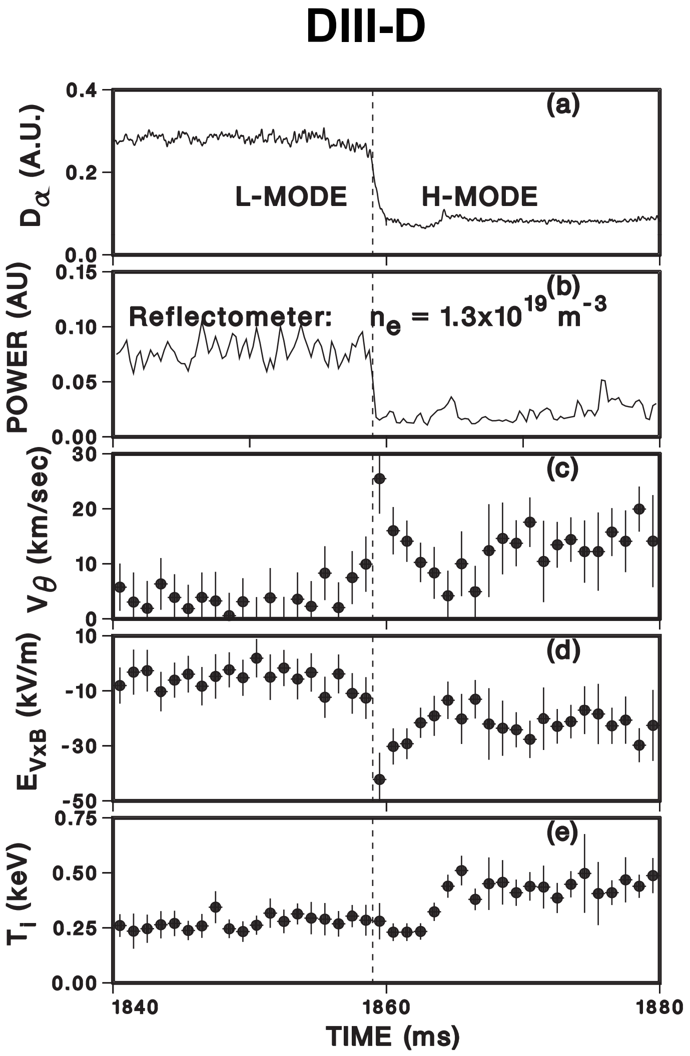
J.W Hughes; from R. MacDermott, Phys. Plasmas **16,** 056103 2009

# Alcator C-Mod (MIT)



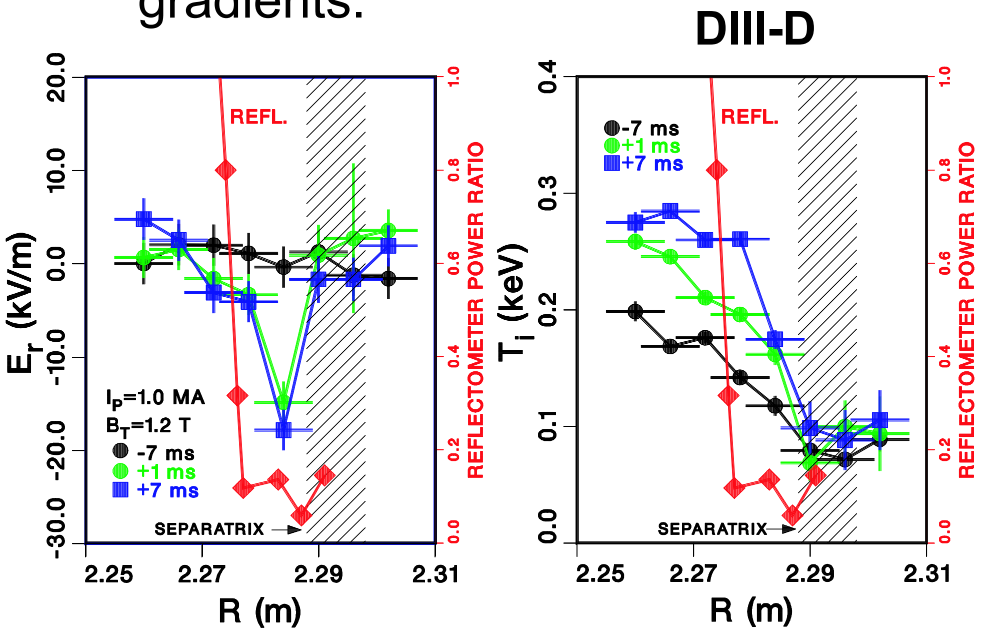
- $R = 0.68$ m
- $a = 0.21$ m
- $B \leq 8$ T
- $I_p \leq 1.5$ MA
- $P_{RF} \leq 5$ MW
- $n_e \sim 10^{20}$-$10^{21}$ $m^{-3}$
- $T \sim 1$-$6$ keV

# Local fluctuations decrease, and $E_r$ well develops, in the region of the transport barrier



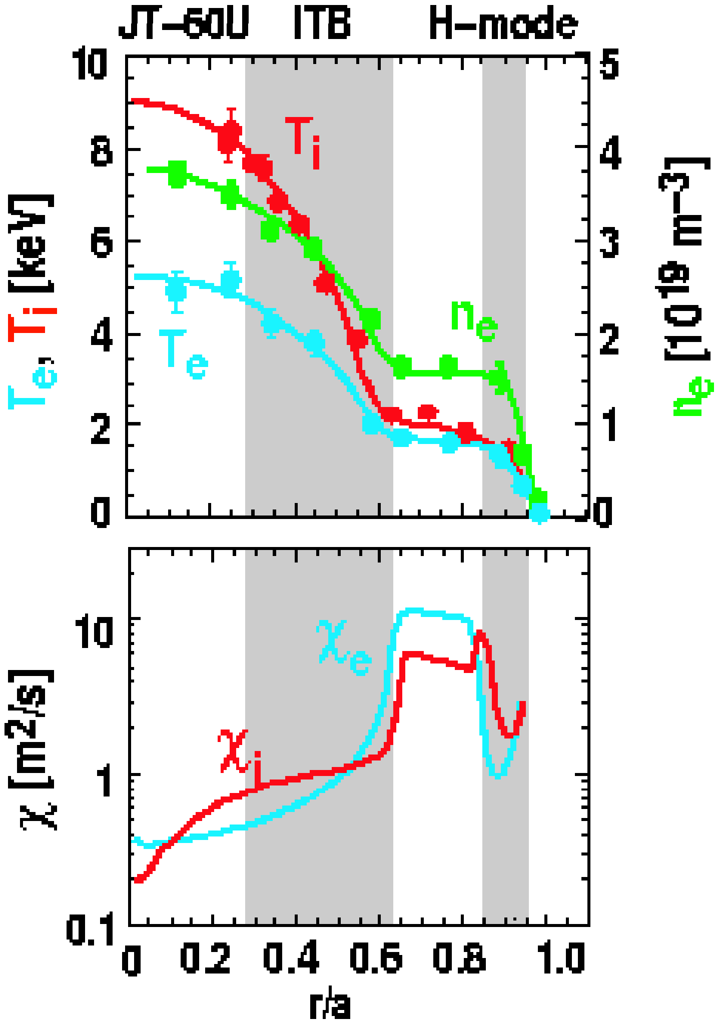
Doyle et al, Phys Fluids B 3(8), 1991.

- Measured by reflectometry, probes, other diags.
- $\tilde{n}_e$ can decrease in ~ 100 $\mu$s.
- Suppression corresponds to region of $E_r$ shear, steep gradients.



Doyle et al, IAEA, 1992.

# Transport and turbulence can be very low in barriers!

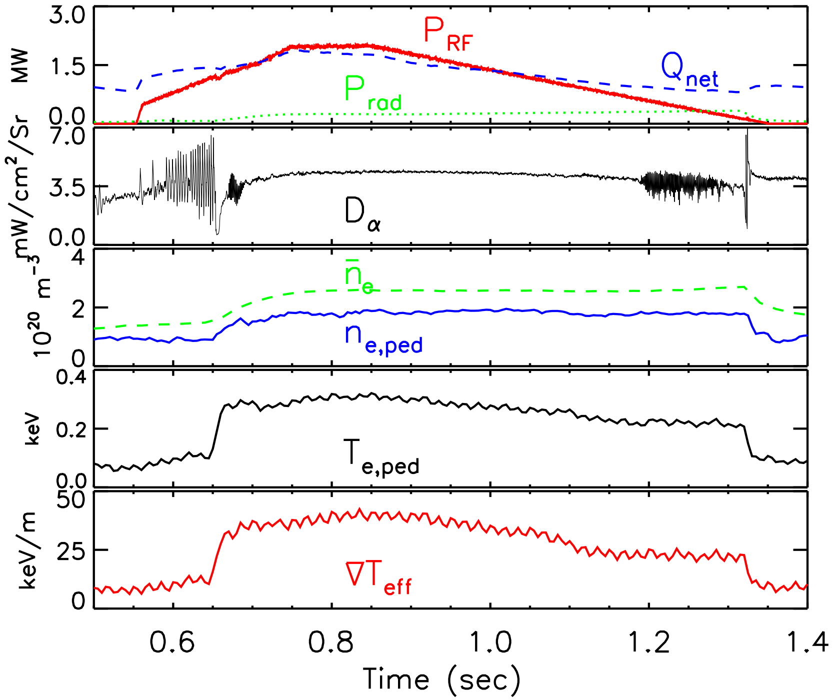


- **Ion, particle transport in barrier often reduced to neoclassical levels!**
- Measured turbulence drops dramatically in barriers, despite high input powers. **WHY?!**

# How are edge transport barriers obtained?

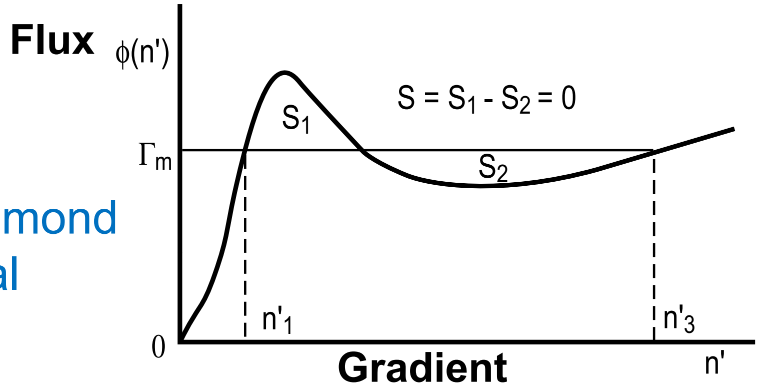
- Normally, turbulence and transport *increase* as input power are raised.
- Counter-intuitively, H-mode barrier forms at HIGH input power.  “L-H Threshold”.
- There is typically hysteresis-lower power for H-L back-transition.

- C-Mod experiment

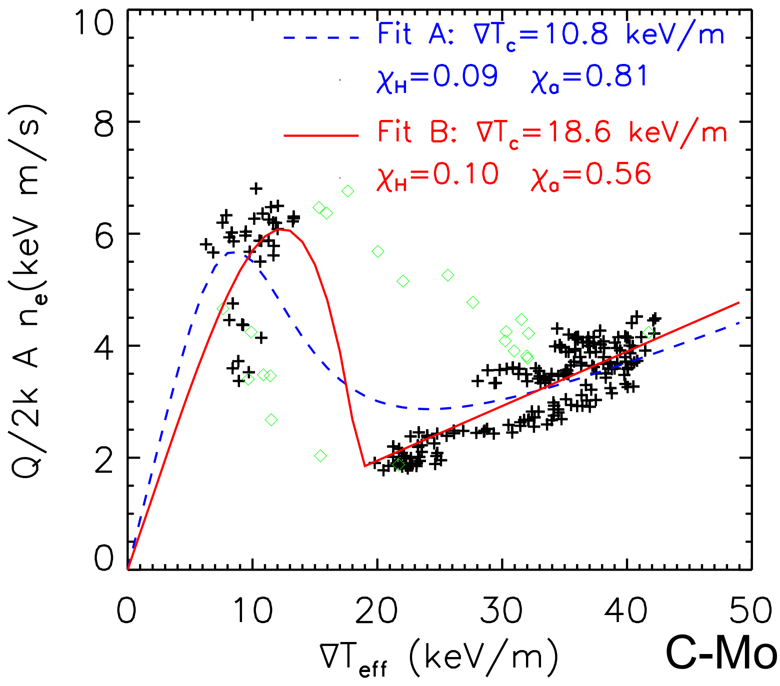


# Above a minimum ‘threshold’ power, transport bifurcates.

Diamond et al



- At certain power flux, get a sudden **bifurcation** in local parameters, transport.
- “Threshold power” is rather scattered, shows big hysteresis.



C-Mod data

- Real physical threshold likely in local plasma parameters (eg. edge T or gradient)

Hubbard, Carreras et al PPCF 44 (2002) A359.

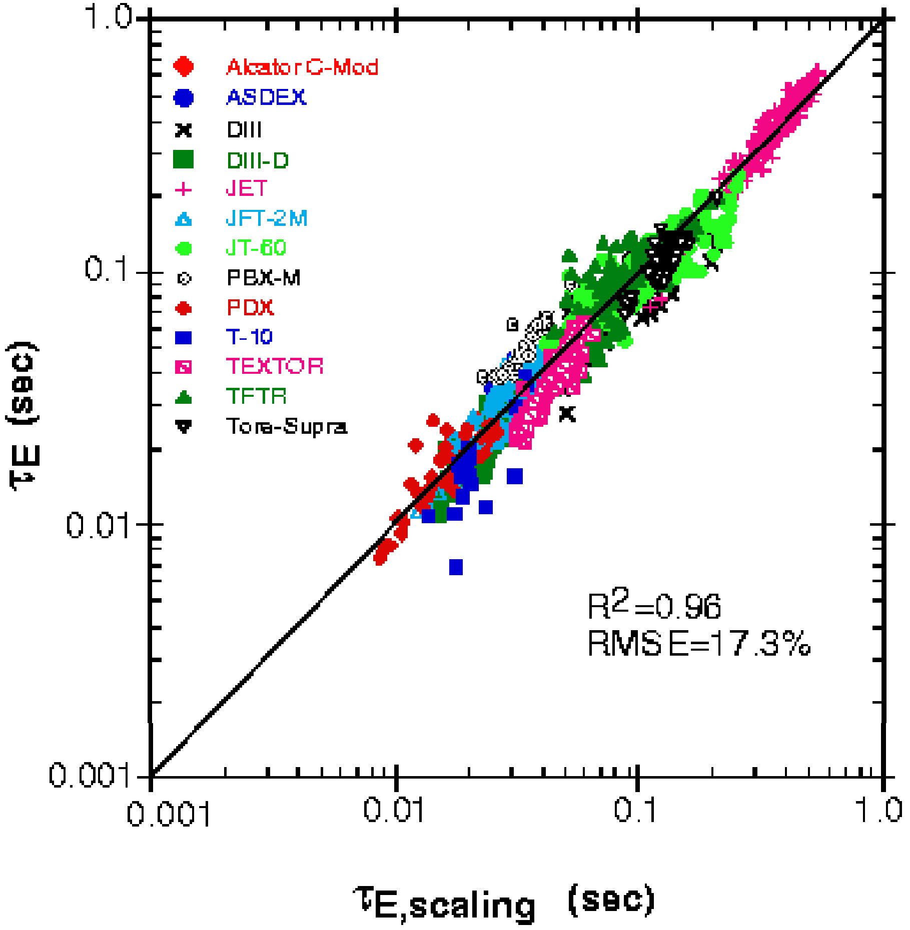
# Importance of edge transport barriers for fusion experiments

Edge Transport Barriers are crucial for fusion experiments, and the subject of much past and present research. Two big reasons:

- **Good news:** Major increase in energy confinement.
- **Problem:** Heat flux from Edge Localized Modes (ELMs)

# Global confinement scalings without barrier (now called “L-Mode”) show strong power degradation.

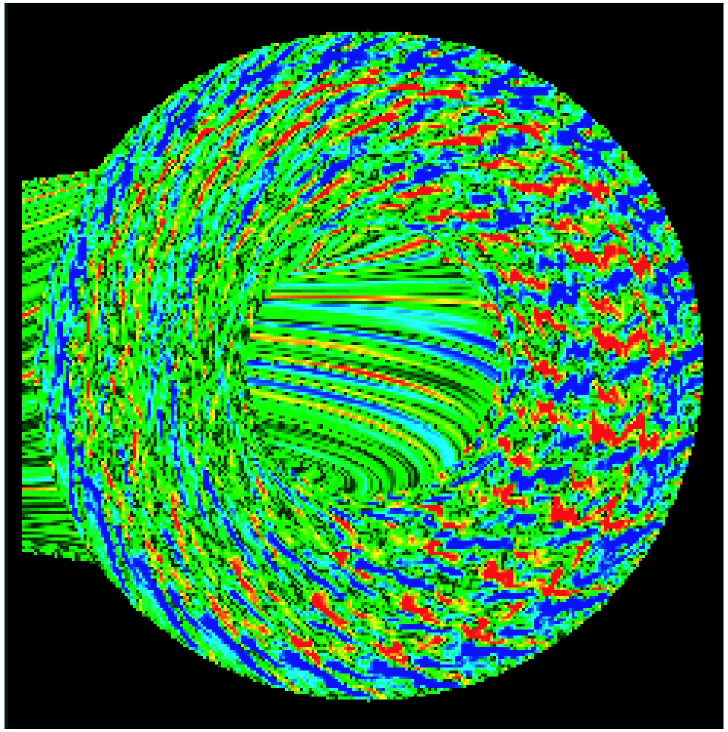
$$\tau_E = 0.037 I_p^{0.74} B_T^{0.2} \kappa^{0.67} R^{1.67} (R/a)^{-0.31} \bar{n}_e^{0.24} M_{eff}^{0.26} P^{-0.57}$$



S. Kaye and ITER conf. group, 1997

- **$\tau_E$ decreases with $P^{-0.57}$** (more heating gives more transport!)
- **But $\tau_E$ also increases with R, $I_p$**
    - To compensate, need to build much bigger tokamaks.
- Projections based on 1970s, early 80’s L-mode confinement were pessimistic about reactor economics.
- ~ 2X improvement in H-mode made a big difference. ITER AND NEARLY ALL CURRENT REACTOR CONCEPTS RELY ON H-MODE!

# Physics behind importance of the narrow edge barrier is profile "stiffness"



No ExB flow

R.E. Waltz et al., Phys. Plas. 1, 2229 (1994)

Simulation of ion temperature gradient-driven turbulence, in annulus 160 $\rho_i$ wide.

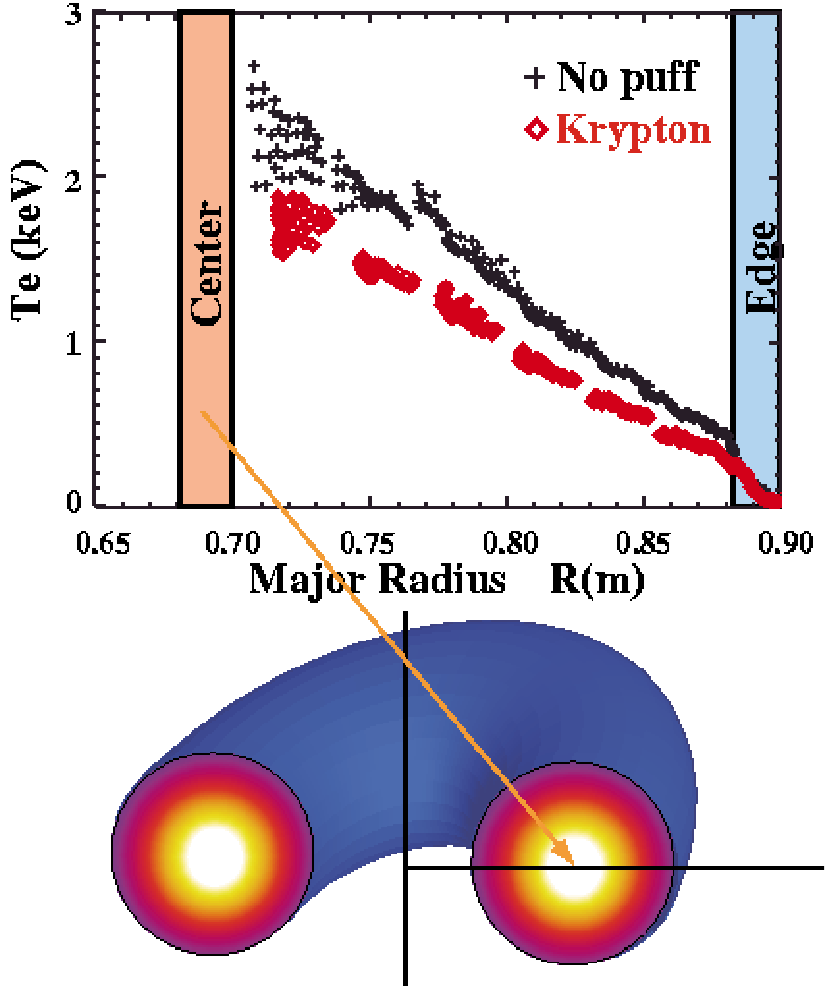
- 'Ion Temperature Gradient' (ITG or $\eta_i$) driven mode dominates ion transport in core; mainly *density* fluctuations.
- Fair agreement with $T_i$ profiles in many experiments.
- Find a **'critical gradient scale length' R/$L_{T,crit}$** above which turbulence, transport increase sharply.

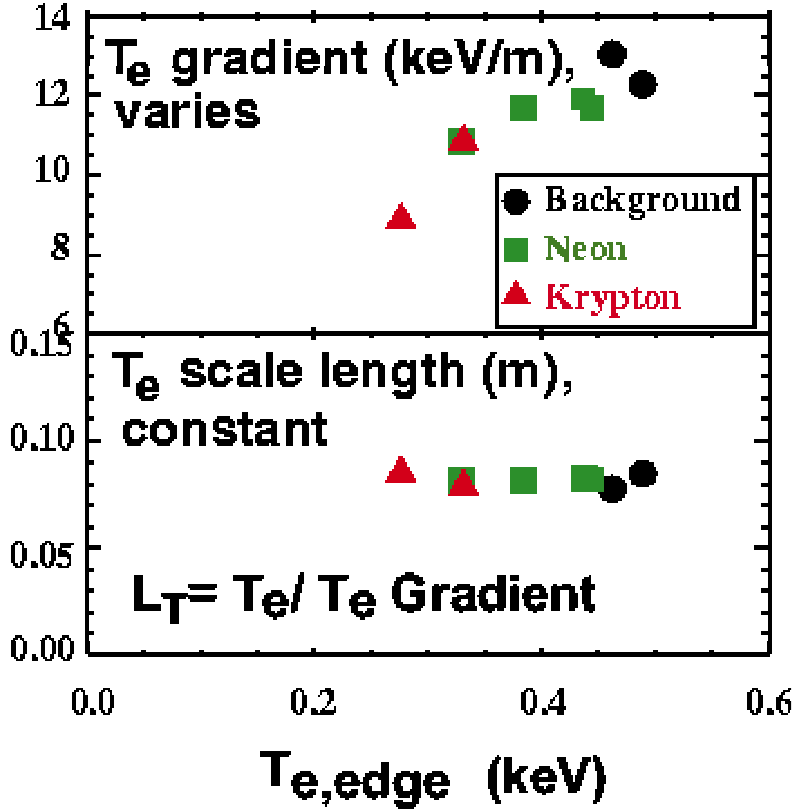
$$L_T \equiv \frac{T_i}{\nabla T_i}$$

- $$\frac{R}{L_T} = \frac{\nabla T_i}{T_i} R$$

- This implies a **'stiff' T profile** shape, sensitive to edge T.

# Profile 'Stiffness' is widely observed experimentally



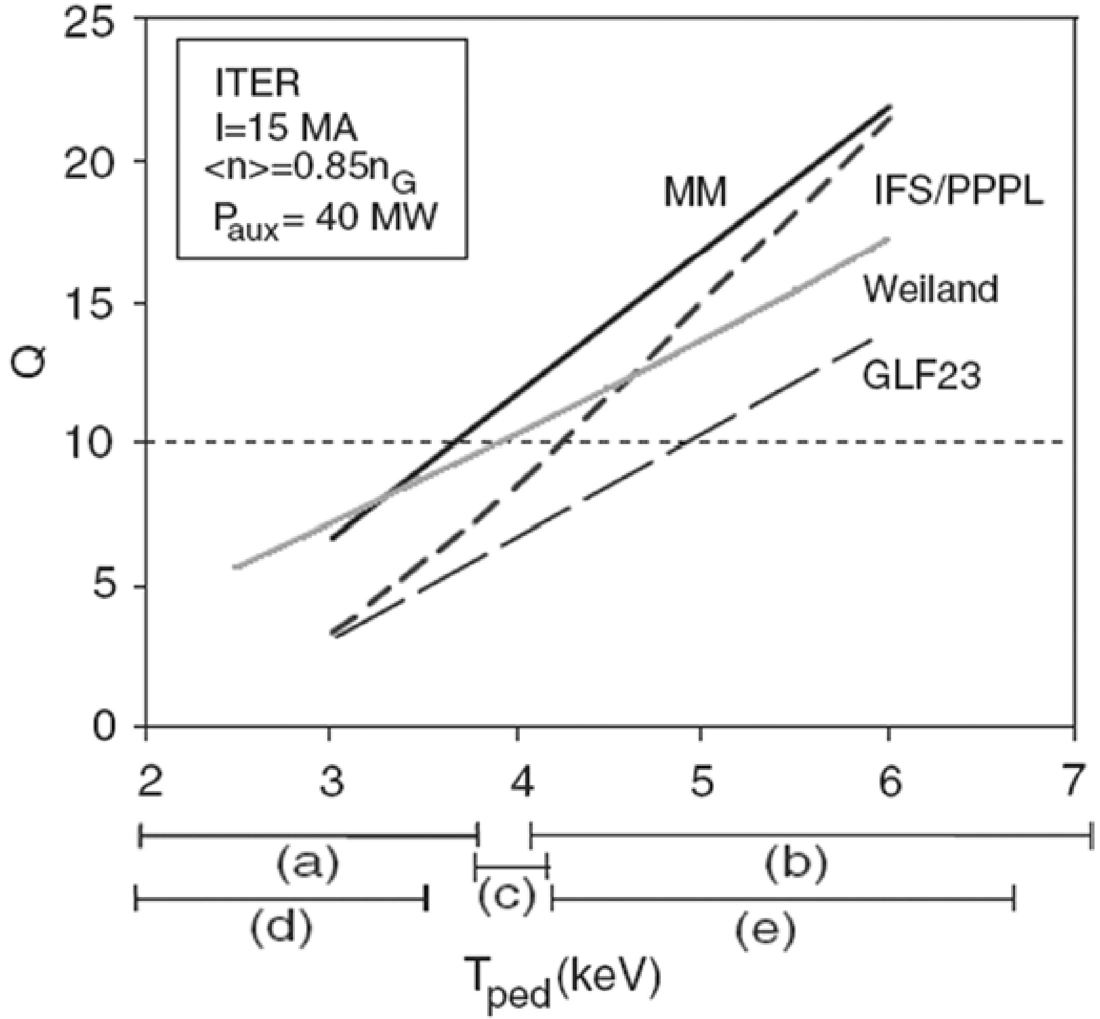


- In C-Mod expt, edge was **cooled** via radiation,
  - core T gradient decreased.
  - $L_T$ stayed constant.

Hubbard, Lipschultz et al, EPS 1999

# $T_{ped}$ has a huge impact on performance of ITER.

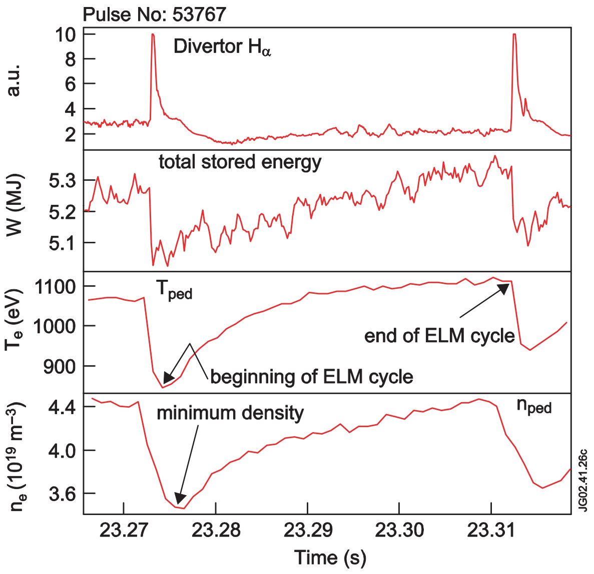
- While the degree of ‘stiffness’ varies between models, all show strong dependence on edge T.
- Range in Q due to uncertainty in $T_{ped}$ (a to e) is much bigger than differences between core models (lines).
- As will be discussed later, it is very important to know $T_{ped}$. Present predictions are either empirical or semi-empirical, and vary widely.



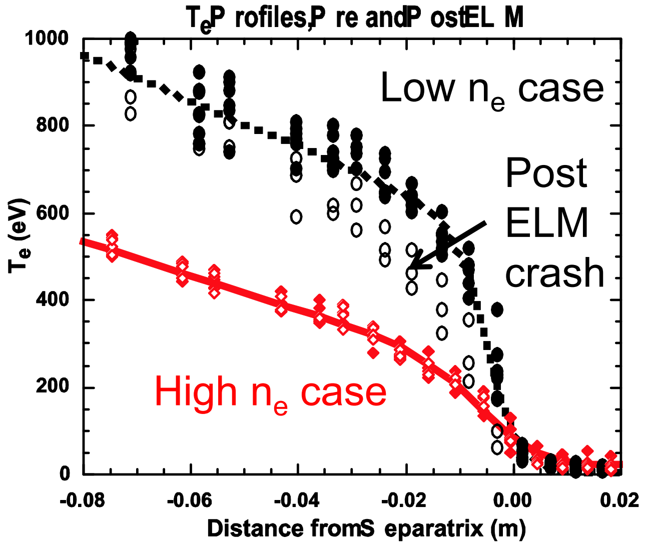
E. Doyle et al, Progress in ITER Physics Basis, Nuclear Fusion 47 (6) Ch. 2. (2007)

# EDGE LOCALIZED MODES are also important – both needed and a concern.

- The strong reduction in edge D, $\chi$ in H-mode means that both density and pressure gradients steepen continuously. Local current also increases due to lower $\nu^*$, higher bootstrap.
- This cannot continue indefinitely. Eventually, pedestal hits a macro (or micro) stability limit.
- Macro-instabilities are generically called “**E**dge **L**ocalized **M**odes”, cause periodic relaxation of the gradient.



**Cycle of large “Type I” ELM on JET**
from Saibene et al, PPCF 44 1769 (2007)



**Pre-and post ELM $T_e$(R) on DIII-D**
from Loarte *et al* 2003 PPCF **45** 1549-1569

# Concern with ELMs is that they release bursts of energy; large ELMs on ITER could erode the divertor

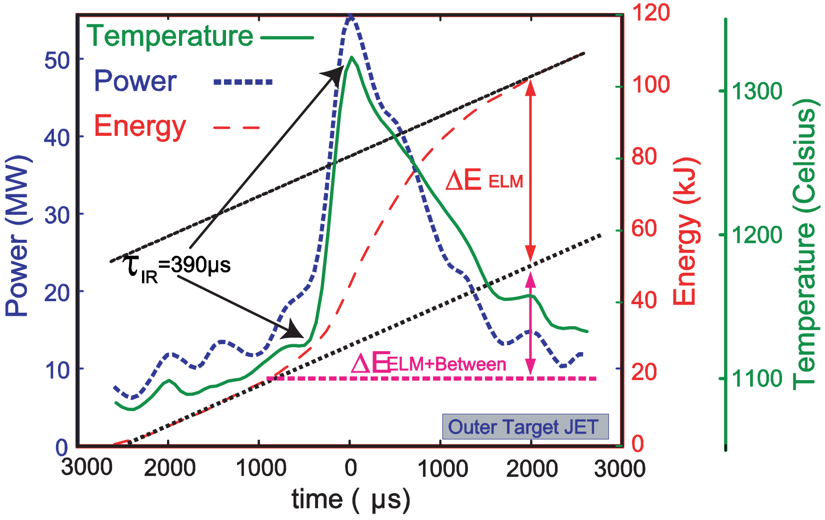


**Figure 8.** Temporal evolution of the divertor surface temperature, deposited ELM power and energy onto the JET outboard divertor target for a typical Type I ELM [162].

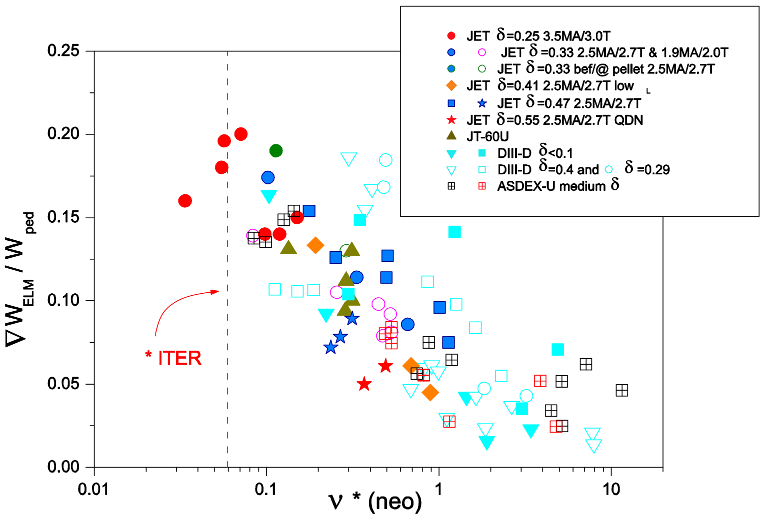


**Figure 11.** Normalized ELM energy loss ( $W_{ELM}/W_{ped}$) versus pedestal plasma collisionality for a large range of Type I ELMy H-mode plasmas in ASDEX Upgrade, DIII-D, JT-60U and JET including various plasma triangularities, ratios of $P_{INPUT}/P_{L.H}$ and pellet triggered ELMs.

ITER Physics Basis 2007, from T. Eich et al. J. Nuclear Materials 313–316 (2003) 919–924

Loarte *et al* 2003 *Plasma Phys. Control. Fusion* **45** 1549-1569

ITER limit is now $\delta W \sim 1$ MJ << $W_{ped}$

# Some type of edge density relaxation mechanism is *needed* to maintain a steady, clean H-mode.

## Continuous fluctuations or small ELMs ideal.

### ELM-free H-mode

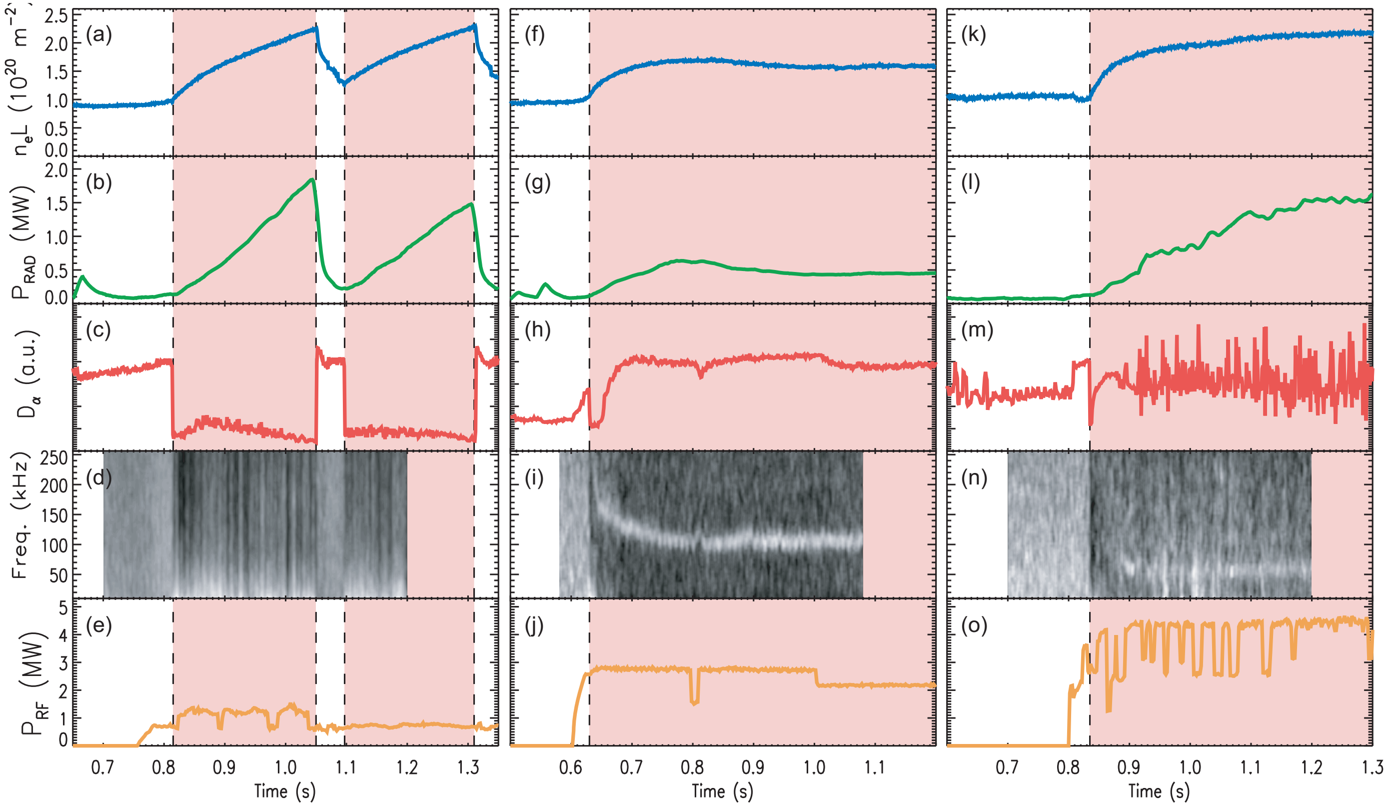
- Low particle transport, transient H-modes.

### Enhanced D-Alpha (EDA)

- Quasicoherent mode leads to steady $n_e$.

### Small ("Type II"?) ELMs

- Small ELMs on top of high $D_{\alpha}$.
- Occurs at higher pressure than EDA.
- Also gives steady $n_e$.



Examples of H-mode regimes on C-Mod.

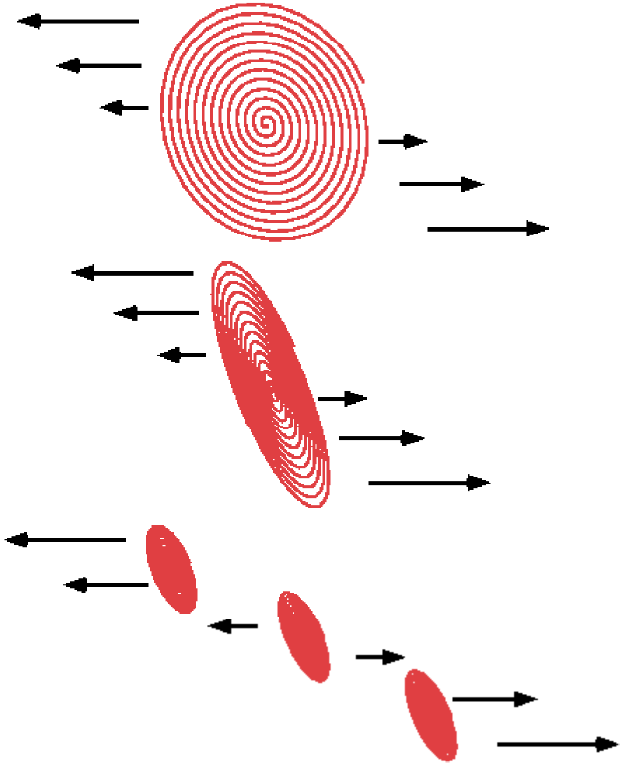
Other small or no ELM regimes observed on other tokamaks.

# Overview of key transport barrier physics.

*What is the present understanding, and what are open scientific issues for current research?*

1. L-H transition mechanism and thresholds
2. Pedestal width, gradient and height.
3. ELM physics, avoidance and control.

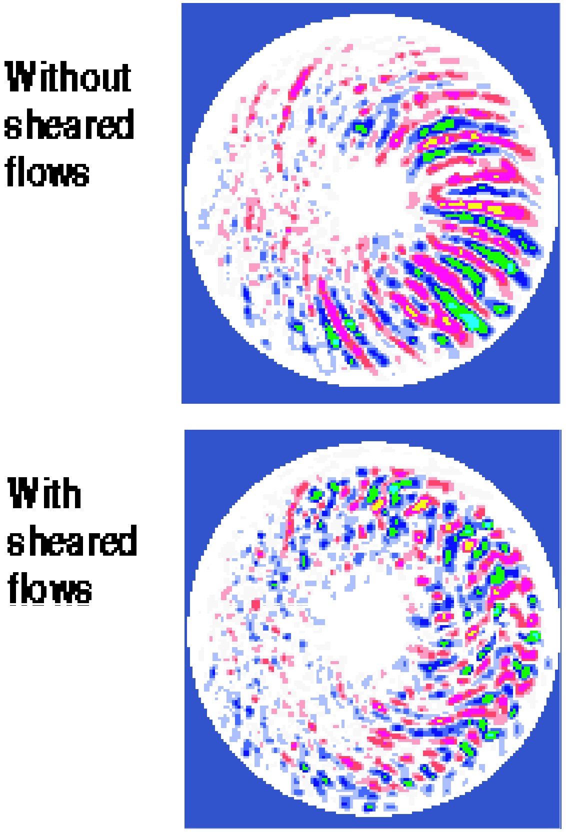
# Turbulence is thought to be suppressed by **plasma-generated flow shear**



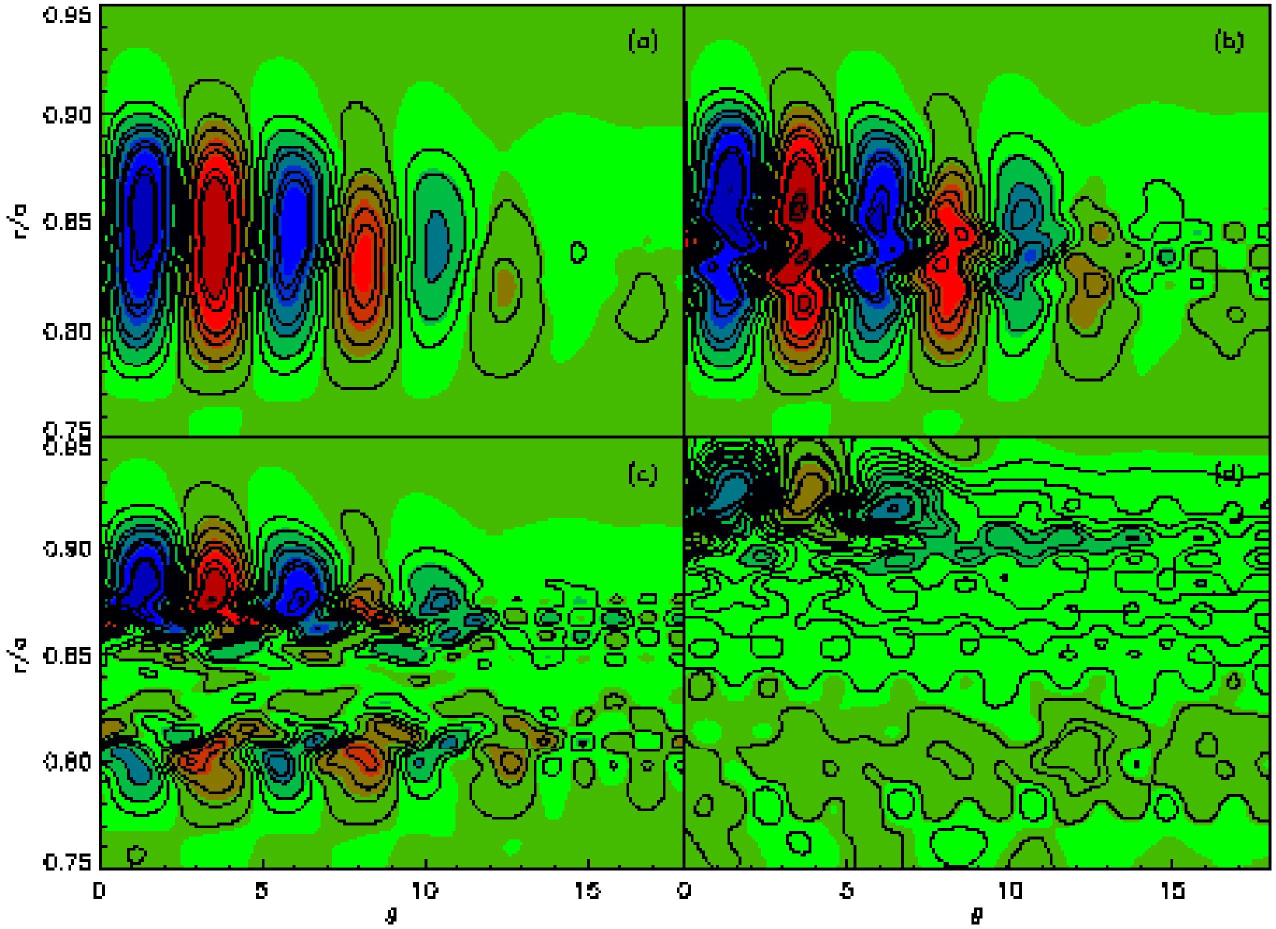
- •Variation in velocity compresses turbulent eddies.
- •Large eddies break into smaller radial scales.

**Turbulence simulations**

(gyrokinetic code, Z. Lin et al)



# Simplified simulation of turbulence suppression.



A) Turbulence grows.

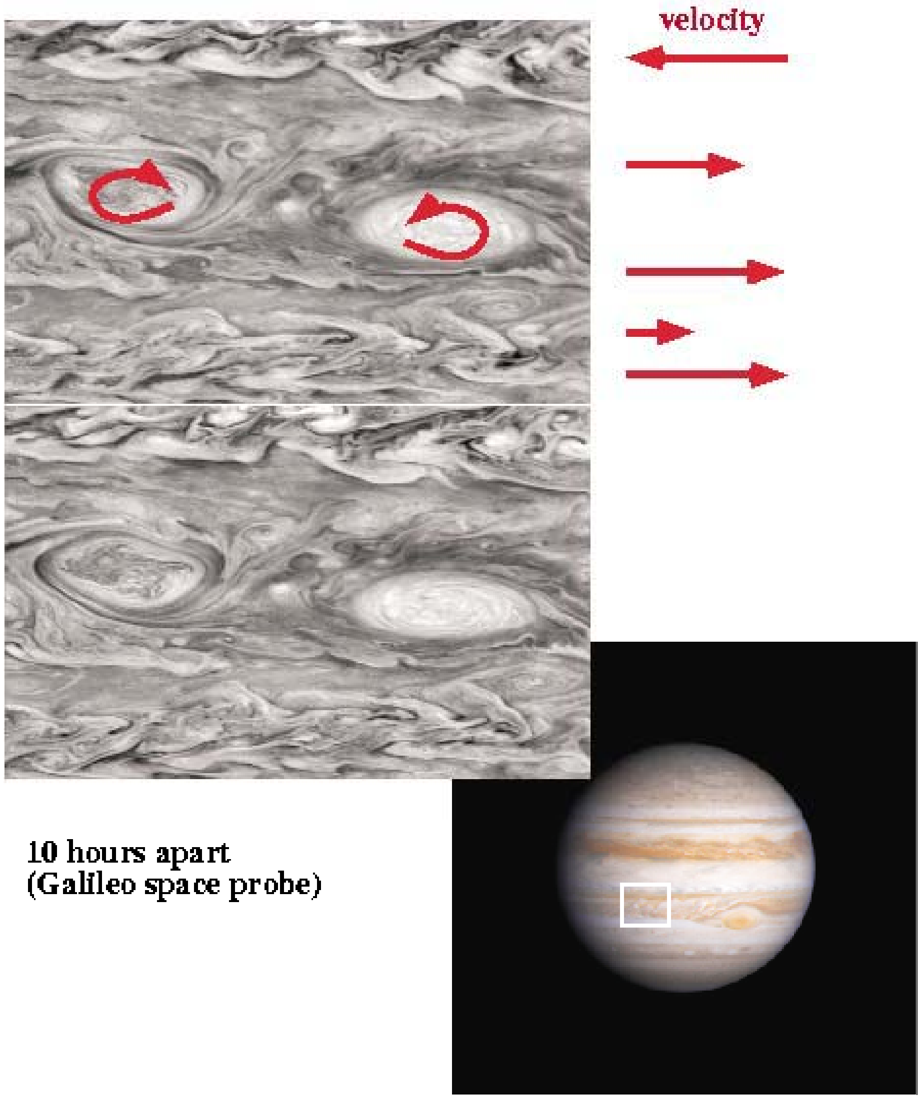
B) Turbulence makes velocity shear grow, distorts fluctuations.

C) Eddies are sheared.

D) Fluctuations are suppressed.

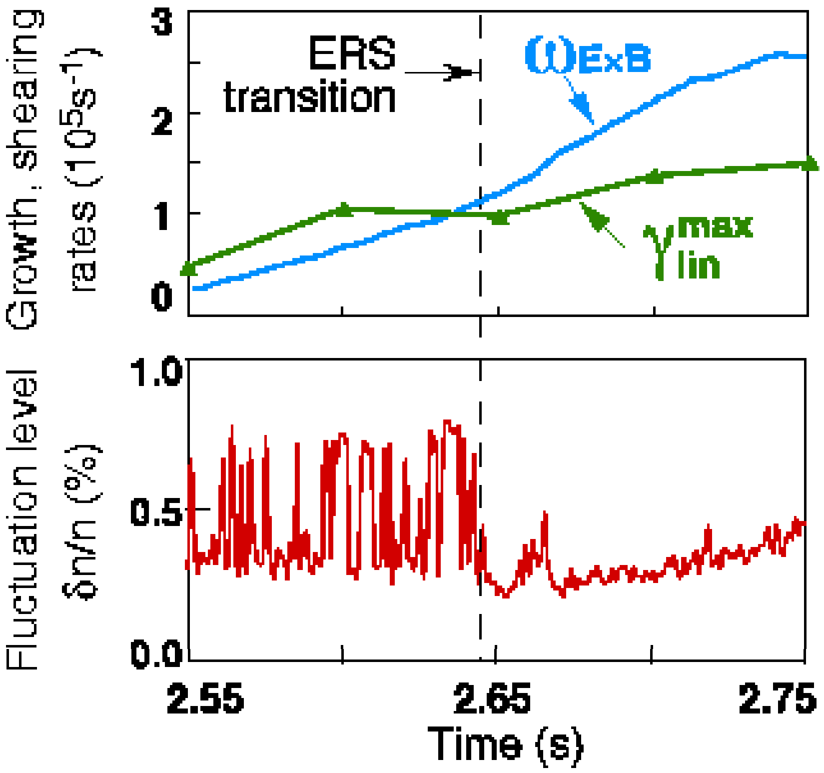
Charlton, Carreras, Lynch *et al*, Oak Ridge NL, 1994.

# Similar physical mechanism is seen in the atmosphere of Jupiter



10 hours apart
(Galileo space probe)

# Flows can be driven by $E_r$ x B



**Internal transport barrier**

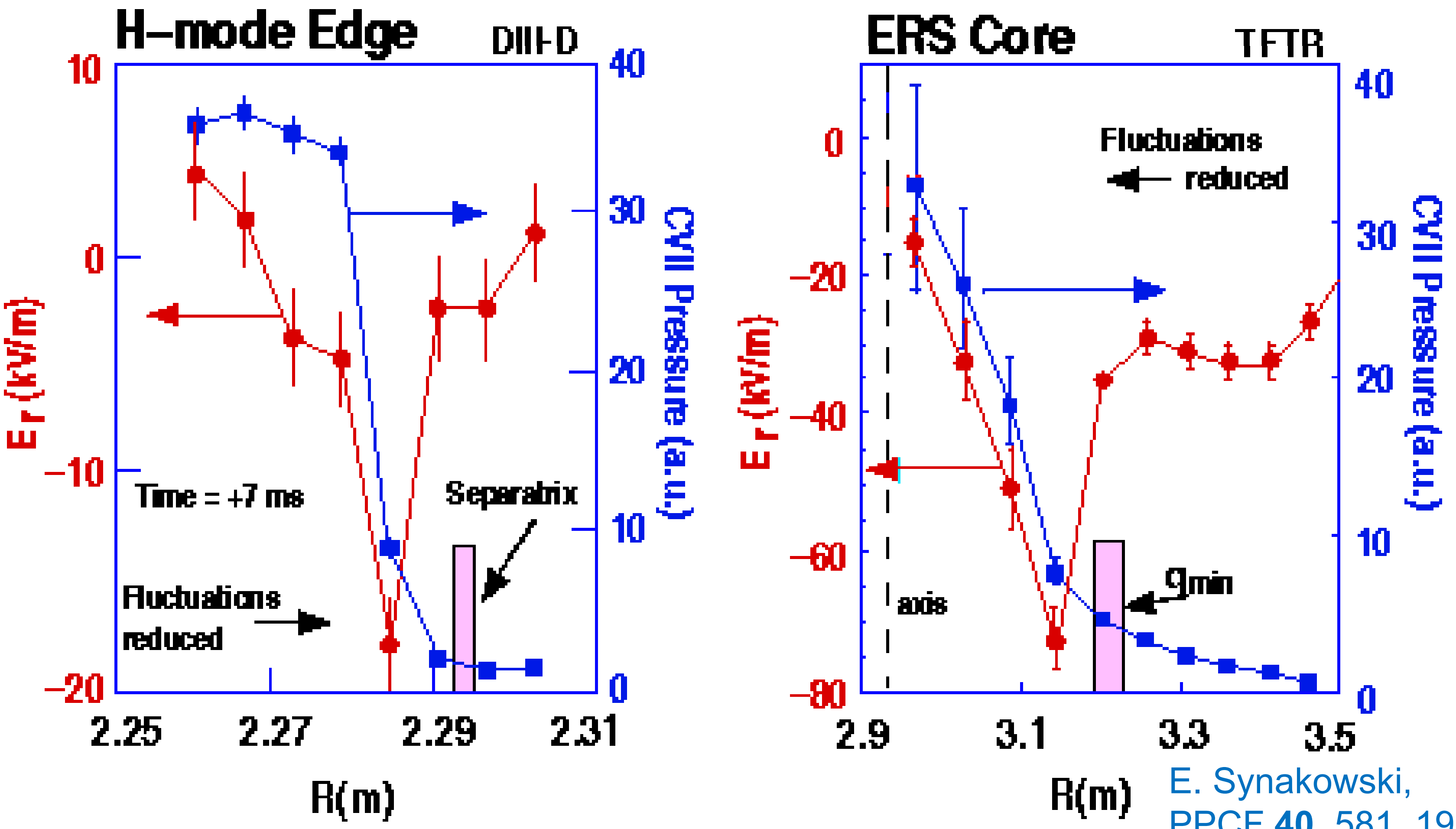
**TFTR Experiment** (E. Mazzucato, 1996)

- $E_r$ shear may be on a large radial scale, or small-scale ‘zonal flows’ generated by turbulence itself.
- **Radial electric field $E_r$** set by pressure gradient, poloidal and toroidal flows.

$$E_r = \frac{\nabla P_i}{Z_i e n_i} - v_{\theta i} B_\phi + v_{\phi i} B_\theta$$

- *Many* possible triggers, feedback loops.
- Very roughly, turbulence is suppressed when **ExB shearing rate** $\omega_{ExB} > \gamma_{max}$. **max. turbulence growth rate**

# Many parallels between core, edge barriers



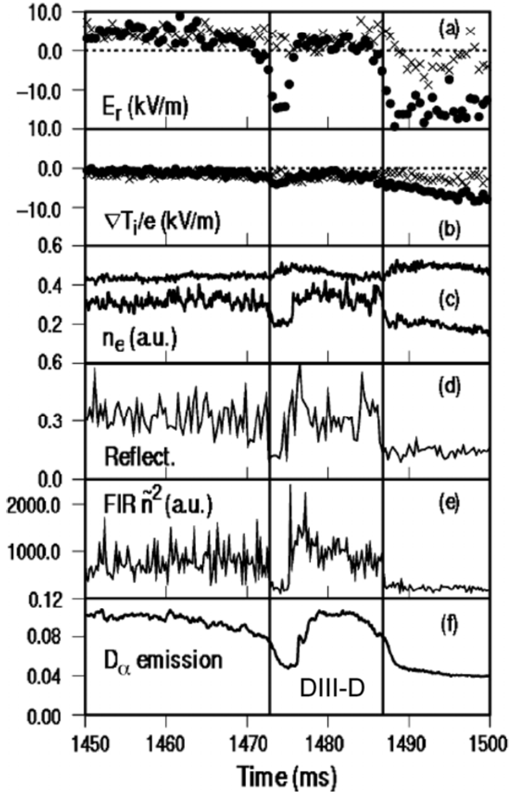
E. Synakowski, PPCF **40**, 581, 1998.

- Strong $E_r$ shear at the barrier in both cases.
- Magnetic shear may also play a role.

# Experiments and theory have established many key features of L-H transitions

- H-modes can be triggered by external $E_r$ shear. [Textor biasing expts, eg. Jachmich et al, PPCF **40** (1998) 1105–1113.]
- Turbulence decorrelates, and fluxes can dramatically reduce, at the transition when ExB shearing rate exceeds $\gamma_{max}$. [eg. TEXT, Ritz et al, Phys. Rev Lett. 65(20) 1990]
- *In fully developed H-Mode,* grad P term usually dominates, $E_r$, and is large enough to suppress turbulence.
- But, $E_r$ changes first, and *at the L-H transition* other terms (eg $V_{pol}$) may be more important. (eg, DIII-D, Burrell et al). Many variables may thus affect transition conditions and dynamics.

See review by F. Wagner, Plasma Phys. Control. Fusion **49**, 12 B11 2007



**DIII-D.**
R. Moyer et al, Phys. Plasmas 2 (1995) 2397.

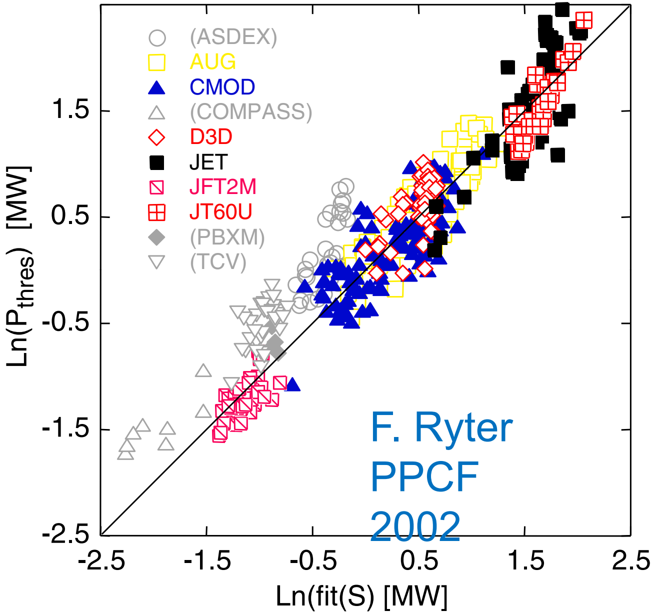
# Still not a detailed *predictive* understanding of transition physics or threshold

Good review by J. Connor and H. Wilson. (PPCF 42(2000) R1-R74.)

- *230 references, 33 local threshold criteria, 22 power threshold scalings!*
- **Theories fall into 3 main groups:**
  - Suppression of certain edge instabilities above certain parameter range. *(many possible instabilities,* $\gamma_{max}$*!)*
  - ExB flow shear stabilization of turbulence. *(many terms in* $E_r$*xB)*
  - Combined scenarios, eg. Suppression of main instability allows pressure gradient to increase, leading to shear stabilization.
- Difficulty in predicting a threshold is partly due to limited understanding of L-mode transport in this near-edge region.
- Likely *many* factors influencing, depending on regimes (eg neutrals, x-point geometry, impurities.)
- Not yet a robust, reliable predictive numerical simulation with relevant geometry and complete physics.

# Global power threshold scalings have large uncertainty, and small margin for ITER

- Global L-H power: *"How much power will it take to make an H-mode?"*
- Generally increases with density, field; exponent varies. Depends on BxGrad B drift
- Considerable scatter, even on individual experiments – affected by details of geometry, wall conditions.
- Latest scaling (Martin 2008) shows ITER power (73 MW) should exceed L-H threshold in D and D-T, but *not by a large margin*.



F. Ryter PPCF 2002

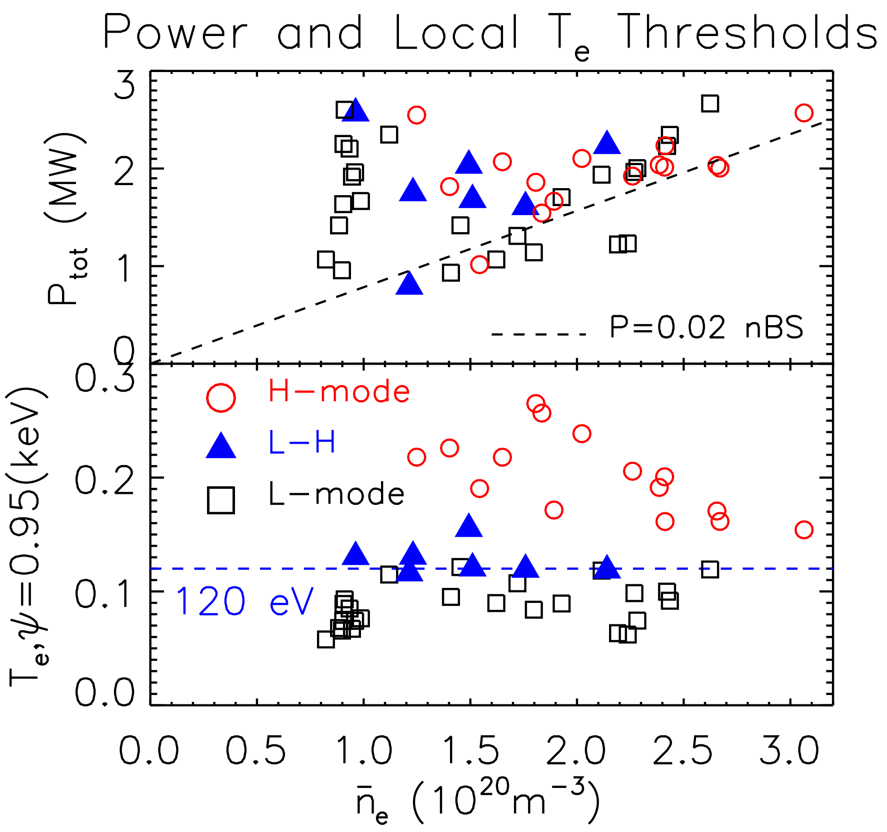
$P_{thres} = 0.043\, n_e^{0.75} B_T^{0.71} S^{0.99}$

$$P_{thresh} = 4.3/A \cdot n_e^{0.78} B_T^{0.77} a^{0.98} R^{1.0}$$

| $\bar{n}_e$ | $B_T$ | $P_{thresh}(D_2)$ | $P_{thresh}(H_2)$ | $P_{thresh}(DT)$ |
|---|---|---|---|---|
| $(10^{20} m^{-3})$ | (T) | (MW) | (MW) | (MW) |
| 0.5 | 5.3 | 55 | 111 | 44 |
| 1.0 | 5.3 | 95 | 190 | 76 |

# More insight into physics may be obtained by looking at local edge parameters at L-H.

- Studies aim to answer: *What local conditions need to be met for an L-H transition to occur?*
- From earliest ASDEX observations, a high edge T is seen to favour H-mode.
- However, this too shows variation with machine parameters and, conditions; likely a related variable, or multiple variables.
  - For example: $T_e$ or $T_i$ gradient, or related dimensionless variables.



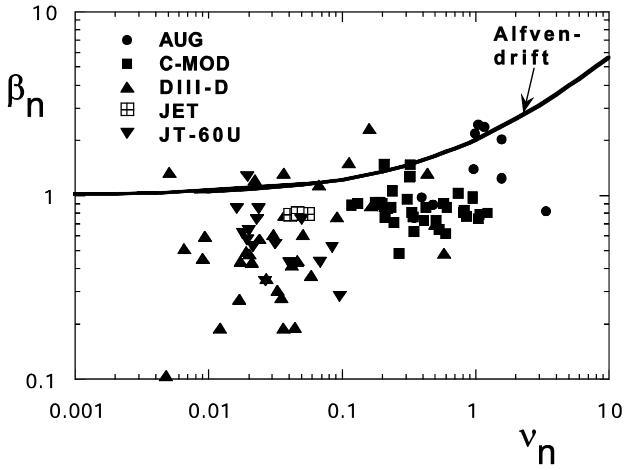
**C-Mod**

Hubbard et al, APS 1997, PPCF 1998

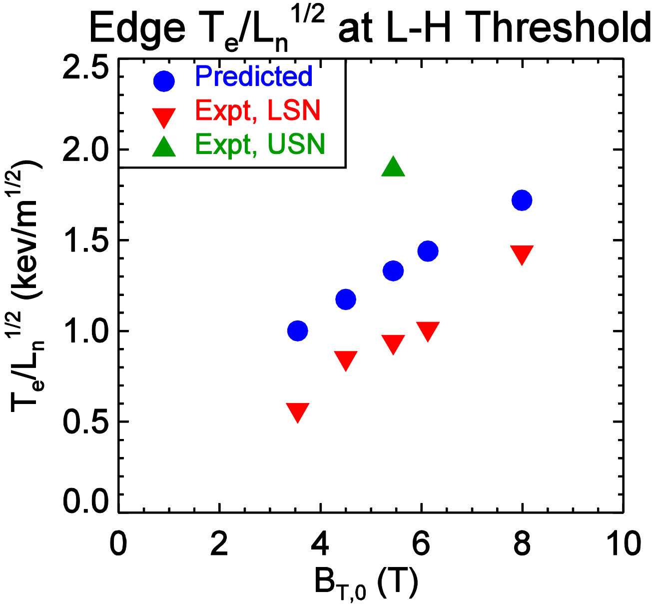
# Local studies have been useful in narrowing down possible mechanisms

As a two of many examples:

- Transition occurs over a wide range of edge collisionality. Does not agree with models which require $\nu^* \sim 1$.
  Could be consistent with drift-Alfven stability.
- $T_e$ threshold, and trends with B, are roughly consistent with a model based on suppression of drift waves by zonal flows . [Guzdar, Phys. Rev. Letters **89** (26), (2002) 265004 ]
  But, this does not capture the Bxgrad B drift dependence of $T_{LH}$ – would need to add mean flows.



ITPA study, IAEA 1998



**C-Mod.** Hubbard EPS 2004

# Complexity of L-H transition points to need for more complete (and challenging) numerical simulations

- **Models likely need to include:**
  - All relevant L-mode turbulence modes.
  - 2-D neutrals and fuelling.
  - X-point geometry.
  - Open and closed field lines.
  - Neoclassical effects.

- Many researchers are developing and testing increasingly complete and sophisticated first-principles gyrofluid or gyrokinetic models (eg, Scott, Chang, Xu).
  See talks by Jenko, Hahm, others at this workshop.

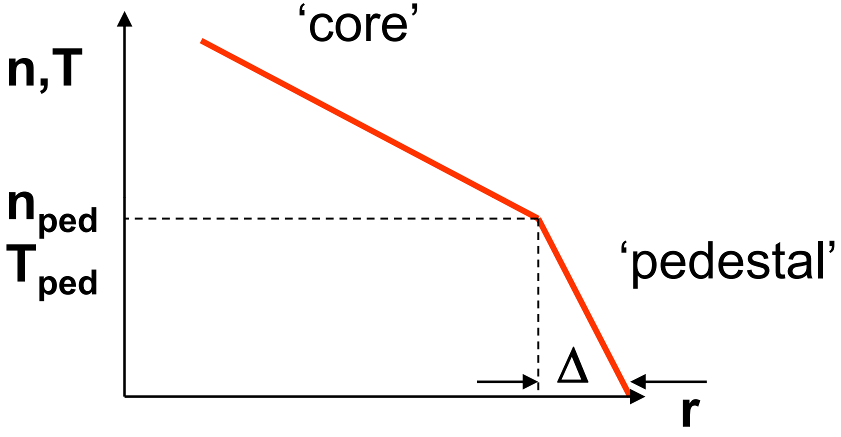
- To date, while some H-mode-like phenomenology has been seen, it has proven a major challenge to simulate a reproducible, self-consistent bifurcation purely arising from the heat and particle flux and resulting turbulence.

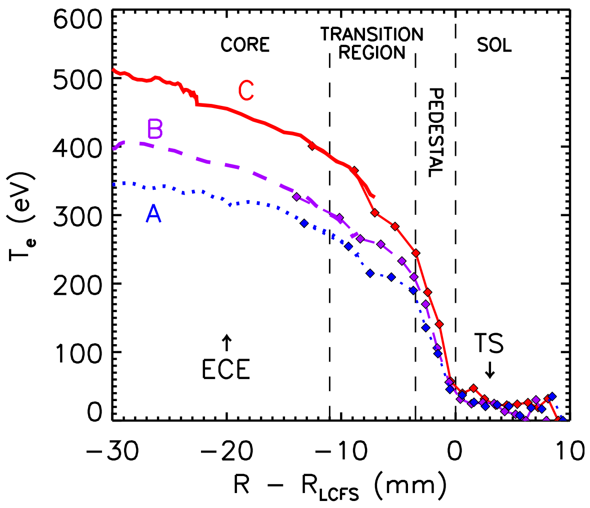
# Physics of Pedestal Structure

- Given the strong dependence of global confinement on the pedestal, it is critical to know

***What are the parameters at the top of the barrier?***

- For simplicity, pedestals scalings are often divided into a **gradient** (set by MHD) and a **width** Δ. *What limits the extent of the barrier??*
- **Some limitations:**
  - Widths of $n_e$, $T_e$, $T_i$, $p_e$ pedestals are similar, but *not* always identical. Often $\Delta_T > \Delta_n$
  - Profile structure can be more complicated than 'cartoon'
  - Grad P limits are not simple 1st stable ballooning
  - Widths and gradients not independent!



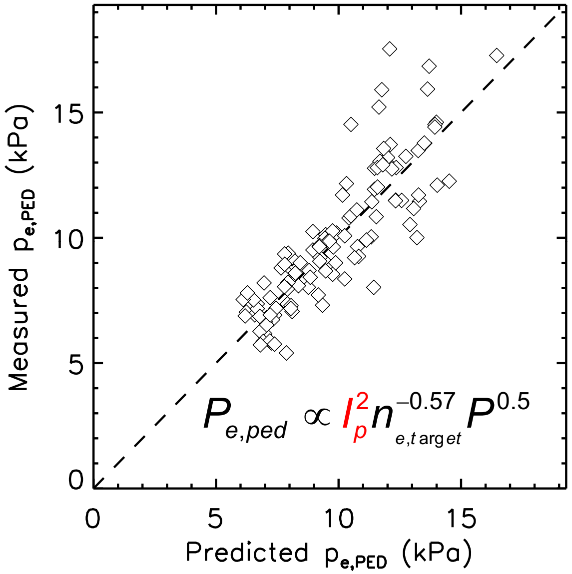


**C-Mod**

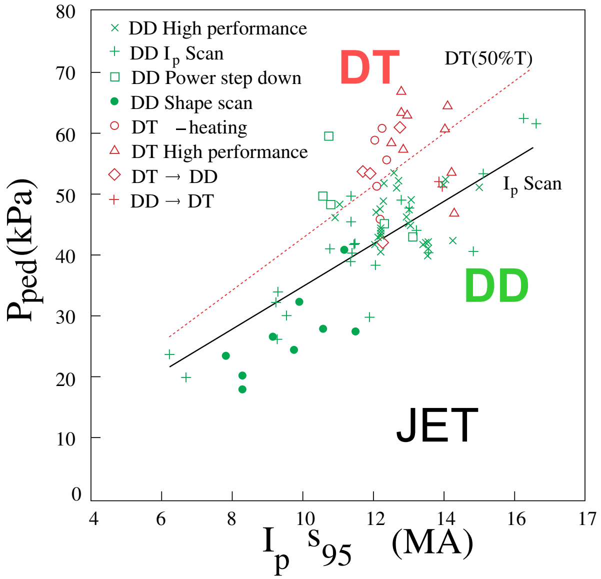
J.Hughes
Phys.
Plasmas
2002

# Pedestal heights on various tokamaks show some common trends

**C-MOD**
Hughes
APS 2001



**JET**
Nave,
PPCF 2000



- Scalings made on DIII-D, AUG, C-Mod, JT60U, JET
- **Pressure pedestal**
  - – Increases with $I_p$
  - – Increases with strong shaping ($\delta$, $s_{95}$ or $q_{95}/q_{cyl}$).
- **Density pedestal**
  - – Increases with $I_p$
  - – Increases with target density, fuelling,
- **Temperature pedestal**
  - – Increases with $I_p$, shaping.
  - – Decreases with $n_e$.
- In most cases, trends are dominated by changes in *gradient*, not width.
- **Widths tend to be ~3-6% of machine size.**

# Attempts at empirical or semi-empirical scalings of pedestal height, width have shown wide variation

- In work prior to ~ 2005, Grad P was usually assumed to scale as 1st ballooning limit.
  - Some 'models' included effect of shape and/or bootstrap current on shear.

- Test various $\Delta$ scalings, eg.
  - Thomsen: $\Delta \sim \rho_{i,pol}^{\mu} R^{1-\mu}$
  - Onjun et al. APS 2001

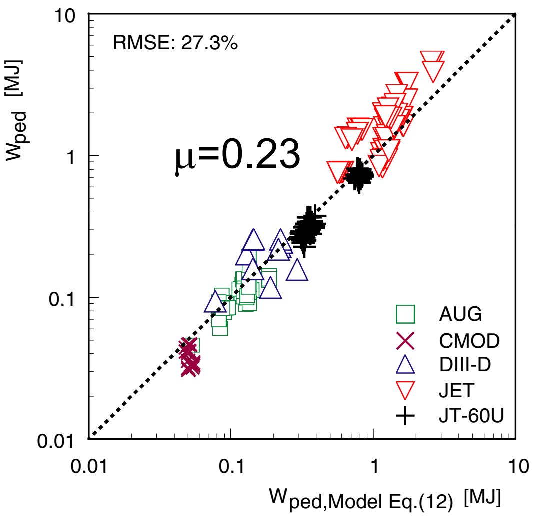
$$\Delta \propto \rho s^2 \qquad \Delta \propto \sqrt{\varepsilon}\,\rho_\theta$$

$$\Delta \propto \rho^{2/3} R^{1/3} \qquad \Delta \propto \sqrt{\rho R q}$$

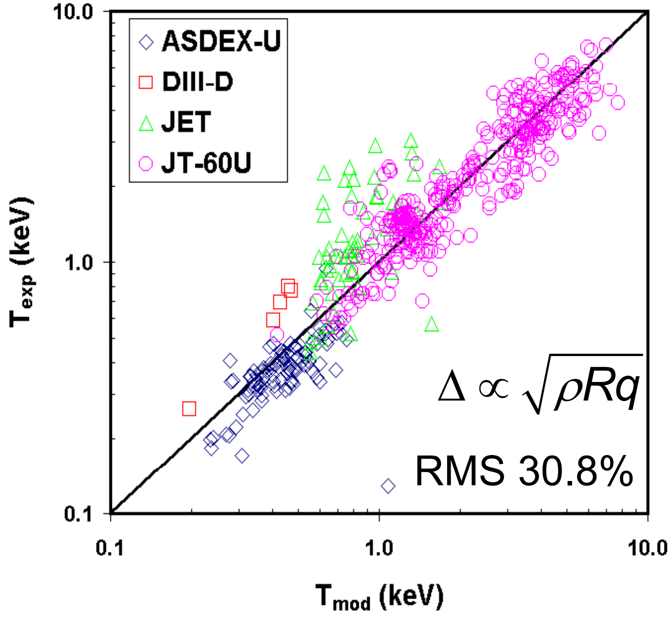
$$\Delta \propto 1/n_{ped} \qquad \Delta \propto \sqrt{\beta_\theta}\,R$$

RMS varies from 30.8-41%.

  - Sugihara, JPS 2002

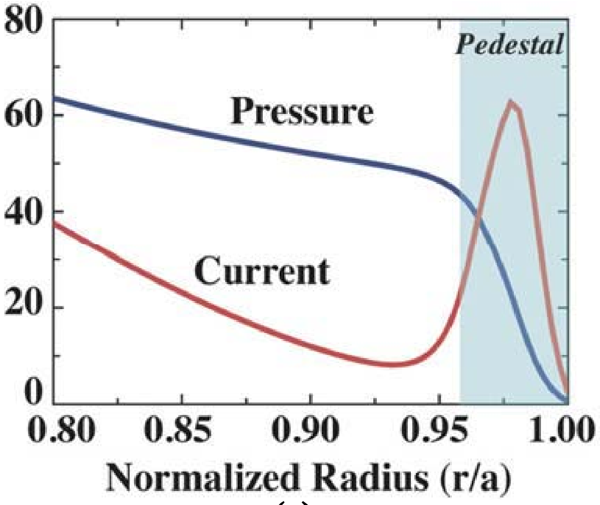


Thomsen and Conf. ITPA HMW Toki, 2001

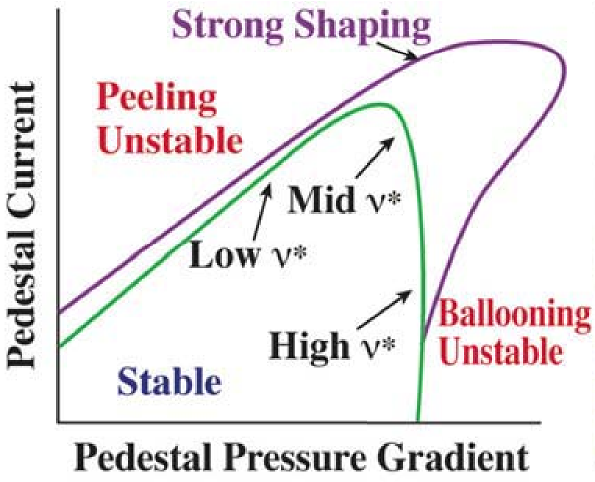


Bateman, Kritz, Onjun, Ped ITPA, Feb 2002

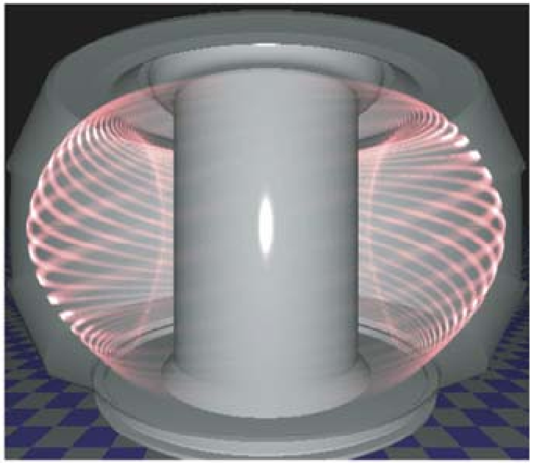
# Pedestal **Gradient** in ELMing H-modes is well explained by Peeling-Ballooning models



(a)

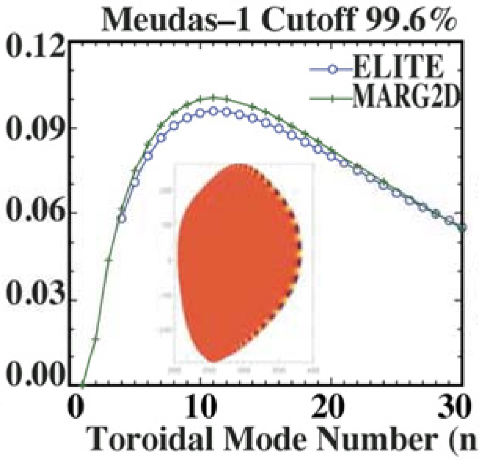


(b)



(c)

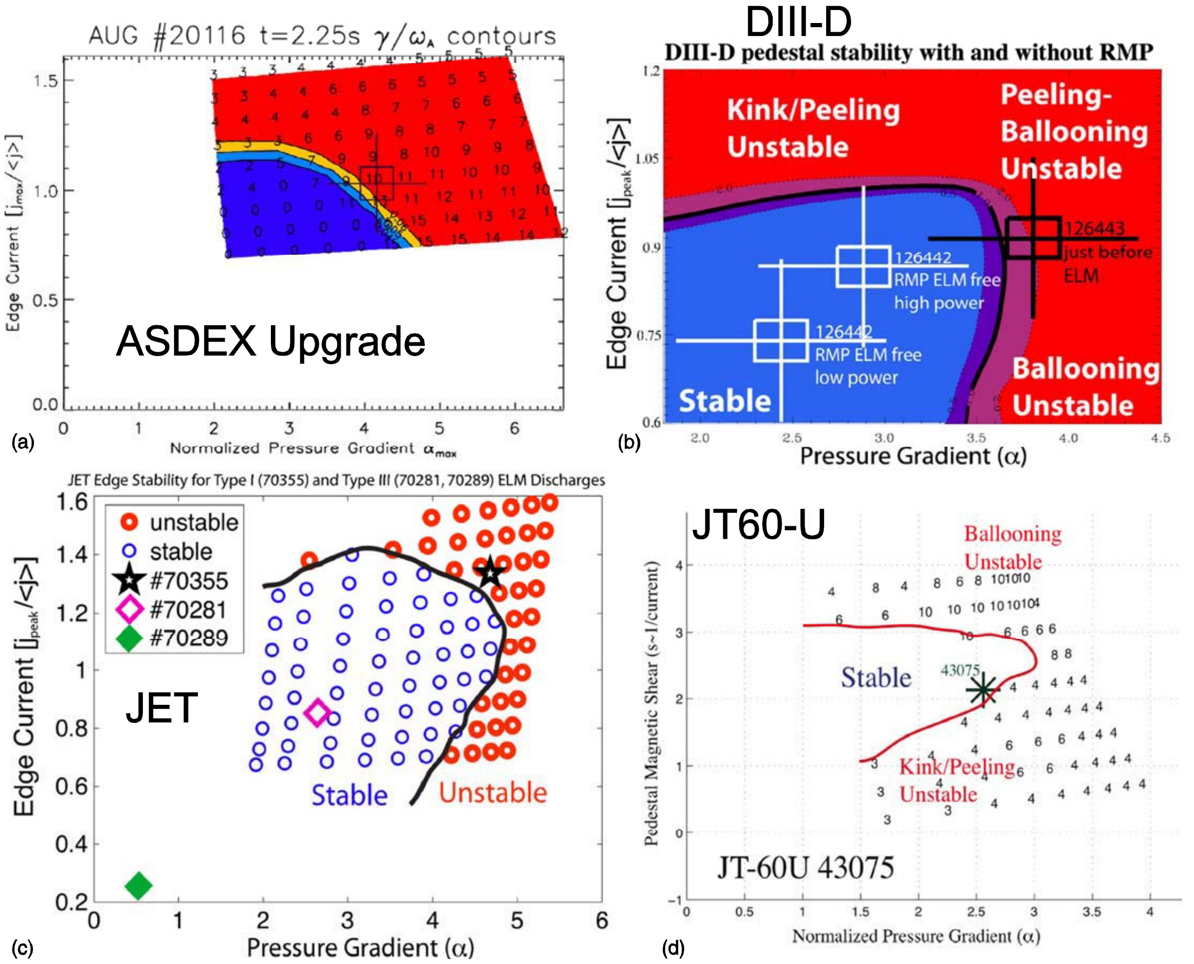
- Ballooning modes limited by pressure gradient, dominant at high collisionality ν*.
- Peeling modes limited by current density, dominant at low ν*.
- In general, both are important, strongly coupled, need to consider a range of n ~ 5-30.



(b)

P. Snyder et al
Nucl. Fusion
49 (2009)
085035 (ITPA
comparison)

# Experimental stability is consistent with Peeling-Ballooning limit

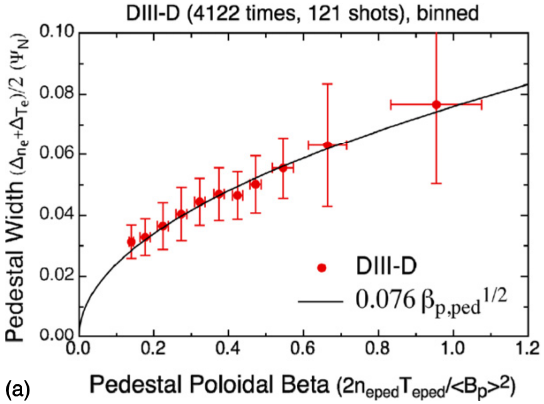


- Using an accurate calculation of the gradient, we can now better test width and height scalings.

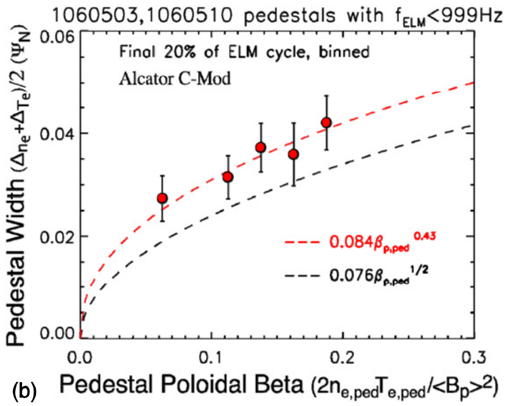
P. Snyder et al Nucl. Fusion 49 (2009) 085035 (ITPA comparison)

# P-B Stability model combined with semi-empirical scaling of pedestal Width ~ $\beta_{ped}{}^{½}$

- High resolution measurements on several experiments fit well with $\Delta \sim \beta_{ped}{}^{½}$

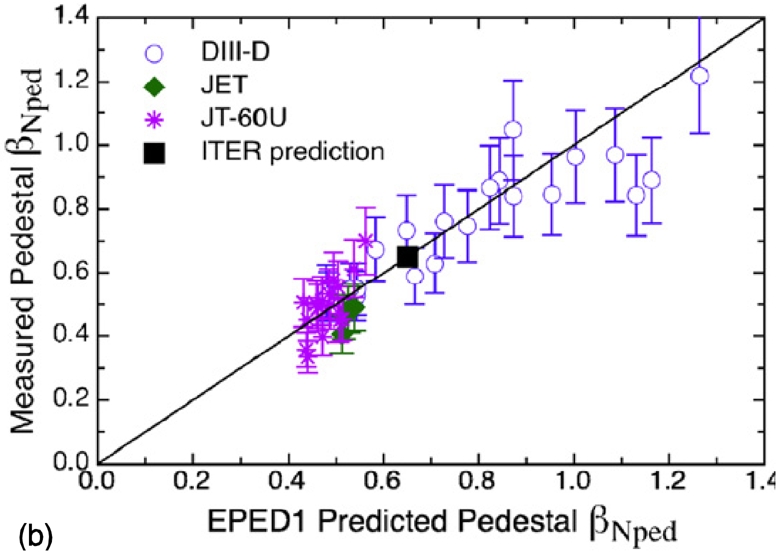


(a)



(b)

**Snyder's "EPED1" model uses this + p-b calculation to compare with ITPA data set, make height predictions for ITER.**



(b)

P. Snyder et al
Nucl. Fusion **49** (2009) 085035
(ITPA comparison)

# For greater confidence and physics understanding, a **first-principles pedestal model** is still needed!

- Should contain the same physics as was discussed for L-H transitions. Ie. Gyrokinetics, neoclassical effects, divertor/SOL, self-consistent turbulence, geometry, 2-D neutrals…

- Major collaborative efforts have begun in recent years, motivated by experimental results and predictions such as those in this talk!

  Eg, in US:
  - XGC0, XGC1 models (Chang, Ku  et al, Center for Plasma Edge Simulation based at NYU); starting with neoclassical physics, now adding turbulence.
  - TEMPEST (LLNL, Xu, Rognlien et al); emphasizing turbulence, 2-D divertor physics..
  - Parallel efforts underway in EU, other countries.

- Goal is to have models which reliably reproduce both L-H transitions and pedestal evolution and structure, and agree with each other and experiment (as for stability models).

# ELM Mitigation and avoidance

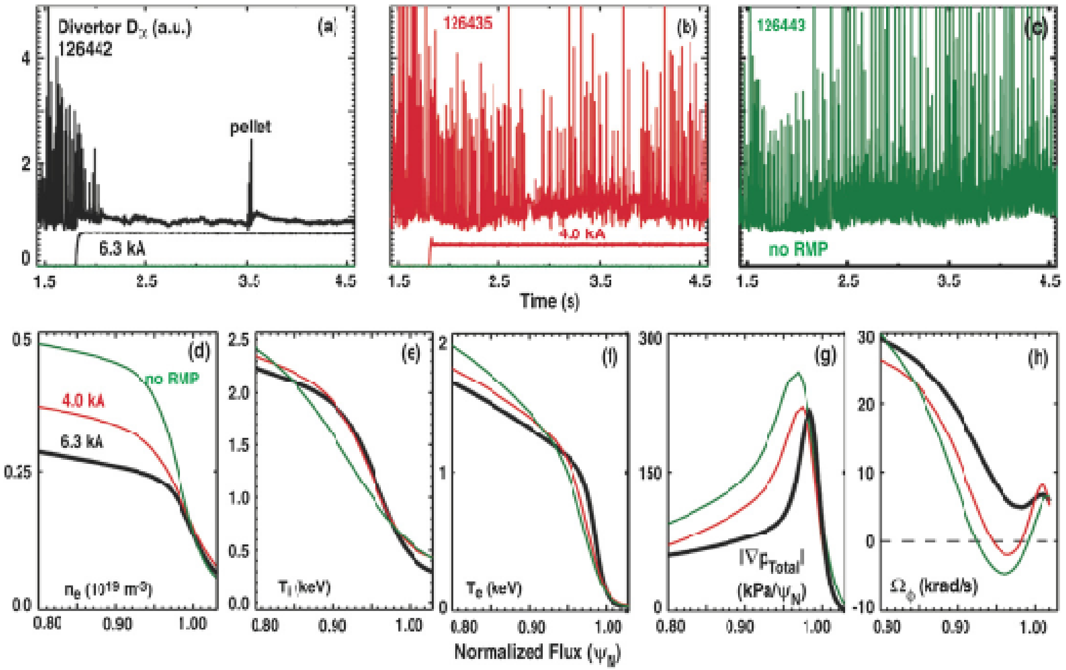
- Peeling-stability models explain well when and why ELMs occur, in most present H-modes.
- 3-D modeling is beginning to simulate crash dynamics.

- BUT, it is now widely agreed that large “Type I” ELMs cannot be tolerated in ITER or future reactor!
  Heat load and PFC erosion would be too big. Need to reduce to ~ 1 MJ/ELM for ITER, about 20x smaller than expected Type I ELMs.

- Two main approaches:
  - Mitigate/reduce ELMs by active means.
  - Avoid ELMs by finding regimes with small or no ELMs, and a more benign edge relaxation mechanism.
- **Both approaches are being actively pursued.**

# Resonant Magnetic Perturbations

- Use external coils to add low m/n magnetic perturbation.
- When this resonates with edge q, can reduce or suppress ELMs.



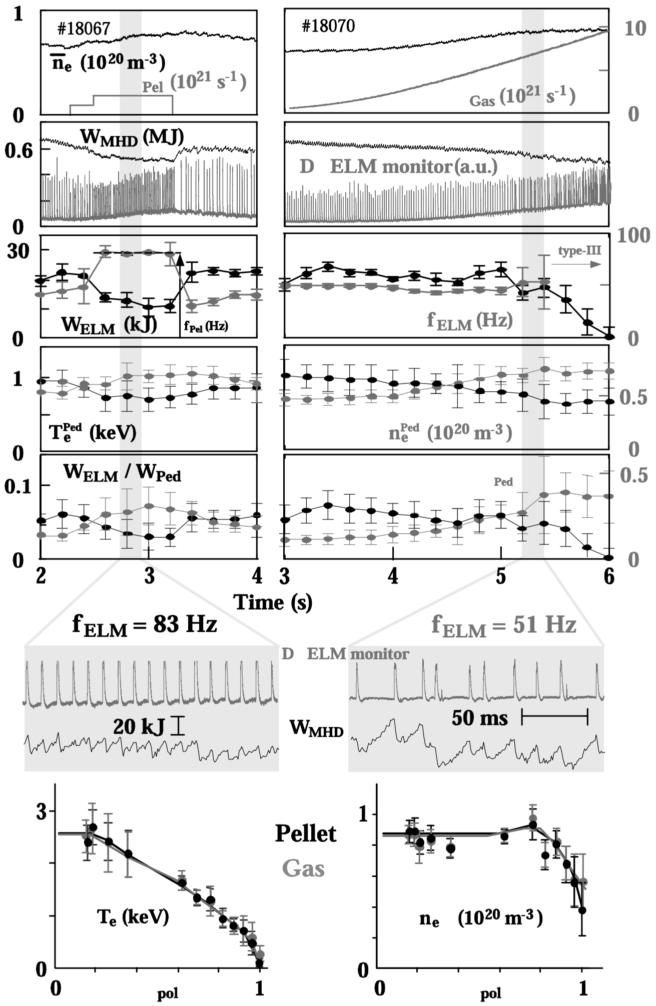
**DIII-D**
T. Evans
Nucl. Fusion
48 (2008)
024002

- So far, *full* ELM suppression only on DIII-D, in narrow $q_{95}$ ranges.
- Pedestal profiles change, keeping below peeling-ballooning limits
- Exact mechanism, requirements for extrapolation (eg to ITER) and the effect on pedestals and confinement are subjects of active research.
- ITER is presently designing a new RMP coil system.

# Pellet 'Pacing'

- It is generally noted that ELM size reduces as frequency increases.
- 'Pellet pacing' deliberately triggers more frequent ELMs using small pellets.
- ELM size does diminish, with similar pedestals similar to gas-fuelled H-modes.
- Due to limits of injectors, only modest (few times) increase in frequency to date.
- *Can we get 20 x decrease in size needed for ITER? Will the large associated fueling be a problem?*

**ASDEX Upgrade.** P. Lang et al, Nucl. Fusion **44** (2004) 665–677

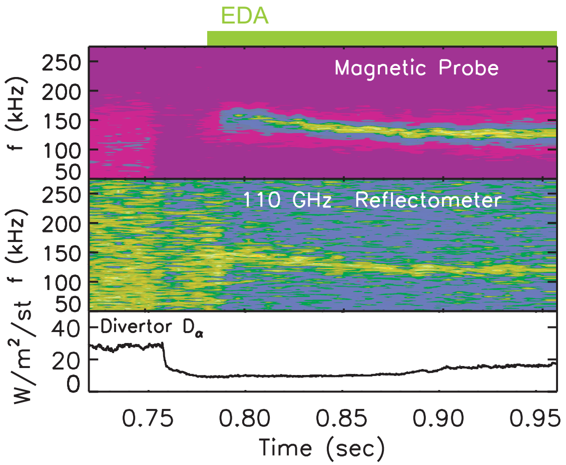


# Many H-mode regimes exist with small or no ELMs.

Some regimes **without ELMs**:

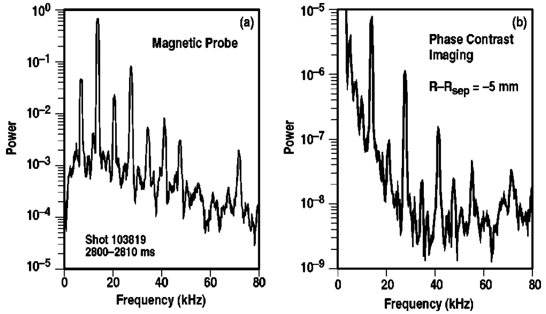
- **EDA** regime on C-Mod (and similar **H**igh **R**ecycling **S**teady) on JFT2M, has a quasicoherent, high m mode ~ 100 kHz.

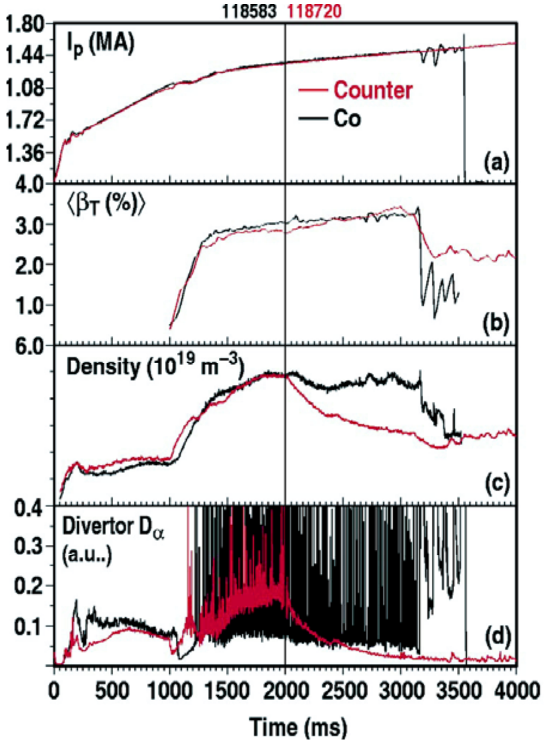
- **Quiescent H-mode** (D3D, AUG, JET, JT60 U) has an 'edge harmonic oscillation'.
  - – In these regimes, stability analysis finds pedestals stay in peeling-ballooning stable region.



**EDA mode on C-Mod**

J. Snipes, PPCF **43**(2001) L23





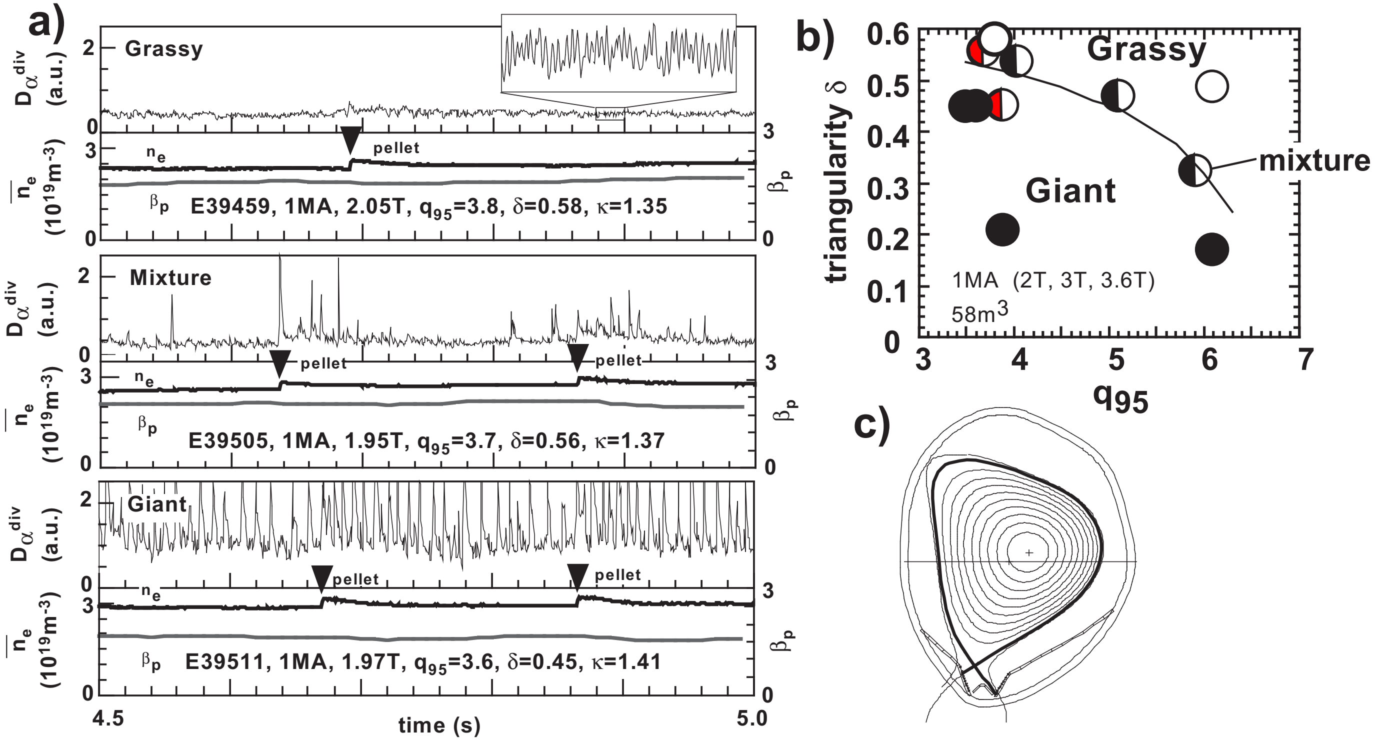
**QH mode on DIII-D**

K. Burrell, Phys. Plasma **12,** 056121 (2005) & Phys. Plasma **8** (2001) 2153

# Small ELM regimes (II).

- **“Grassy” or “Type II” regimes**
  have ELMs, but smaller amplitude.
  - At peeling ballooning limit, but a more localized mode structure.

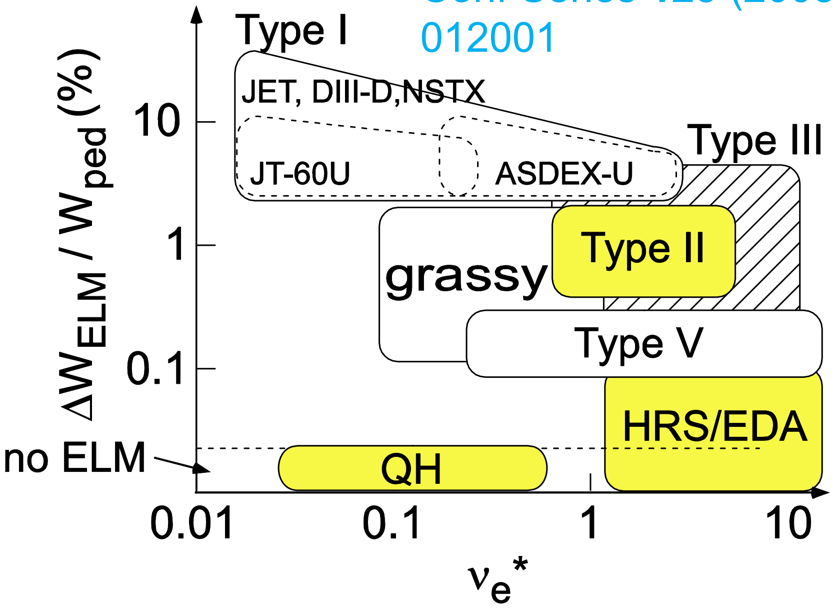
**Grassy ELMs on JT60-U**
Y. Kamada, Plasma Phys Control Fusion **44**(2002) A279



# Issue is operational space for which regimes occur. *Can we count on them for ITER?*

- Tend to occur in limited ranges of ν* or pressure.
- Very sensitive to details of shaping, $q_{95}$ etc (presumably due to magnetic shear effect on stability).
- QH mode, until recently, needed counter-rotation. Size of other ELMs also sensitive to rotation (which is likely different on ITER).
- Operation spaces of regimes are expanding with experimental research and better theoretical understanding.

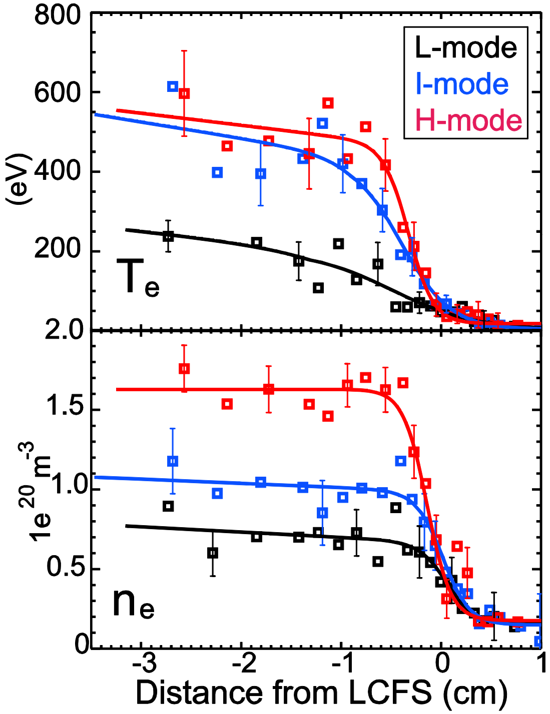
N. Oyama, J. Phys. Conf Series **123** (2008) 012001

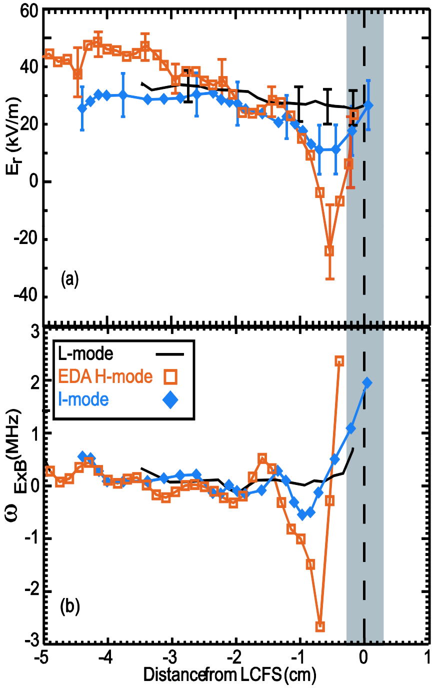


- Also need much more research on pedestal structure and confinement in regimes without large ELMs.

# “Improved L-Mode” regime has an energy barrier but no particle barrier (or ELMs).

- Occurs only with ion BxGrad B drift *away* from X-point, when L-H threshold is higher. [Ryter 1999]
- Improvement in energy transport is gradual, not a bifurcation.
- No change in $D_\alpha$ or particle transport – not a classic “H-mode”.
- $E_r$ shear well develops, but not as deep as in H-mode.





- Interesting regime for understanding barrier physics, and possibly as an operating scenario – good energy confinement, no particle accumulations or ELMs.
- *Why do energy and particle transport respond differently? May help understand threshold conditions.*

**C-Mod**
R. MacDermott,
Phys. Plasmas
**16,** 056103
2009

# Summary: Physics of Edge Transport Barriers and Importance for Fusion Experiments

- Edge Transport Barrier or H-Mode “pedestal” has an impact on fusion experiments which is disproportionate to its narrow size.
- Widely observed on most divertor tokamaks, and other magnetic confinement experiments, for over 25 years, and is the basis for ITER and reactor designs.
- General understanding of transition and barrier formation in terms of turbulence suppression, most likely due to ExB shear.
- However, not yet a robust, self-consistent model for barrier formation and width.
- Pedestal stability is well explained by peeling-ballooning models. Combining with semi-empirical width model gives best available predictions.
- Large ELMs are not acceptable in a burning plasma.
  Need expanded research on mitigation methods (RMP coils, pellets) and on regimes without large ELMs. Given current uncertainties, all three approaches are of interest for ITER.

# Good review papers on transport barriers:

- **H-mode pedestals** A.E. Hubbard, Plasma Phys. and Control. Fusion **42**, A15, 2000 (not the latest scaling results now).

- **Internal and Edge transport Barriers**, E. Synakowski, Plasma Phys. and Control. Fusion **40**, 581, 1998.

- **H-mode physics:** F. Wagner "A quarter-century of H-Mode studies", Plasma Phys. and Control. Fusion **49**, B1-B33, 2007.

- **L-H Transitions:** J. Connor and H. Wilson., PPCF **42**(2000) R1-R74.

- **ELMs:** N. Oyama, 11th IAEA TCM on H-mode Physics and Transport Barriers, J. Phys. Conf Series **123** (2008) 012001.|(jcps.iop.org)

- The conference series on **"H-mode Physics and Transport Barriers",** held every two years since 1987; review and contributed papers are published, until 2006 in Plasma Physics and Controlled Fusion. Next meeting will be Sept 30th 2009, and papers will be in Nuclear Fusion.
- **ITER Physics Basis:** Nuclear Fusion **39**(12) 1999 and **47**(6) 2007.
- **Pedestal ITPA group** website is also a great resource. http://itpa.ipp.mpg.de/