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Transport and Stability of the Pedestal in Tokamaks

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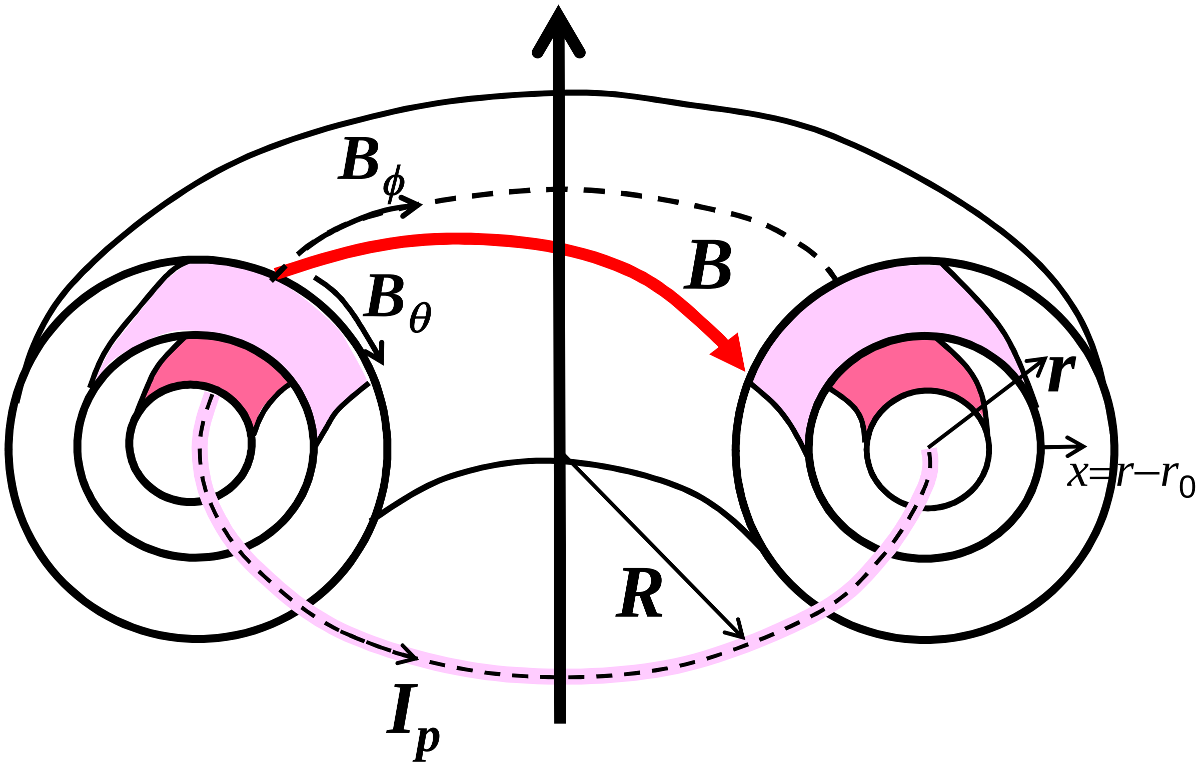
Outline

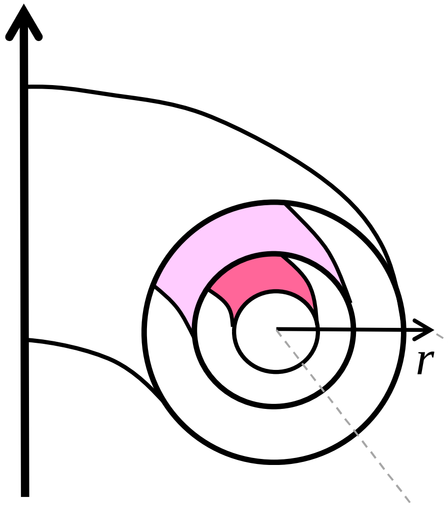
- Background
  - The H-mode, the pedestal and Edge Localised Modes (ELMs)
- Pedestal stability
  - Plasma eruptions – ELMs
  - Ideal MHD stability
  - ELM control
- Determining the pedestal confinement properties
  - Micro-instabilities and associated turbulence
  - Interaction of turbulence and eruptions
  - Towards an integrated model for ELMs and the pedestal
- Summary

Background: Tokamak Geometry

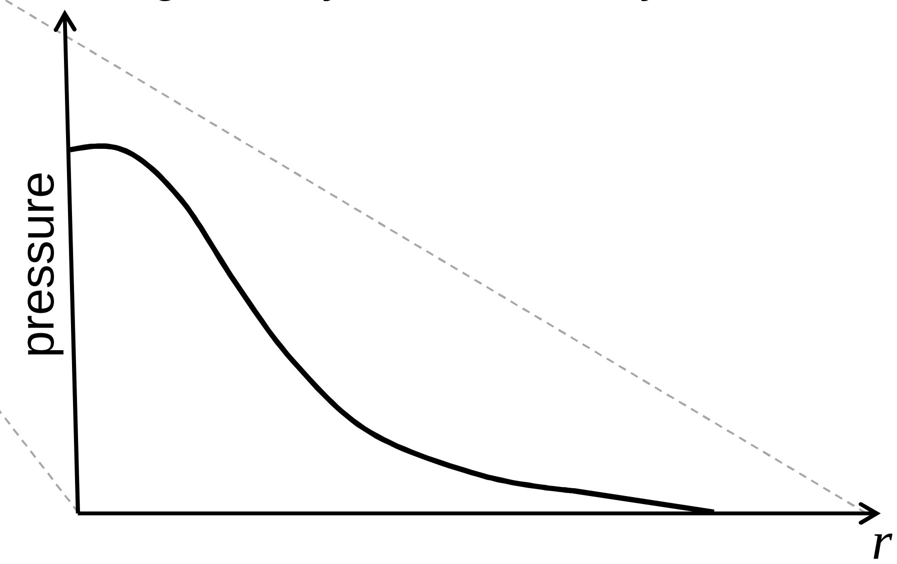
- A tokamak confines the plasma with a toroidal magnetic configuration
  - A toroidal component to the field is provided by coils
  - A poloidal component is provided by a toroidal current
  - The magnetic field lines lie in a set of nested toroidal flux surfaces



Background: Tokamak confinement

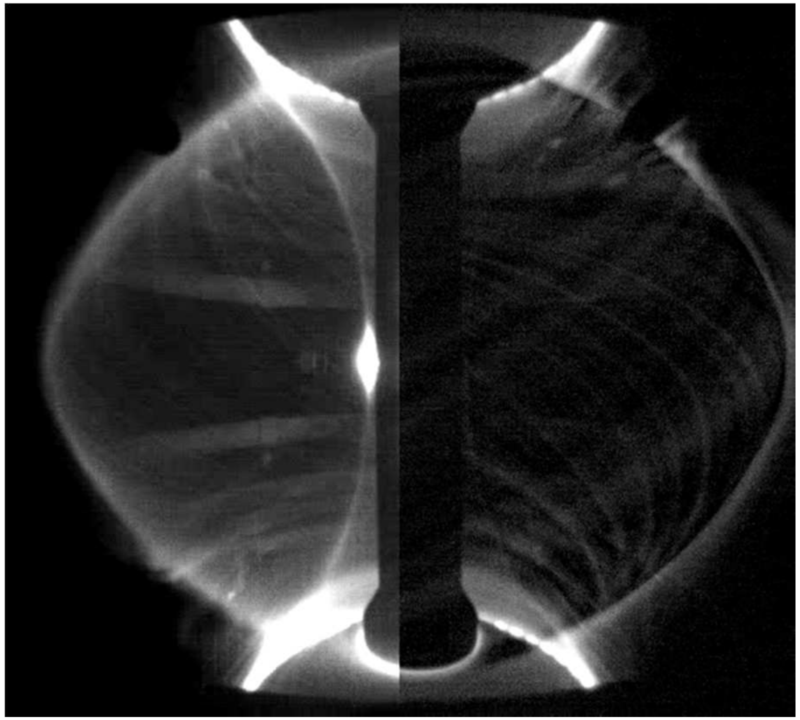


- A pressure gradient is maintained across the flux surfaces
  - The fusion power $\sim p^2$
- High fusion power either requires
  - a steep pressure gradient – good confinement
  - a larger device to achieve high central pressure
- Confinement is key to the feasibility of fusion
  - this is generally determined by turbulence



Background: The H-mode

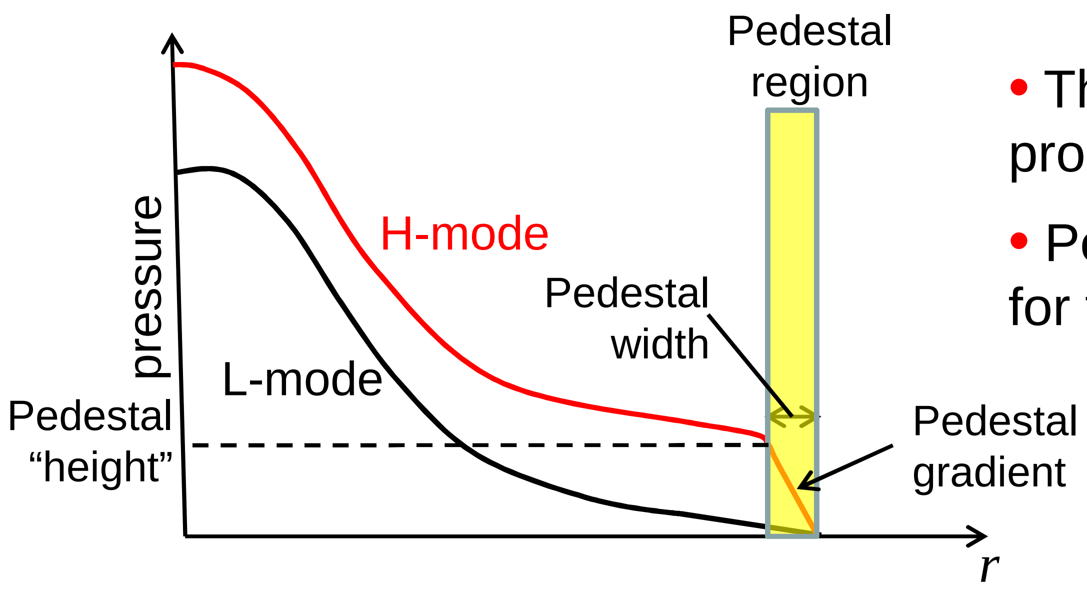
- As plasma heating is increased through a well-defined threshold, there is a bifurcation to an improved confinement state, called H-mode
- An example from the UK's MAST tokamak…



Courtesy B. Dudson

Background: The pedestal

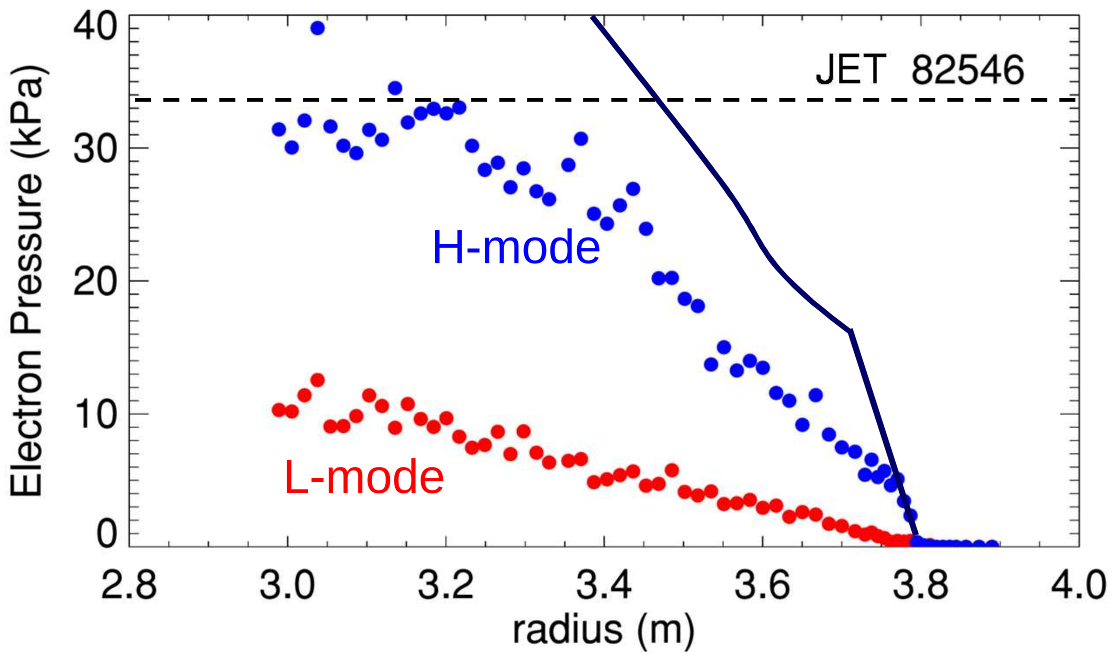
- The improvement in confinement is due to a region of steep pressure gradient at the plasma edge
  - Turbulence is suppressed there, reducing the transport of heat and particles
  - Such a region is referred to as a transport barrier
- At the plasma edge, this is referred to as the pedestal region



- The pressure in the plasma core is proportional to the pedestal pressure
- Pedestal physics is very important for tokamaks

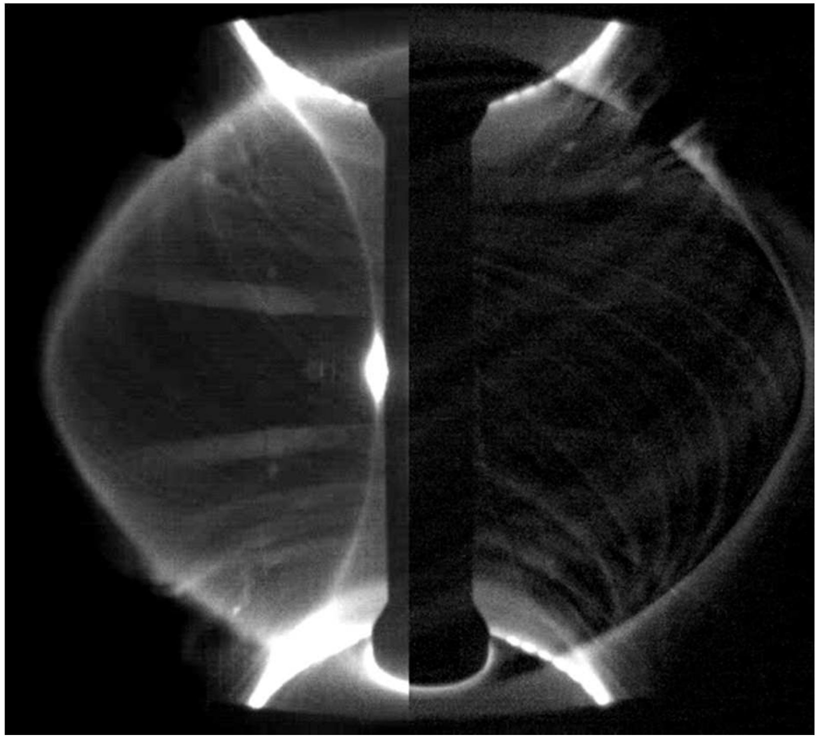
Background: The importance of the pedestal

- Understanding how the pedestal forms and what determines the width is key
  - If we can learn how to broaden the pedestal width, we could achieve fusion conditions in smaller devices
  - Less power to be handled in the exhaust region



Background: Plasma Eruptions - ELMs

- The high plasma pressure gradients in the pedestal region trigger filamentary eruptions of plasmas
- These are Edge-localised Modes, or ELMs
- On ITER, these "Type I ELMs" would cause excessive erosion
  - We must learn how to minimise their impact on plasma-facing materials



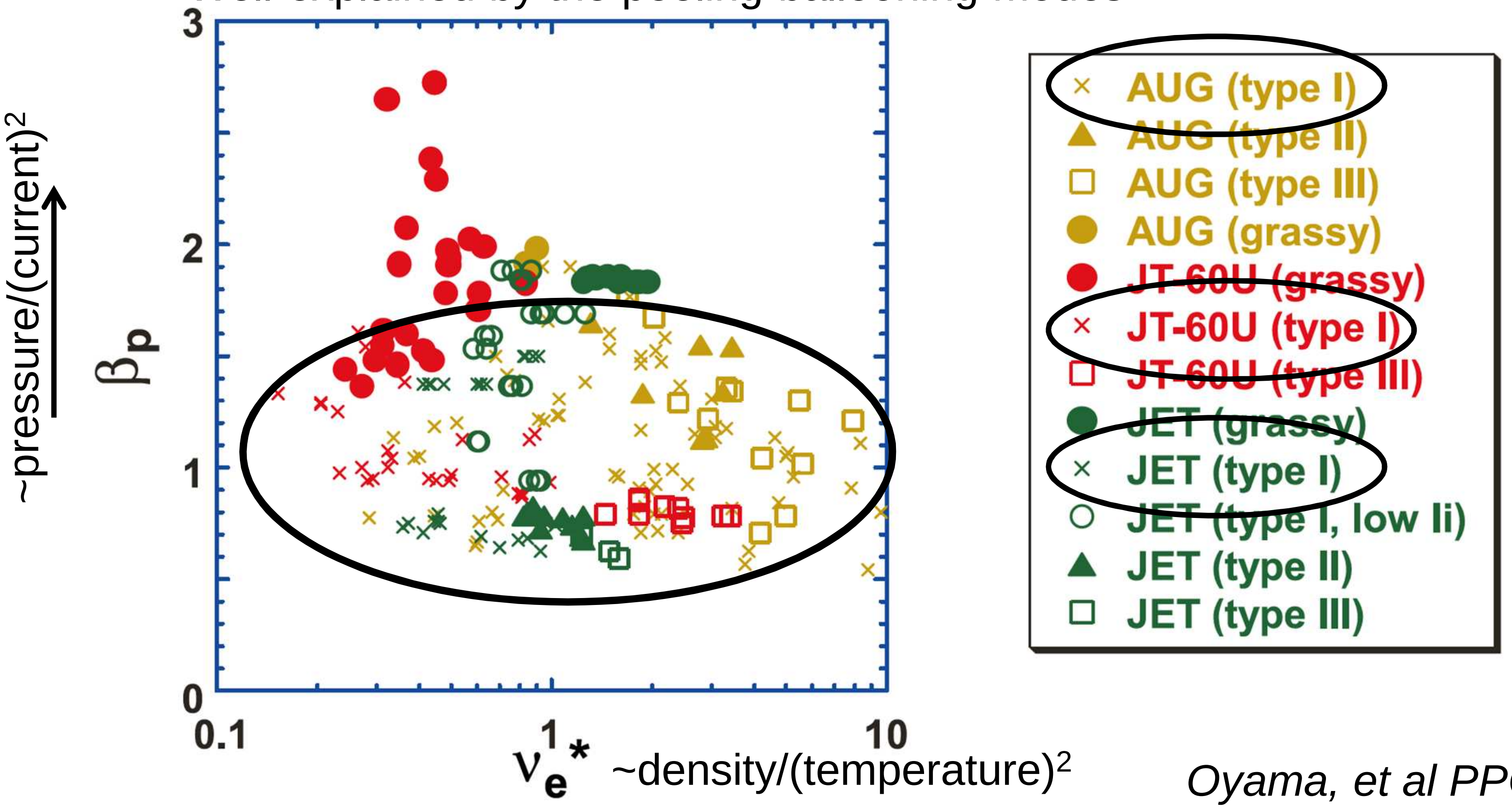
Background: Summary of pedestal physics

- The pedestal is controlled by three physics mechanisms:
  - The mechanism for turbulence suppression to form the pedestal
  - The plasma eruptions called ELMs, and their control
  - How the remaining turbulence and pedestal stability interact to determine the pedestal width and height (or gradient)

Edge Localised Modes –
A whole zoo exists

Type I ELMs: Large, robust plasma eruptions

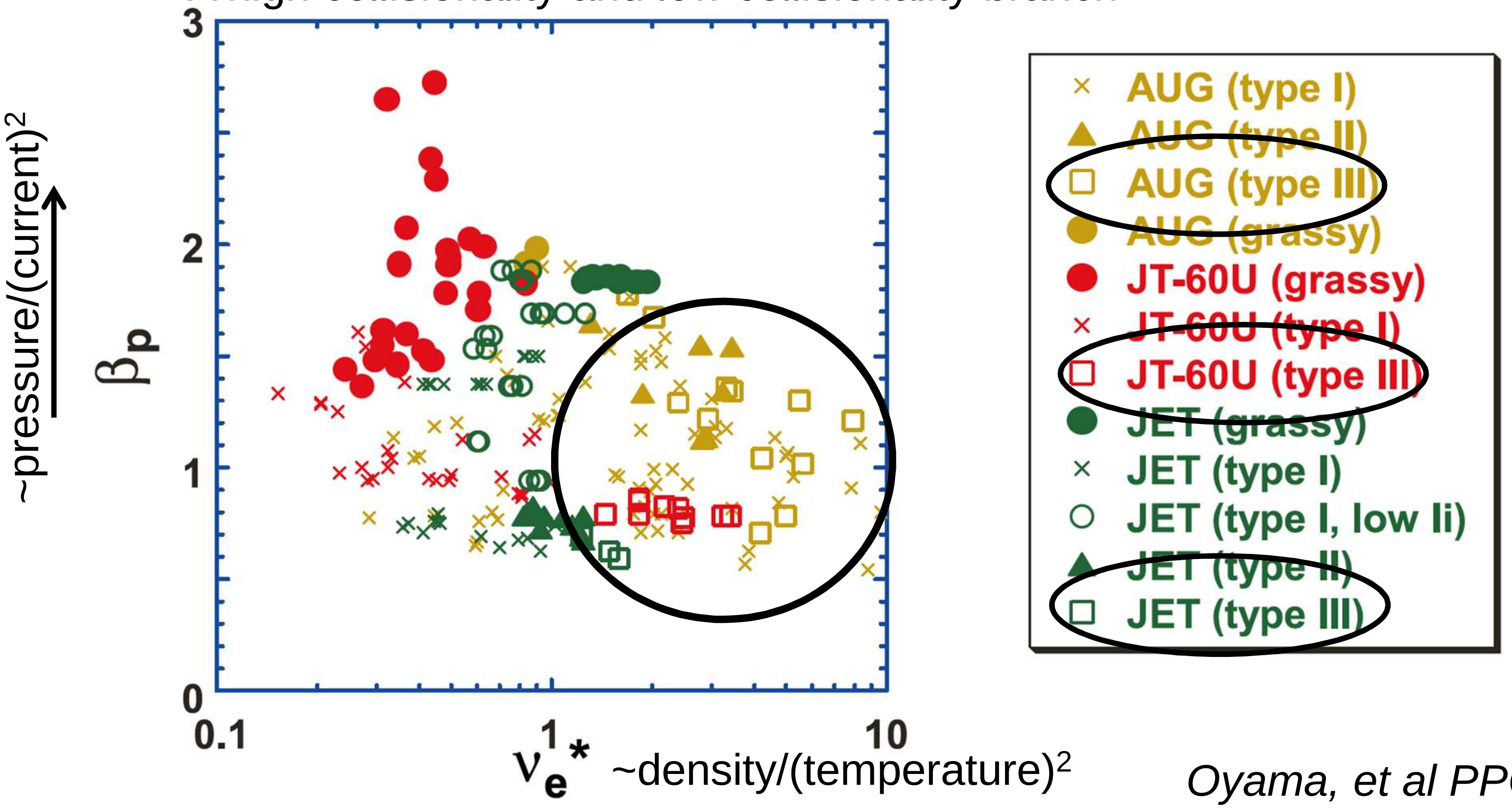
- Type I ELMs are the most prevalent, over a wide range of parameters
  - Good confinement, but large ELMs
  - Cannot be tolerated on ITER
  - Well-explained by the peeling-ballooning modes



Oyama, et al PPCF (2006)

Type III ELMs: More benign, but degrade confinement

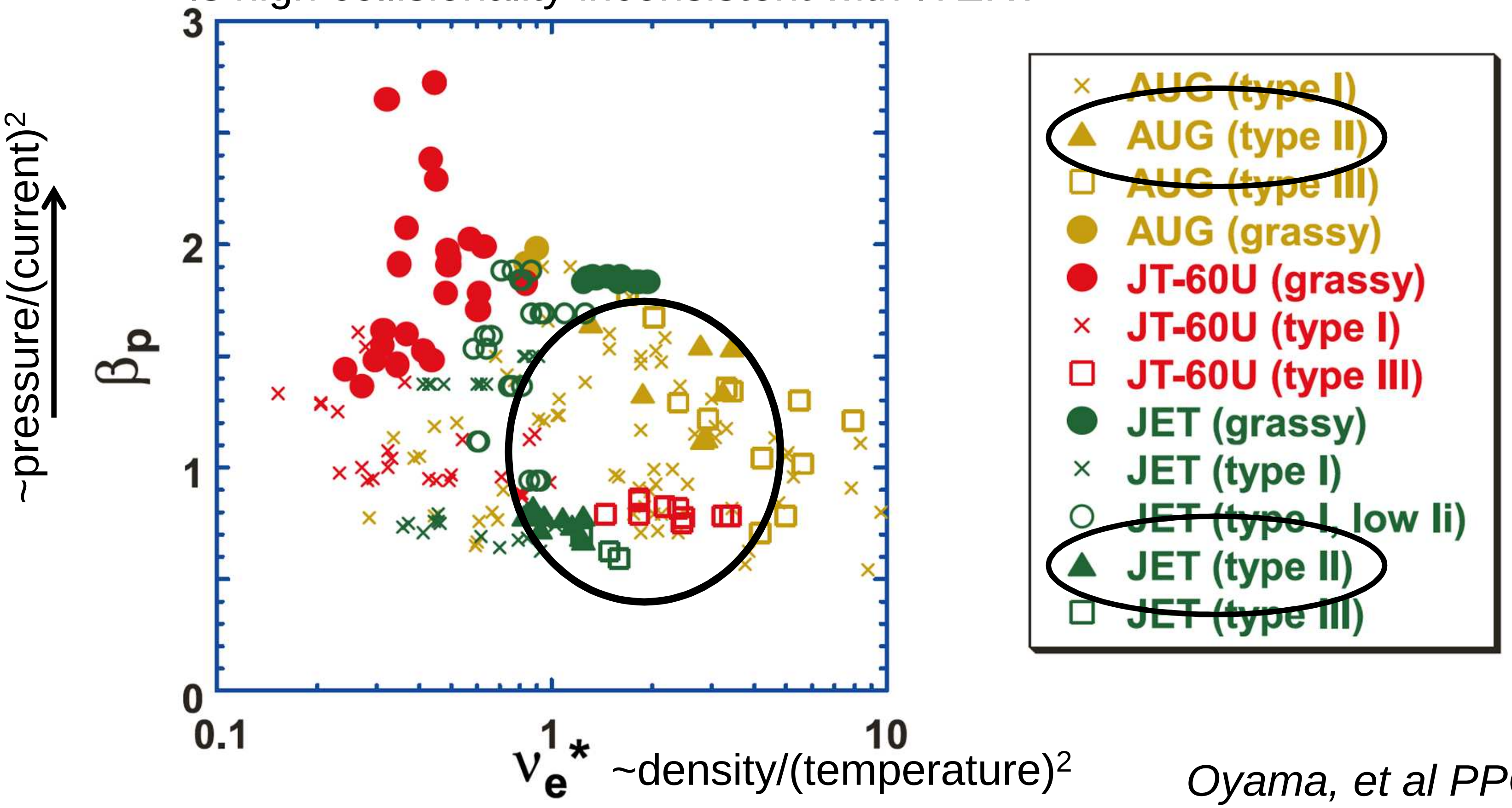
- Type III ELMs typically occur close to the L-H transition
  - Small ELMs, but reduced confinement
  - Confinement degradation not desirable for ITER
  - A high collisionality and low collisionality branch



Oyama, et al PPCF (2006)

Type II ELMs: Small ELMs with good confinement

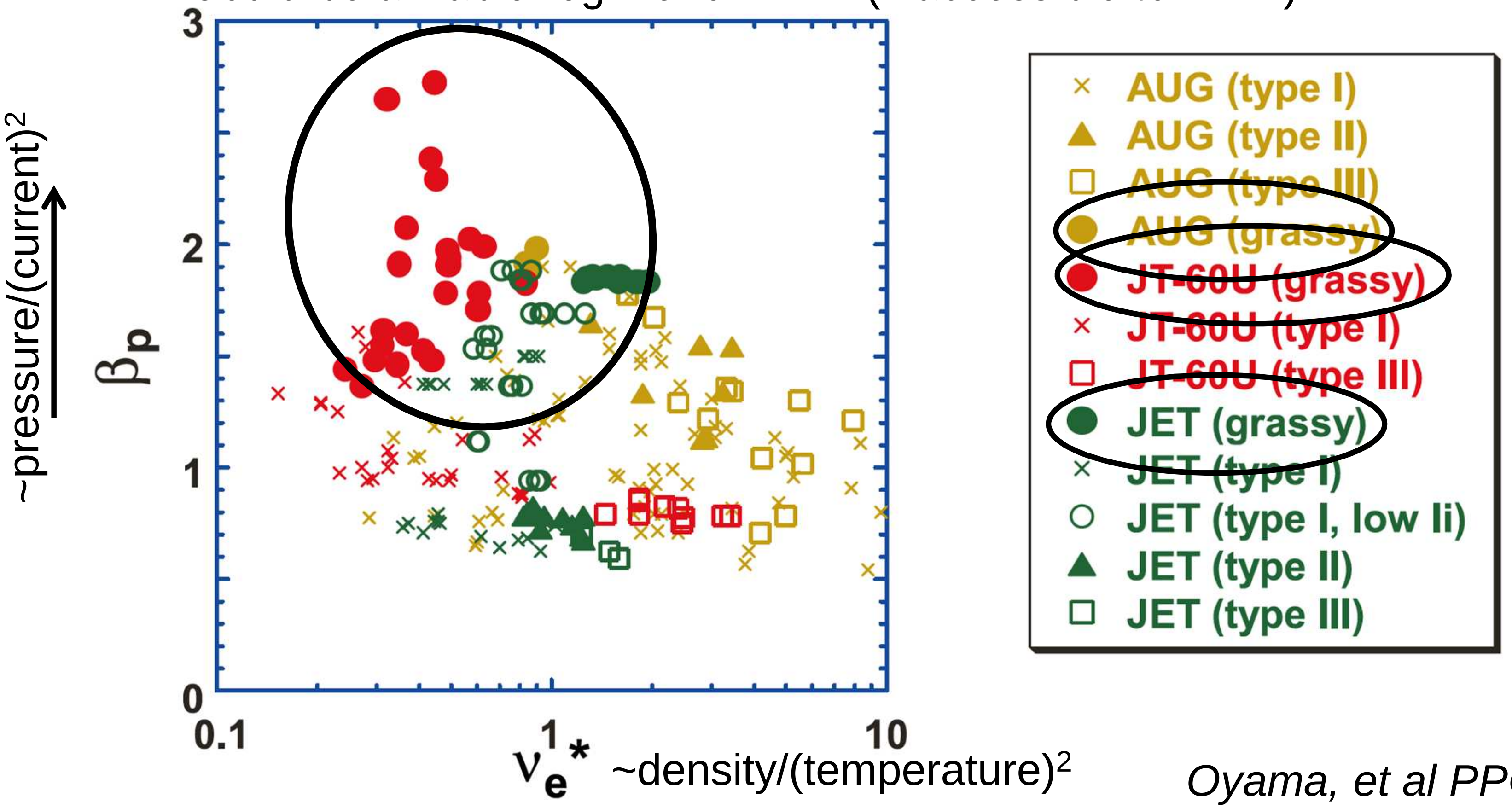
- Type II ELMs occur at high collisionality in plasmas with strong shaping
  - Small ELMs, and good confinement
  - They can co-exist with Type I ELMs
  - Is high collisionality inconsistent with ITER?



Oyama, et al PPCF (2006)

Grassy ELMs: Small ELMs with good confinement

- Grassy ELMs occur at low collisionality, strong shaping
  - High β_p and q_{95} required (low current?)
  - Small ELMs, and good confinement
  - Could be a viable regime for ITER (if accessible to ITER)



Oyama, et al PPCF (2006)

ELM summary table

ELM Type	Access criteria	Confinement	Size	ITER implication
Type I	High power; wide parameter regime	Good	Large	Excessive erosion
Type II	Strong shaping; high collisionality; high q95	Good	Small	Collisionality too high for ITER?
Type III	Lower power; high and low collisionality branches	Poor	Small	Confinement unacceptable; inaccessible at high power?
Grassy	Strong shaping; high β_p; low collisionality	Good	Small	Possible tolerable ELM regime

Pedestal Stability:
Edge Localised Modes

Linear ideal MHD: the peeling-ballooning mode

- Change in energy δW associated with a radial plasma displacement, X

$$\delta W = \pi \int d\psi d\chi \left\{ \frac{JB^2}{R^2B_p^2}|k_{\|}X|^2 + \frac{R^2B_p^2}{n^2JB^2}\left|\frac{\partial(JBk_{\|}X)}{\partial\psi}\right|^2 \right.$$

Line-bending: Stabilising

$$-\frac{2Jp'}{B^2}\left[\frac{\partial}{\partial\psi}\left(p+\frac{B^2}{2}\right)|X|^2 - \frac{if}{2JB^2}\frac{\partial B^2}{\partial\chi}\frac{X^*}{n}\frac{\partial X}{\partial\psi}\right]$$

Curvature Stabilising inboard; Destablising outboard

$$\left. -\frac{X^*}{n}JBk_{\|}(\sigma' X) + \frac{\partial}{\partial\psi}\left[\frac{1}{n}\sigma X JBk_{\|}^* X^*\right] + \cdots \right\}$$

Kink drive

Boundary term: Peeling drive

Pressure gradient

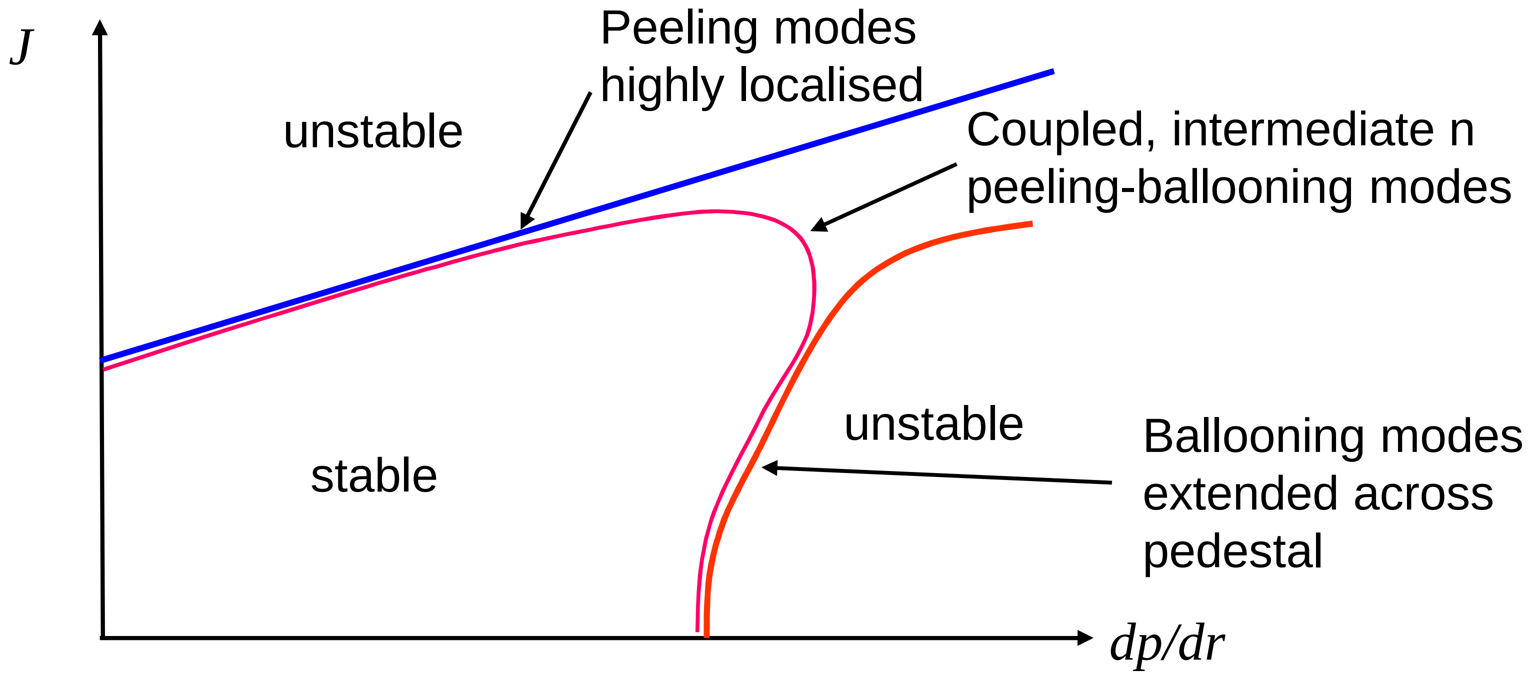
Current density gradient

Current density

- In the pedestal, the current and pressure gradient are coupled via the bootstrap current – $J_{bs} \sim dp/dr$

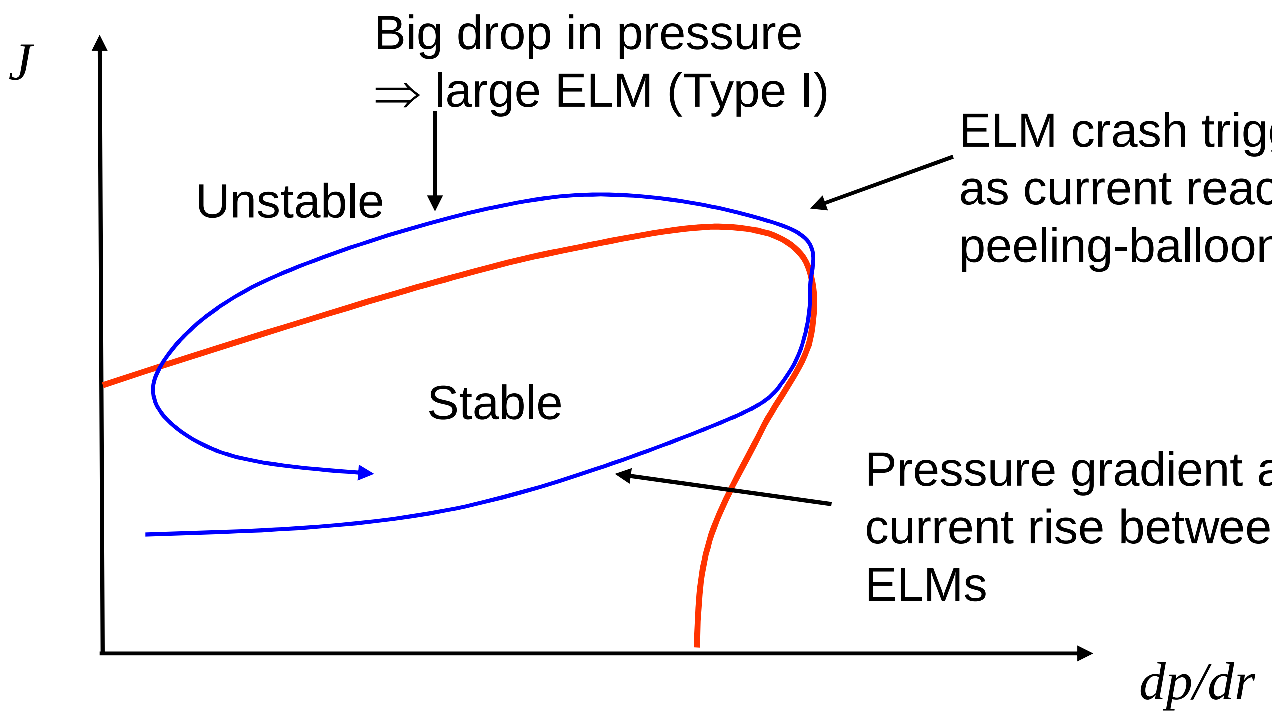
Edge Localised Modes: The Peeling-ballooning model

- The large "Type I" ELMs seem to be triggered by coupled peeling-ballooning modes:
  - The ballooning mode is destabilised by pressure gradient, but stabilised by current density
  - The peeling mode is destabilised by current density, but stabilised by pressure gradient
  - The modes can couple, leading to a somewhat complicated stability boundary



Edge Localised Modes: The Type I ELM cycle

- The coupled peeling-ballooning mode stability diagram provides a model for **Type I ELM** cycle
  - Current and pressure gradient are linked through the bootstrap current
  - Nevertheless, they evolve on different timescales
  - Peeling-ballooning mode initiates a crash event through the unstable region
  - As the mode extends right across the pedestal region, it affects all of this region, resulting in a large ELM

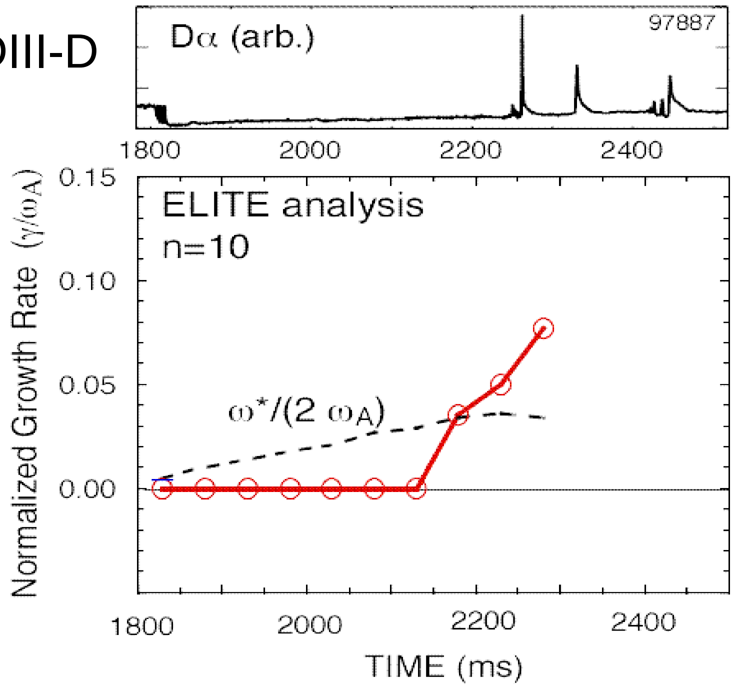


Experiments on all tokamaks consistent with peeling-ballooning trigger

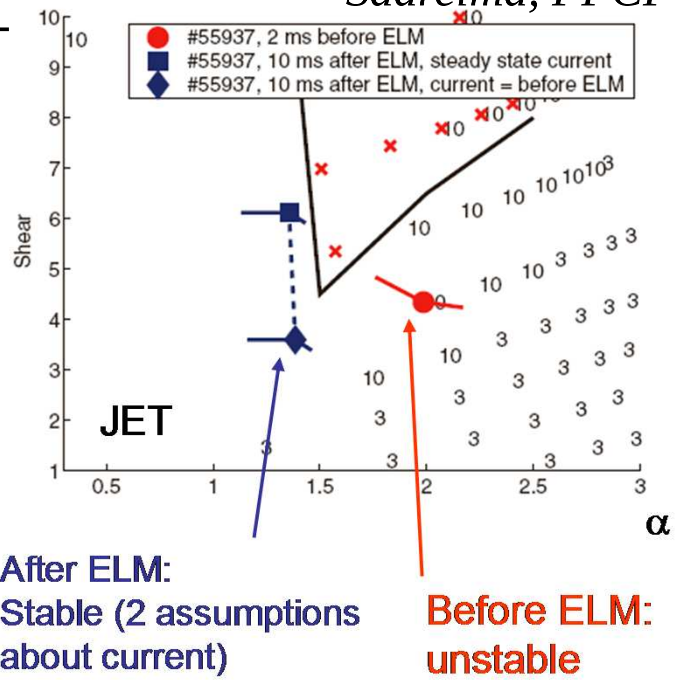
- Experiments around the world consistently confirm pressure gradient close to peeling-ballooning threshold at Type I ELM onset
  - Gives confidence in the theory for large ELMs
  - But does not explain smaller Type II and Grassy ELM regimes

Saarelma, PPCF 2005

DIII-D



JET



Snyder, Phys Plas 2002

Many ELMs on AUG show pressure gradient saturates long before ELM

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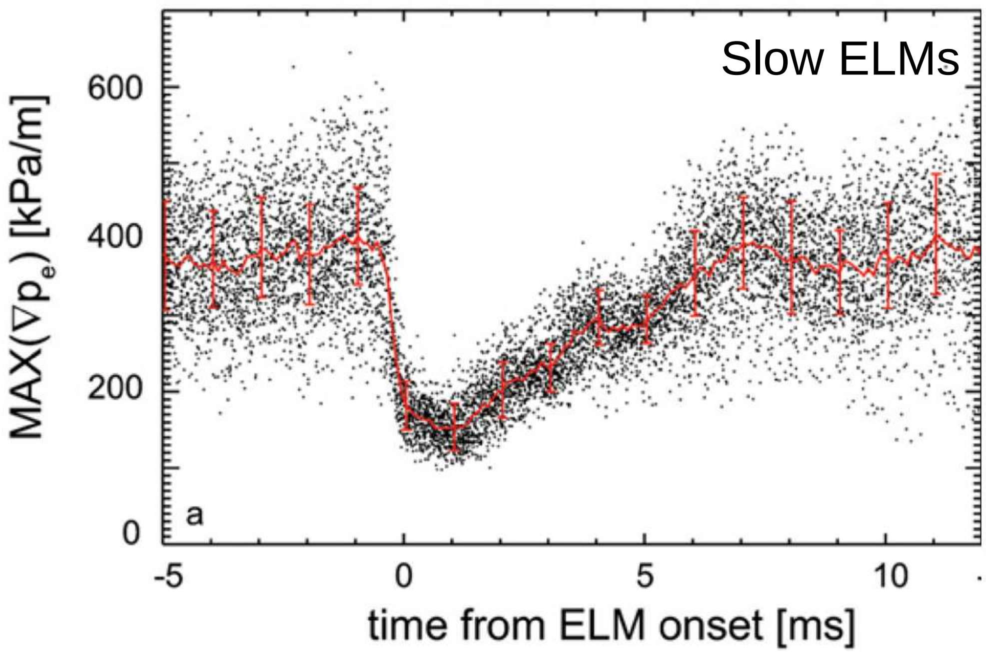
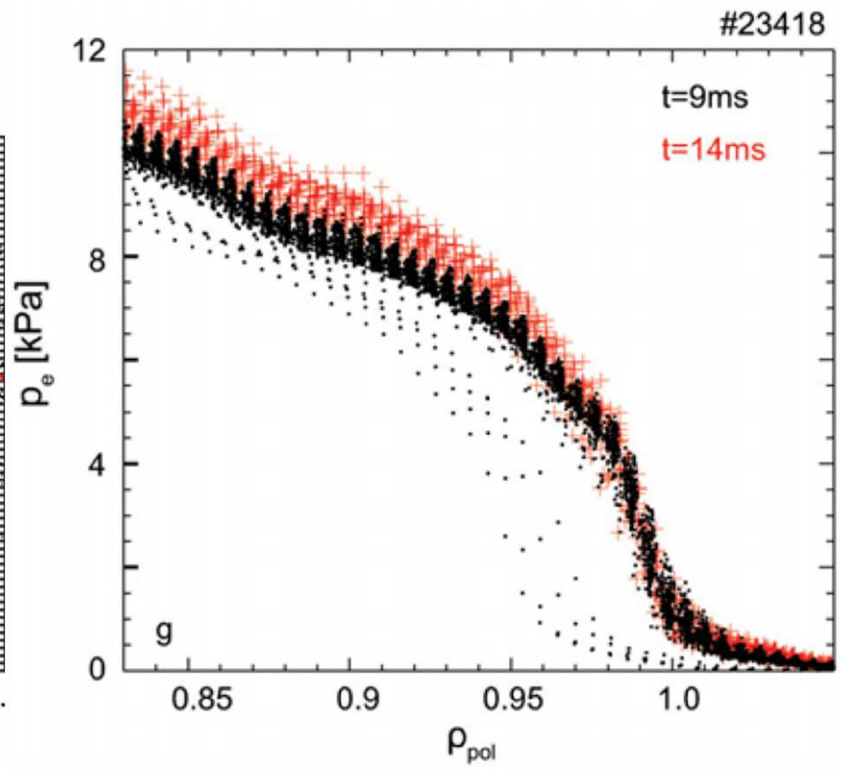
- AUG data shows pressure gradient often saturates before the ELM
  - The duration of this saturation is too long to be explained by current diffusion
  - There seems to be more to the story than simply pressure gradient
  - But there is some evidence that the pedestal continues to broaden
  - We shall return to this later…

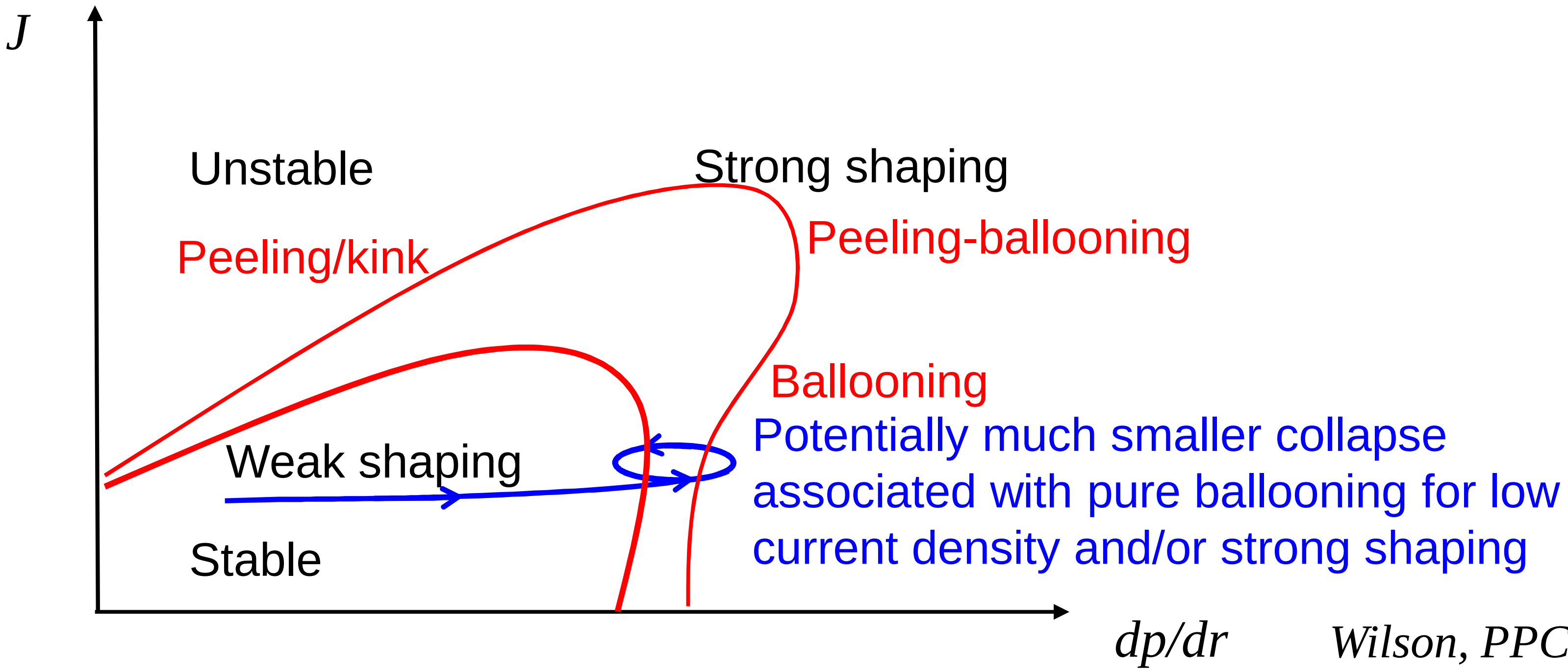




Burckhart, et al PPCF 2010

Edge Localised Modes: Smaller ELM cycle scenarios

- The coupled peeling-ballooning mode stability diagram could explain some smaller ELM scenarios
  - Higher shaping/q95/β_p increases stability boundaries – Grassy ELMs?
  - Higher collisionality lowers edge current density – Type II ELMs?
  - Perhaps profiles only experience (a more benign?) pure ballooning mode
  - Note, high pressure gradient consistent with good confinement



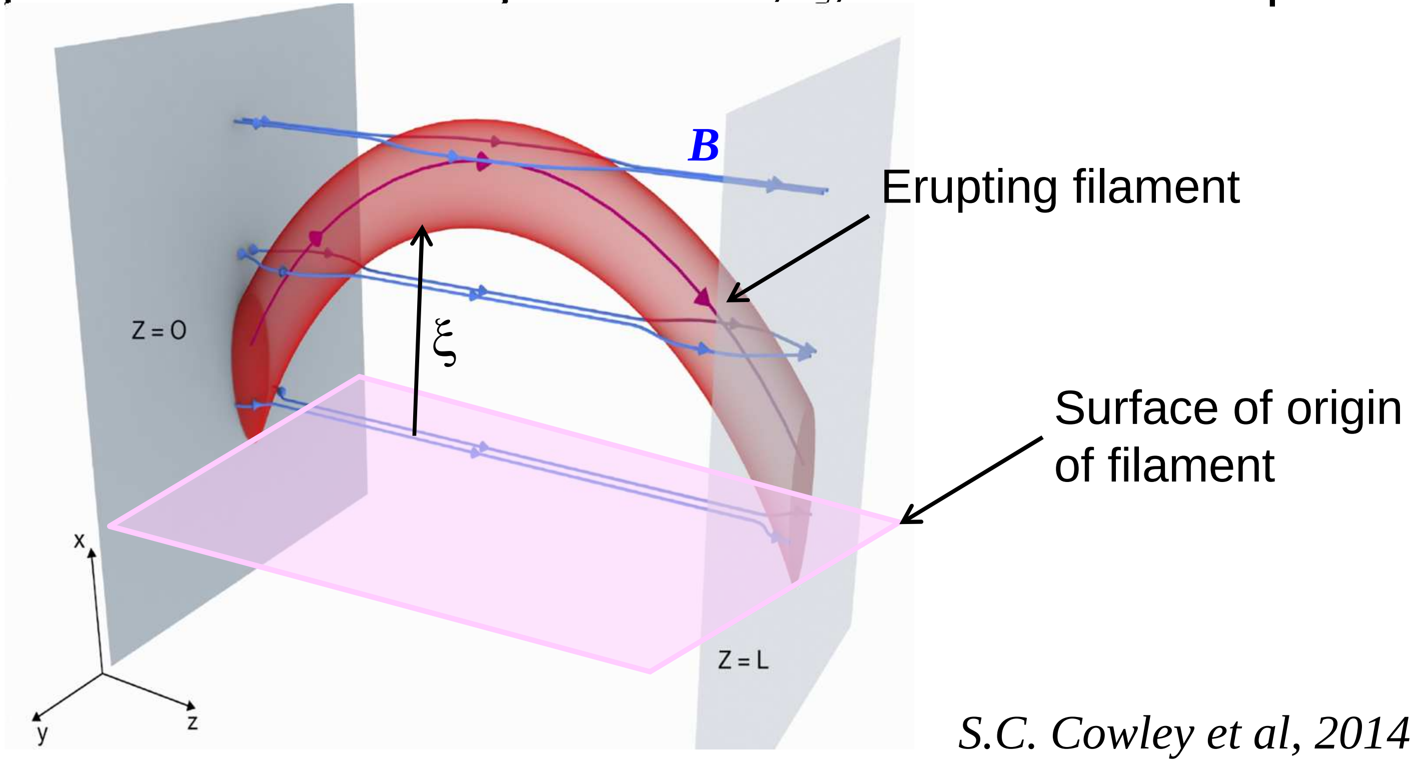
Wilson, PPCF, 2006

To Understand ELM Dynamics we must go to a non-linear model

Edge Localised Modes: Why is the ELM so violent?

- To understand this, we must proceed to non-linear ideal MHD theory
  - Describes the evolution of a long, thin plasma filament
  - Expand in the ratio of perpendicular (to B) to parallel wavelength
  - Treat the early non-linear evolution

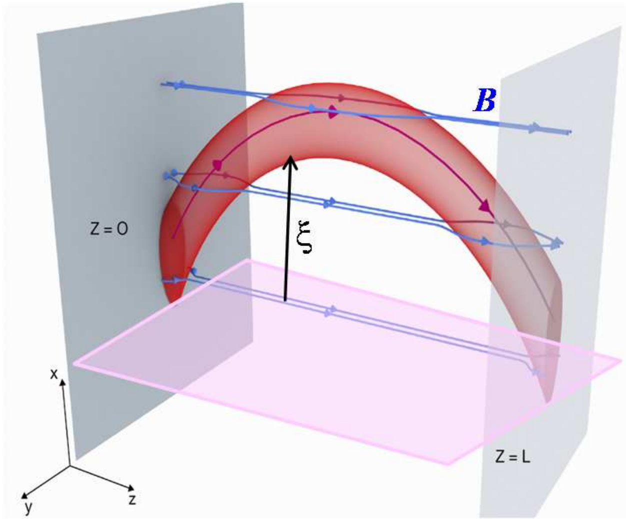
- Derive an expression for the displacement, ξ, of a filament of plasma



S.C. Cowley et al, 2014

Non-linear ballooning mode theory

- The leading orders in the expansion describe the behaviour of ξ along the direction of ***B***
  - Simply the linear ballooning mode equation



- Higher orders introduce the non-linearities and predict the filamentary nature of the eruption:

$$\frac{\partial^2}{\partial t^2}\frac{\partial \xi}{\partial y} = C_1\left[2(1-\mu)\frac{\partial \hat{\xi}}{\partial y} - C_0\int^y dy' \frac{\partial^2 \hat{\xi}}{\partial x^2}\right] + C_2\frac{\partial \hat{\xi}^2}{\partial y} + C_4\frac{\partial \hat{\xi}}{\partial y}\frac{\partial^2 \overline{\hat{\xi}^2}}{\partial x^2}$$

inertia

Linear instability drive

"Finite *n*" linear term (stabilising)

Non-linear drive term

Cubic non-linearity determines radial structure

Hurricane, et al PoP (1997)
Wilson, Cowley PRL, 2004

Solutions exhibit finite time singularity

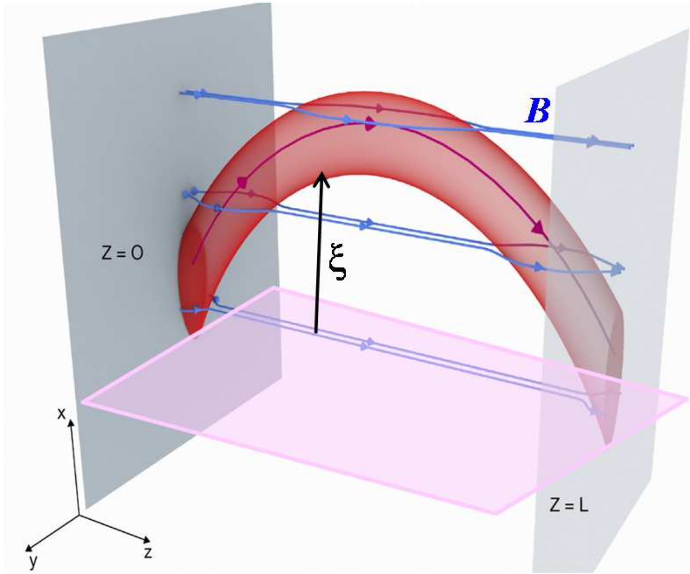
$$\frac{\partial^2}{\partial t^2}\frac{\partial \xi}{\partial y} = C_1\left[2(1-\mu)\frac{\partial \hat{\xi}}{\partial y} - C_0\int^y dy'\frac{\partial^2 \hat{\xi}}{\partial x^2}\right] + C_2\frac{\partial \hat{\xi}^2}{\partial y} + C_4\frac{\partial \hat{\xi}}{\partial y}\frac{\partial^2 \overline{\hat{\xi}^2}}{\partial x^2}$$

- Balance inertia and quadratic non-linearity

$$\frac{\partial^2 \xi}{\partial t^2} \sim \xi^2 \qquad \Rightarrow \qquad \xi \sim \frac{1}{(t_0 - t)^2}$$

- Balance the non-linear terms

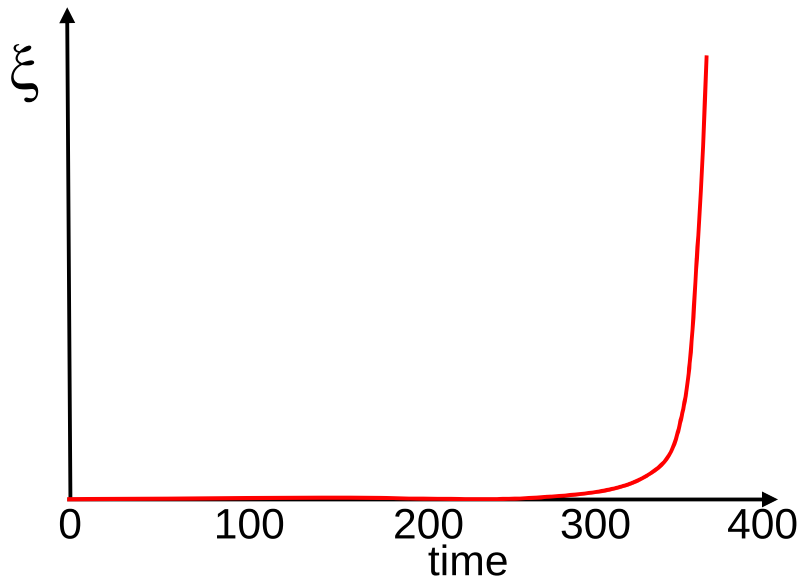
$$\frac{(\Delta x)^2}{\Delta y} \sim \frac{1}{(t_0 - t)^2}$$

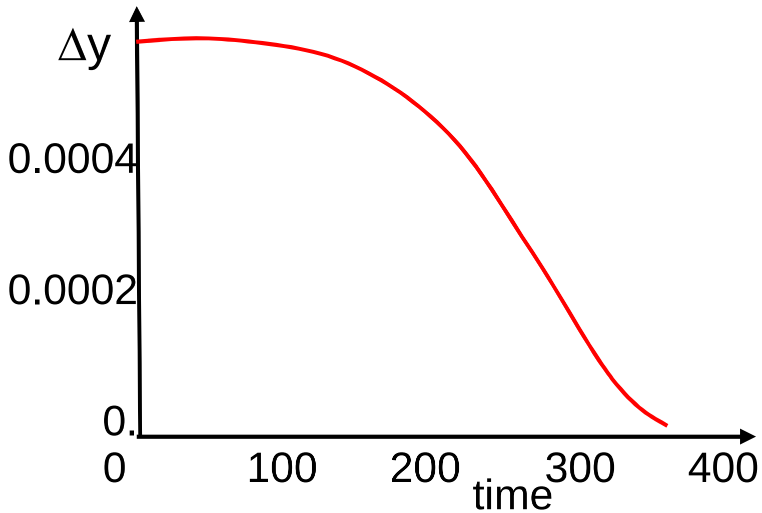


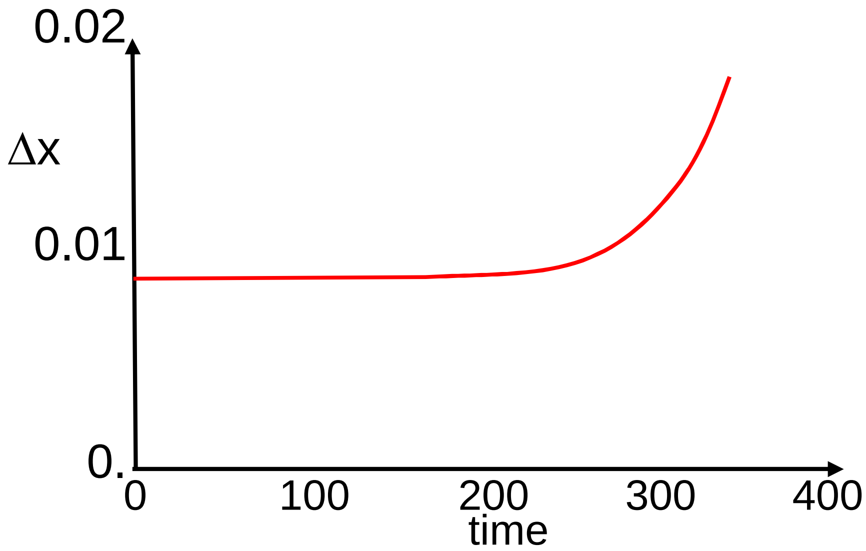
- As time approaches the finite time singularity $t \rightarrow t_0$:
  - Filament erupts explosively (even near linear marginal stability)
  - Filament narrows in the y-direction
  - Filament broadens in x-direction

Cowley, Artun; Phys Rep, 1997)

Numerical solutions to non-linear ballooning reproduce these features



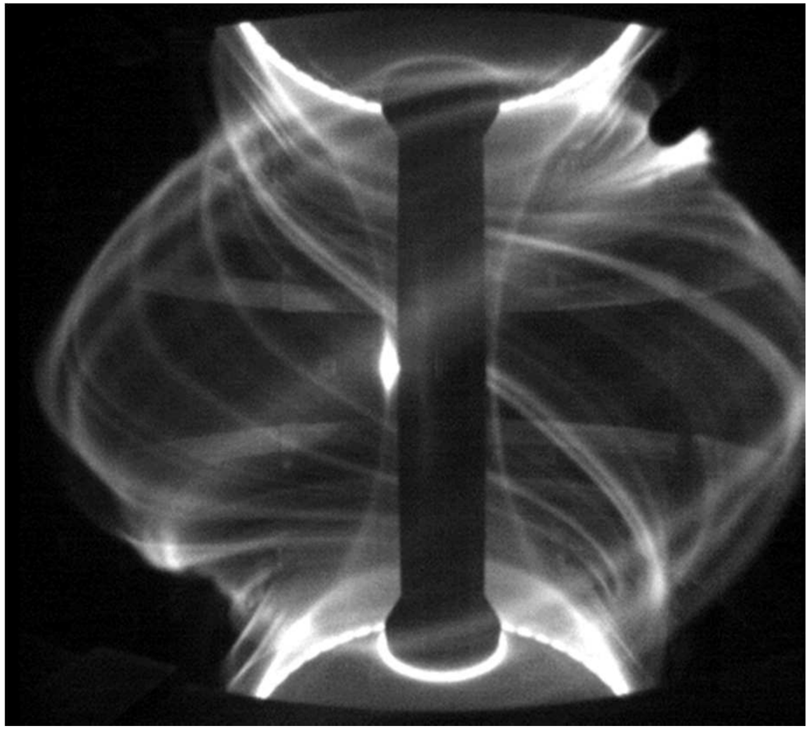




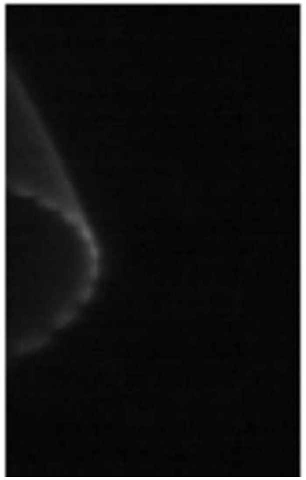
S. Henneberg, et al, 2014

Filaments can erupt far from plasma: An issue for plasma-facing ITER components

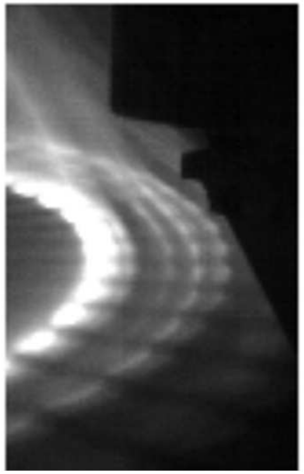
- Filaments erupting far from plasma surface are an issue for plasma-facing components in ITER
  - Potentially form a "hose-pipe" from the hot pedestal plasma to close material surfaces
  - Localised "hot-spots" on material surfaces



Between ELMs

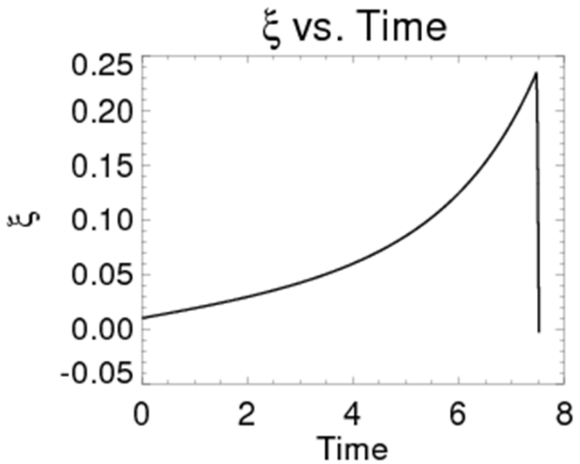


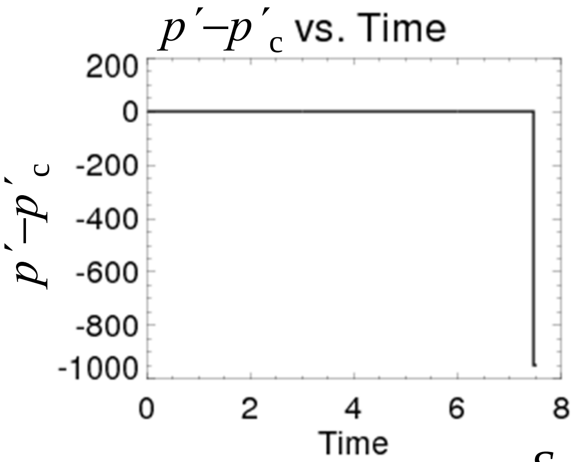
During ELMs



Can we predict the energy ejected in an ELM?

- In ideal MHD, plasma is tied to magnetic field lines
  - must go beyond ideal MHD to have a rigorous model for ELM size
- However, we can adopt the following semi-heuristic model
  - Impose an increase in pressure gradient, passing through marginal stability
  - When non-linear and linear terms balance, assume non-ideal processes result in transport (but don't say what the mechanism is)
  - Crash the pressure gradient until ξ is momentarily stationary
  - This then yields a prediction for energy ejected





2^{nd} order time derivative

S. Henneberg, et al, 2014

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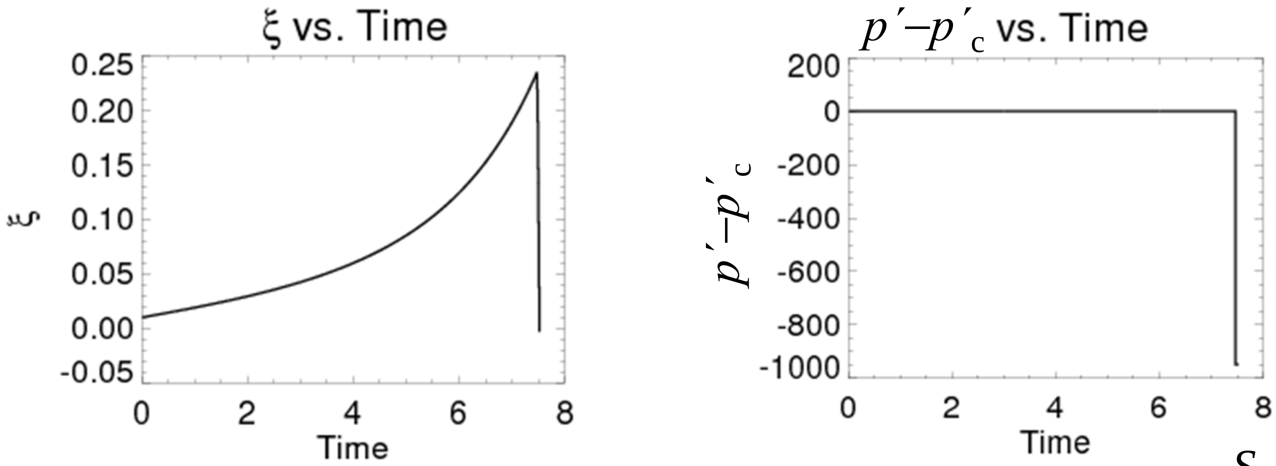

2nd order time derivative

S. Henneberg, et al, 2014

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  – The mechanism for turbulence suppression to form the pedestal
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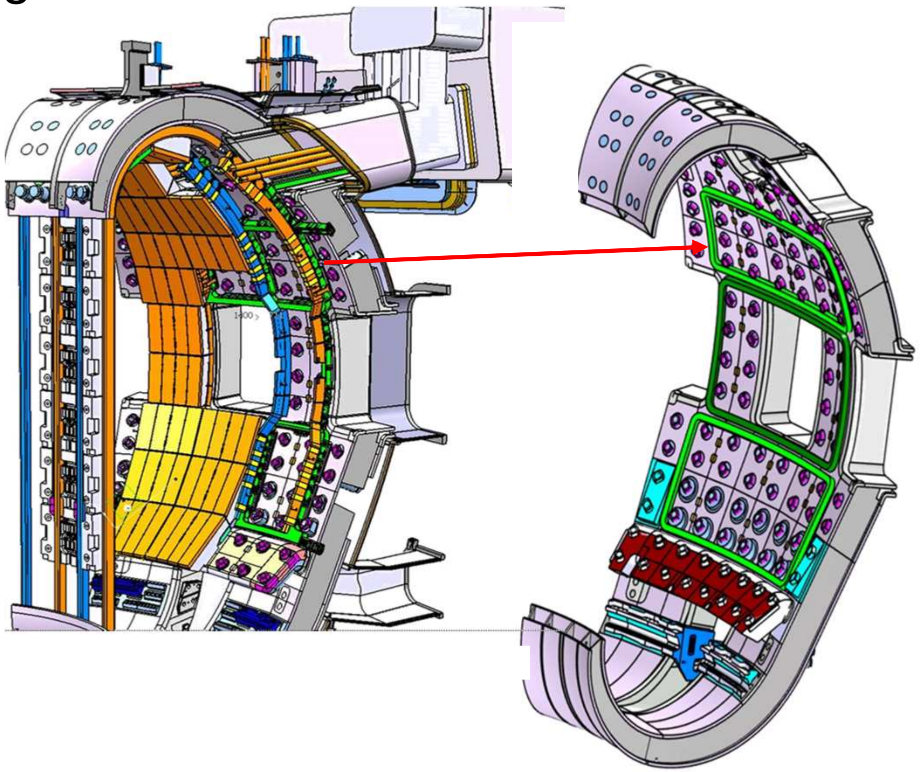
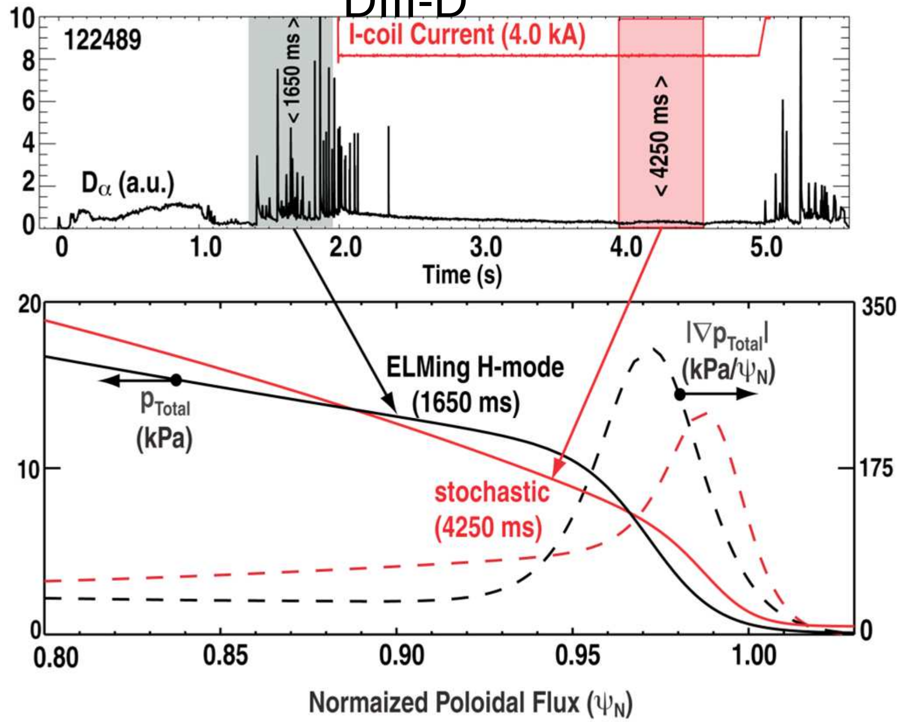
ELM control on DIII-D: Resonant Magnetic Perturbations

- Can we degrade confinement at the plasma edge without affecting the core?
- A system of coils perturbs the confining magnetic field, reducing pressure gradient



DIII-D

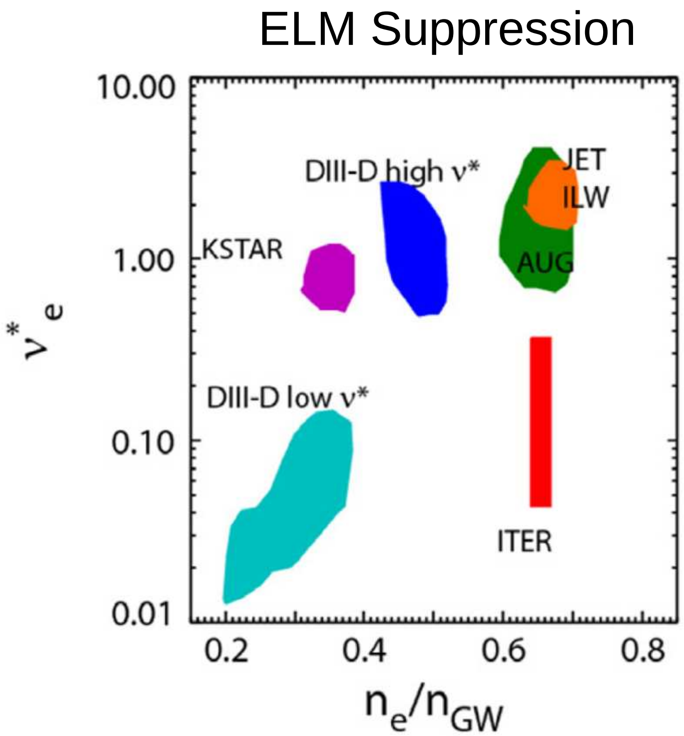


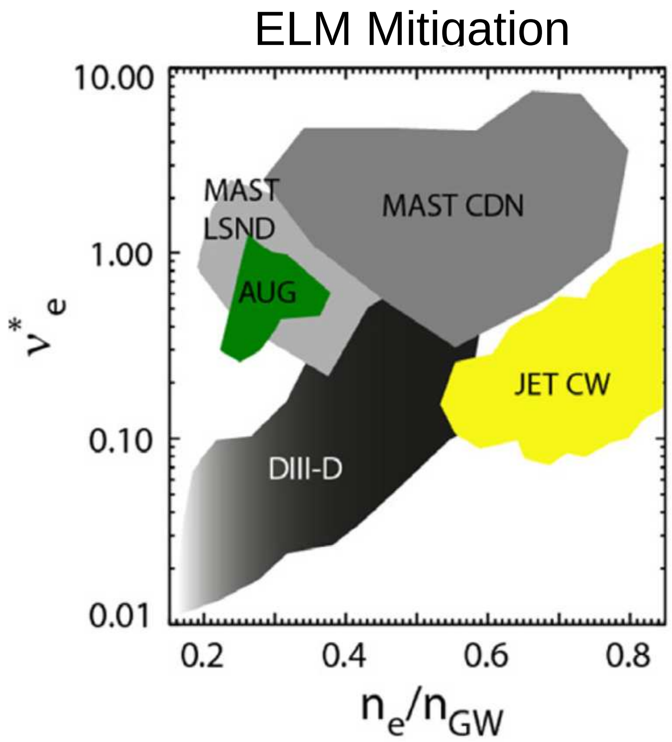
T. E. Evans, et al., Phys. Plas 13 (2006) 056121

- Only works under certain conditions: not fully understood
- The physics of plasma interacting with such magnetic fields in subtle
- Needs rigorous theoretical models and further tests on other tokamaks

RMP ELM suppression on several tokamaks

- RMP ELM suppression observed at ITER-relevant parameters
  - But parameters not matched simultaneously
  - And not on all tokamaks





A Kirk, et al PPCF 2013

- ELM mitigation observed much more widely

ELM control on MAST: Resonant Magnetic Perturbations

- ELM suppression physics has been studied in depth on MAST

MAST ELM control coils

RMP ELM control on MAST: ELM mitigation, but not suppression

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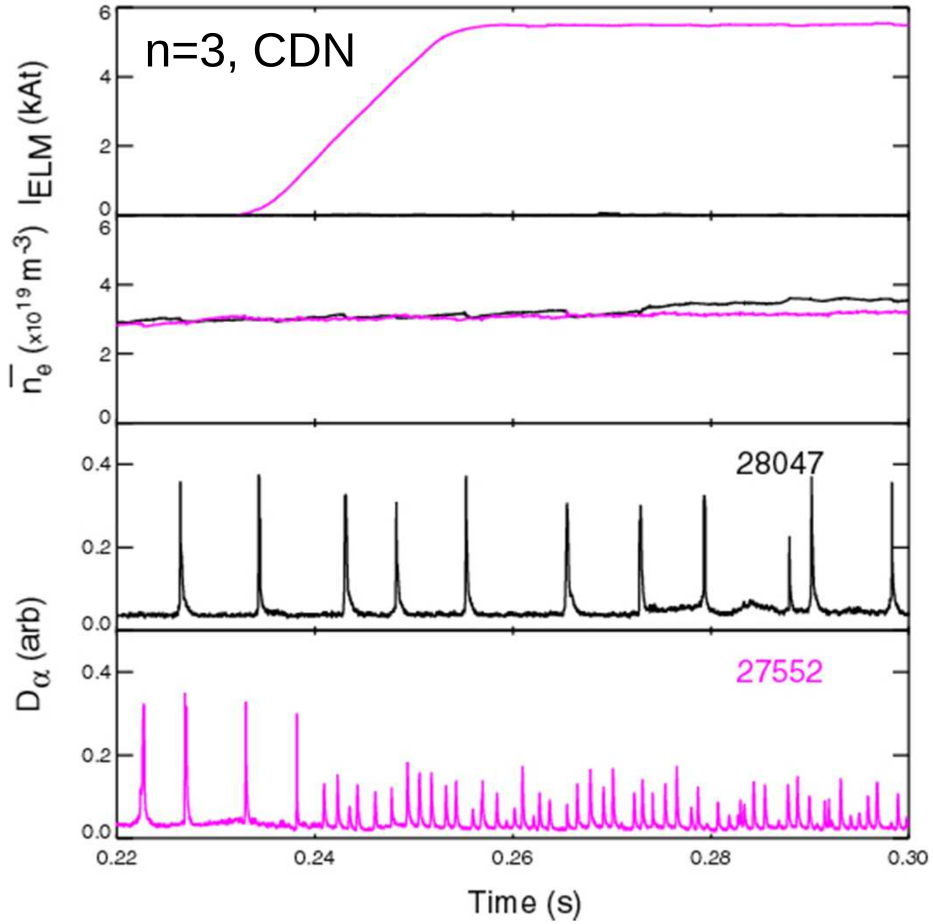
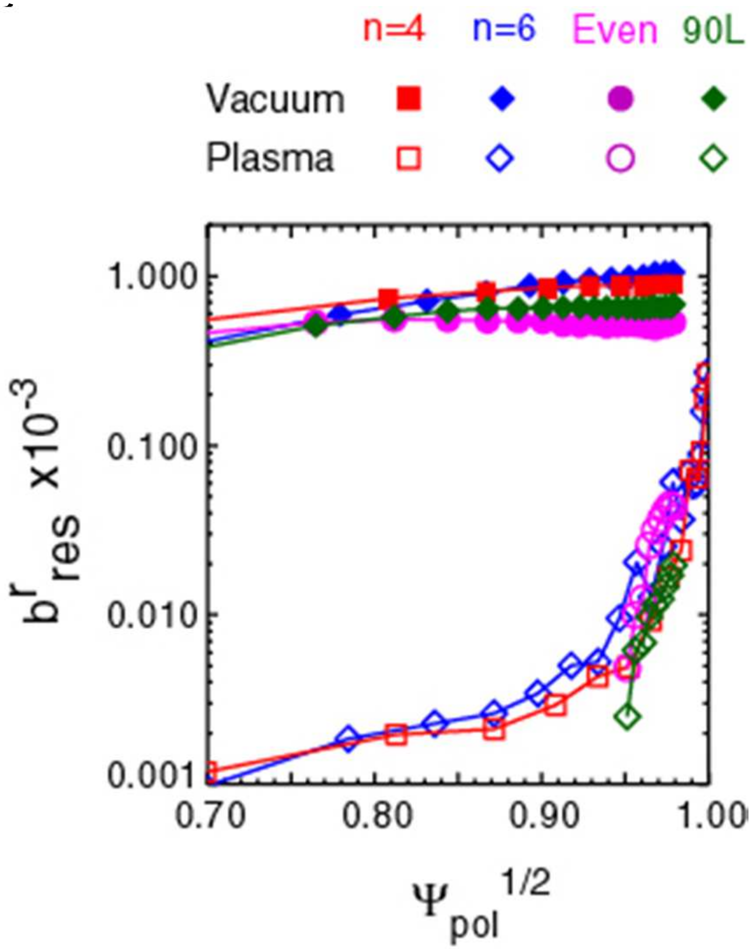
- Key to understanding is the plasma response





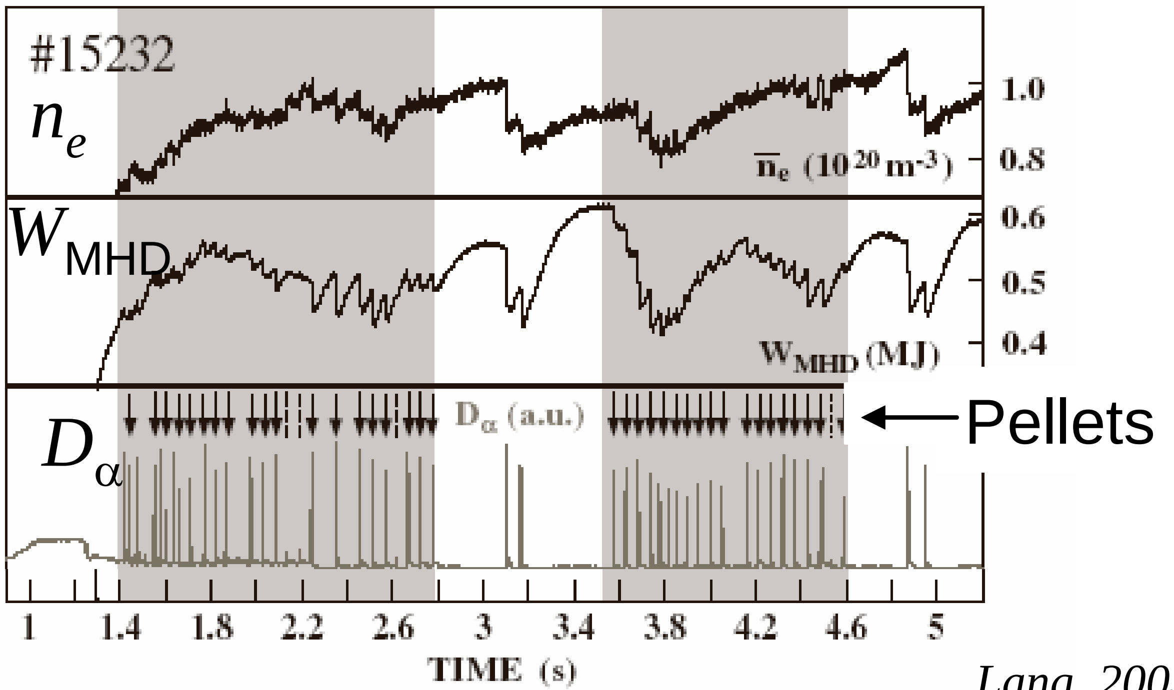
- Part of the challenge is understanding the response of the plasma to the magnetic perturbations

A Kirk, IAEA Fusion Energy Conference,2012

ELM control: Pellet injection

- Can pellets be used to trigger an ELM before the stored energy is large?
  - Aim is to produce smaller, more frequent, ELMs (size ~1/frequency)
  - Successfully demonstrated on AUG, JET and DIII-D
- Key question – is there a maximum ELM frequency/minimum ELM size?

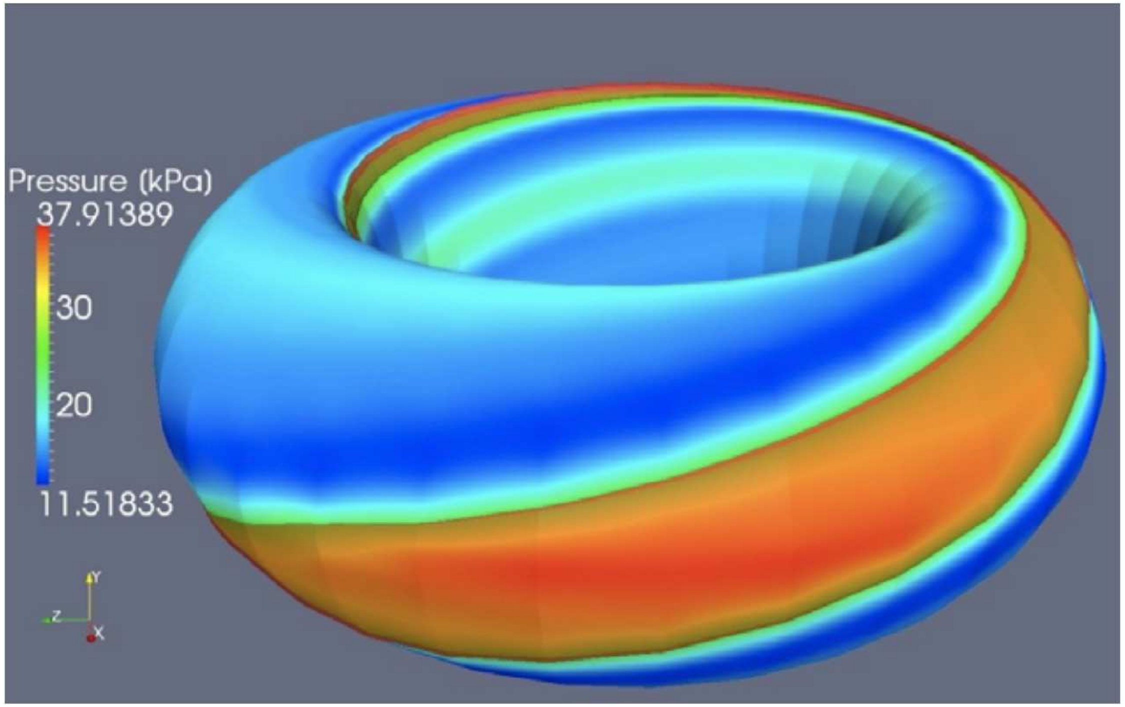
ASDEX Upgrade: pellet triggering



Lang, 2003

ELM control by pellet injection: Nonlinear MHD modelling reveals mechanism

- Nonlinear modelling with JOREK MHD code reveals possible mechanism for pellet triggered ELM
  - Small pellets diffuse away, while larger ones drive a large density perturbation

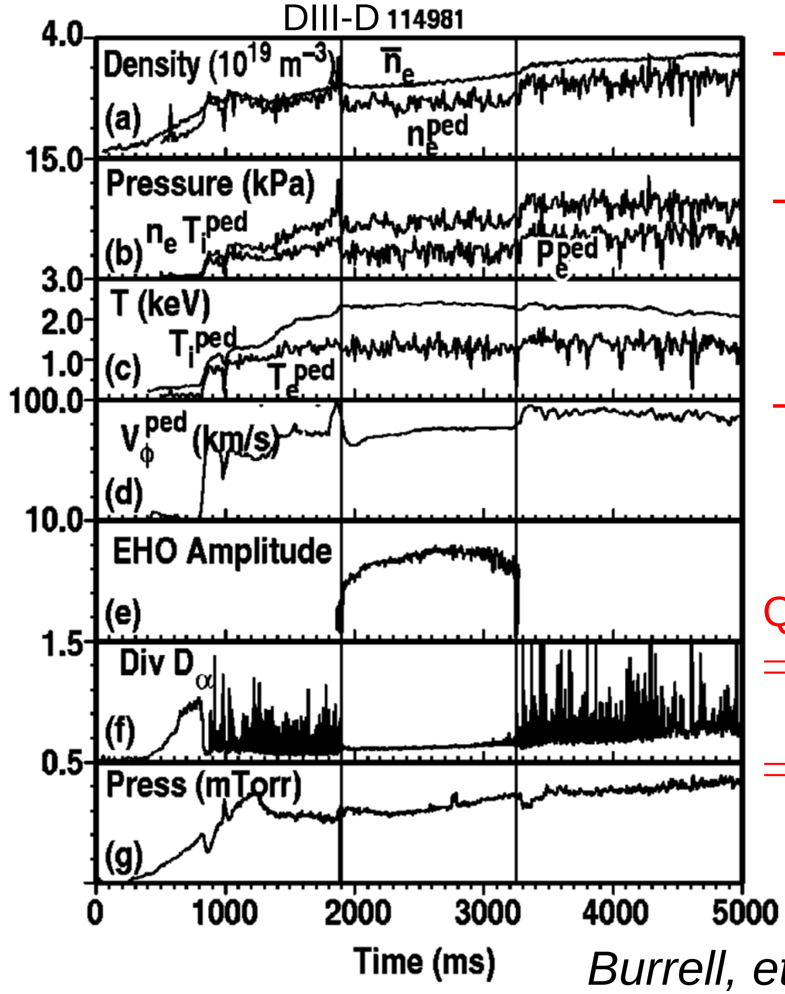


Futatani, et al, Nuclear Fusion 2014

- Adiabatic process, so no immediate pressure rise
  - Plasma cools to compensate density rise
- Leads to parallel temperature gradients which rapidly equilibrate
  - Higher pressure triggers the ELM

Regimes without ELMs: The QH-mode

- Regimes without ELMs include the EDA-mode and QH-mode
  - Consider QH mode, which may have relevance for ITER

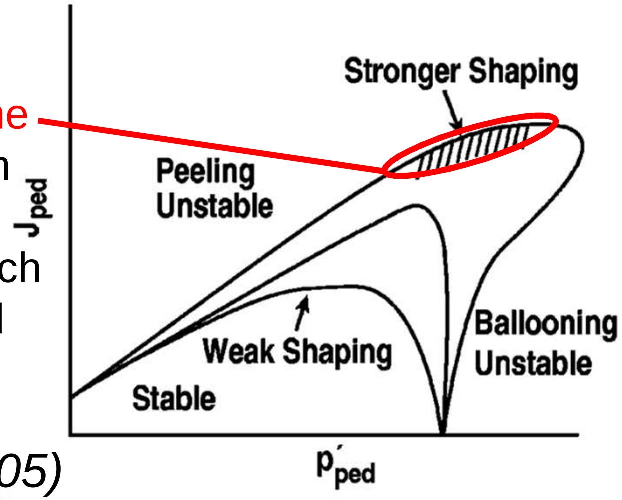


  - A large, coherent magnetic structure sits in the pedestal (the Edge Harmonic Oscillation, or EHO)
  - We believe this enhances transport in the pedestal, keeping the pressure gradient below the peeling-ballooning limit for ELMs
  - Requirements of strong shaping, low current and sufficient edge flow shear consistent with peeling-ballooning stability

QH Mode operating regime

⇒ Suggests EHO is low n kink

⇒ Conditions must be such that this is destabilised before ballooning



Burrell, et al Phys Plasmas (2005)

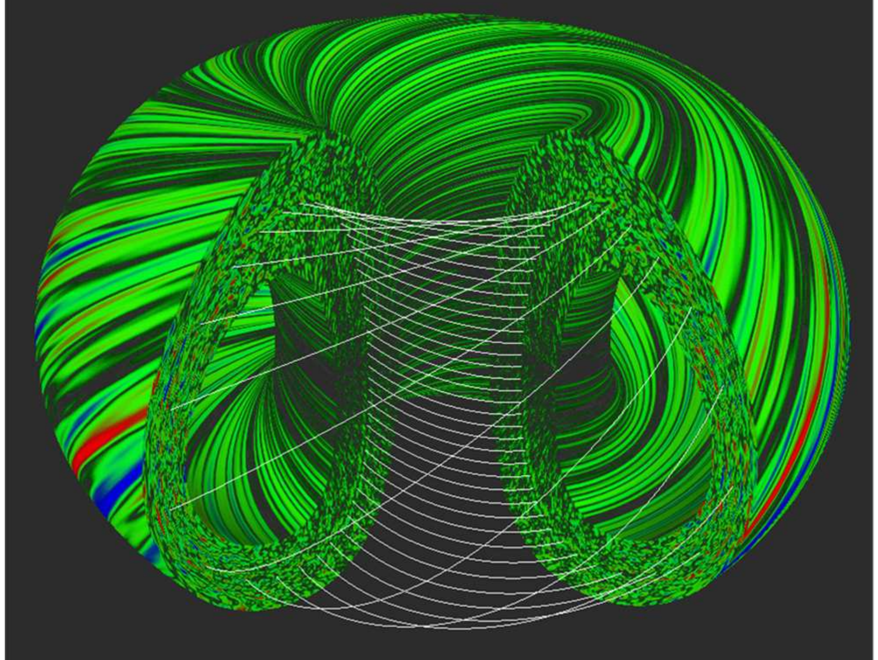
Background: Pedestal physics

- The pedestal is controlled by three physics mechanisms:
  - The mechanism for turbulence suppression to form the pedestal
  - The plasma eruptions called ELMs, and their control
  - How the remaining turbulence and pedestal stability interact to determine the pedestal width and height (or gradient)

The nature of tokamak turbulence: Basic properties

- Turbulence can be driven by a range of plasma "micro-instabilities"
- In a tokamak plasma, these have a number of generic properties:
  - – Limited spatial variation along magnetic field lines
  - – Small scale eddy structures across magnetic field lines:

    $\sim(r\rho_i)^{1/2} \sim(1\text{m} \times 2\times10^{-3}\text{m})^{1/2} \sim 4\text{cm}$
  - – It is these eddies that lead to enhanced transport
  - – Suppress the turbulence, and you will improve the confinement



Simulation from Gyro code

The nature of tokamak turbulence: Influence of plasma flow

- Sheared flows can suppress turbulence and/or reduce the size of turbulent eddies
  - Flows are observed and likely play a key role in the pedestal formation

Code: GYRO

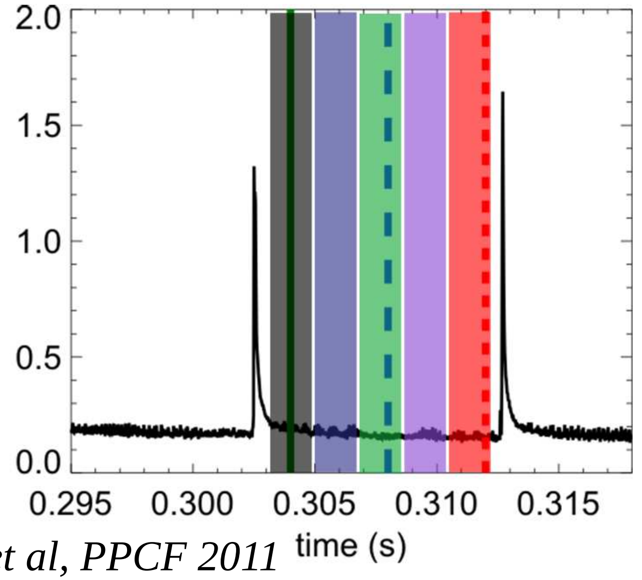
Authors: Jeff Candy and Ron Waltz

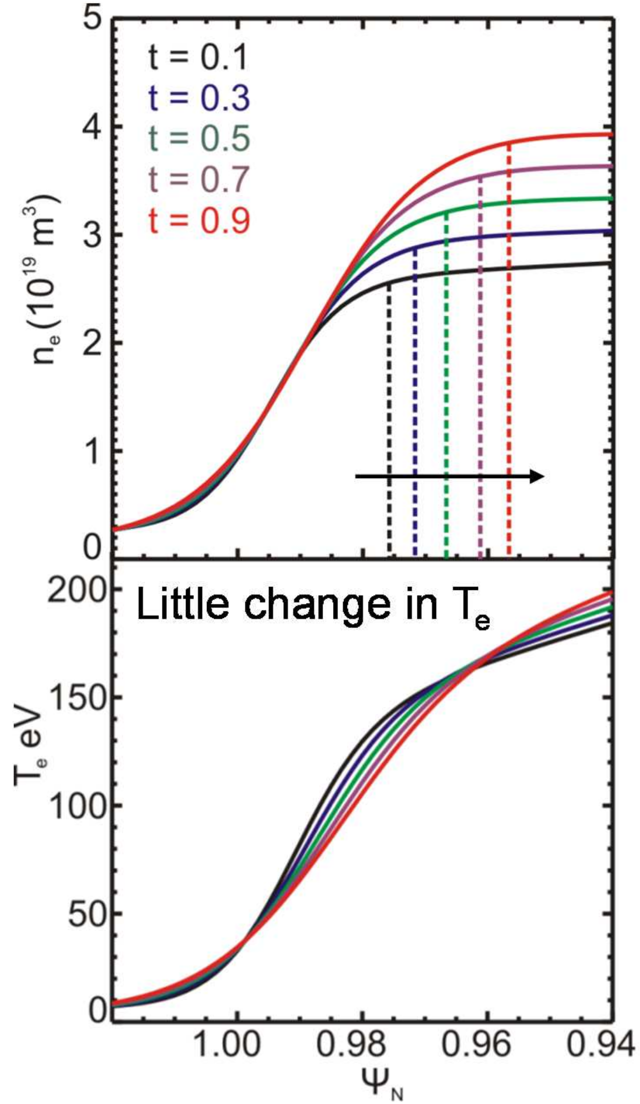
- Key long-standing questions remain:
  - Quantifying the impact of flows on turbulence
  - Where does the flow come from in the first place?

Which micro-instabilities determine the pedestal structure?

Micro-instabilities Background

- Transport processes in the pedestal can be explored by considering the pedestal evolution between ELMs
- On MAST (and DIII-D, not JET), it is found that
  - The temperature profile does not evolve significantly
  - The density pedestal widens at fixed gradient

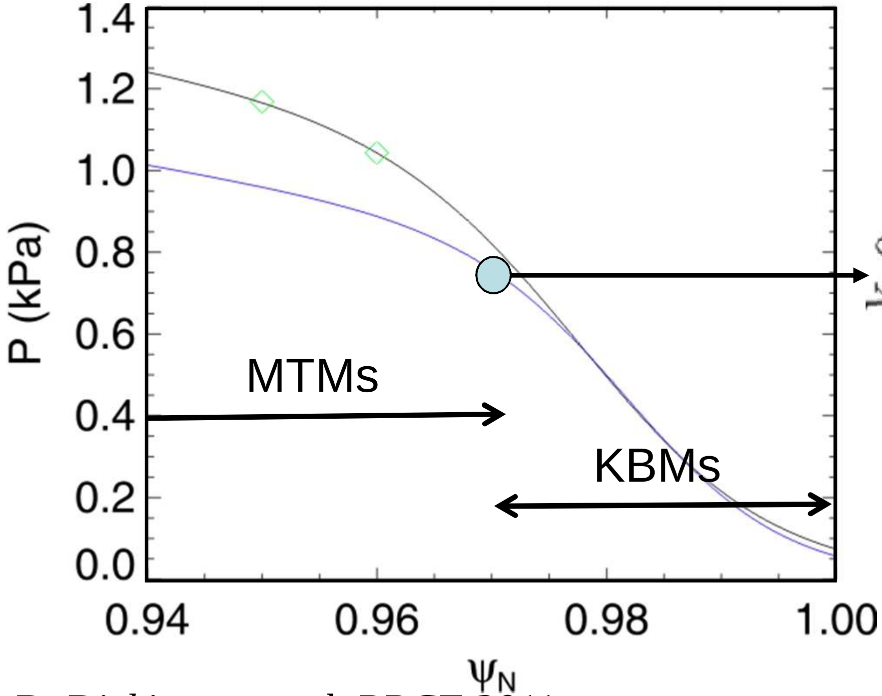


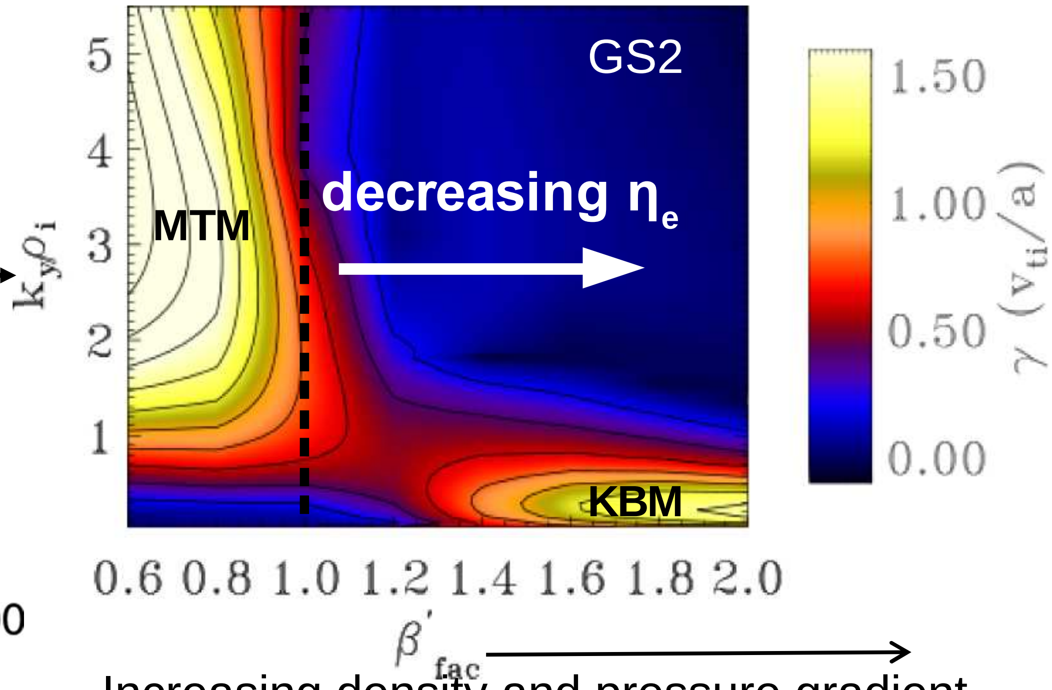


D. Dickinson, et al, PPCF 2011

Micro-instabilities in the pedestal

- Gyrokinetic simulations of the MAST pedestal show:
  - At low density gradient, the micro-tearing mode is unstable
  - At higher density gradient this mode is stabilised, but the kinetic ballooning mode is instead destabilised as the pressure gradient rises

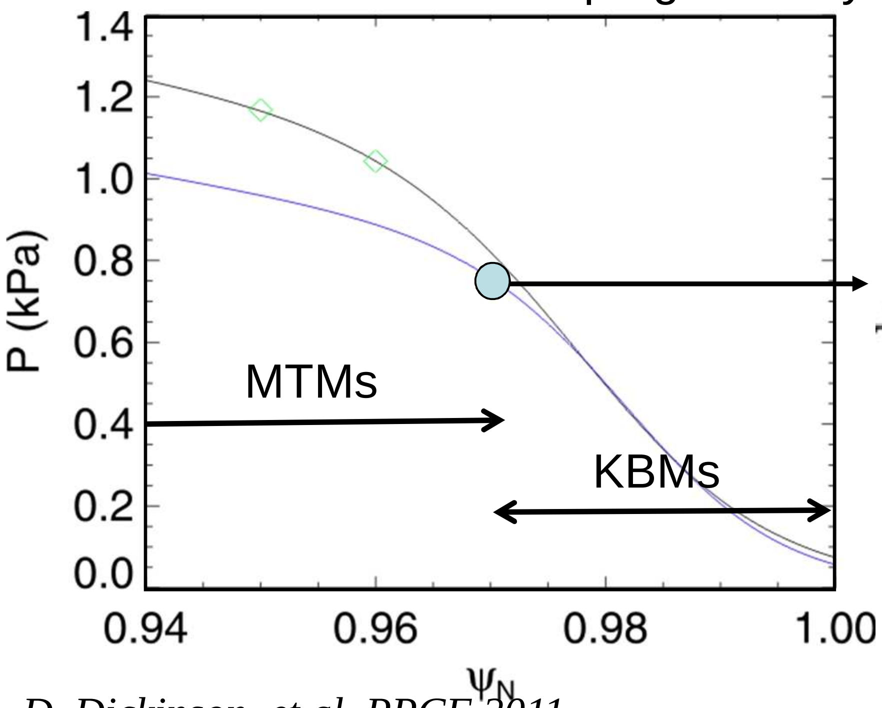


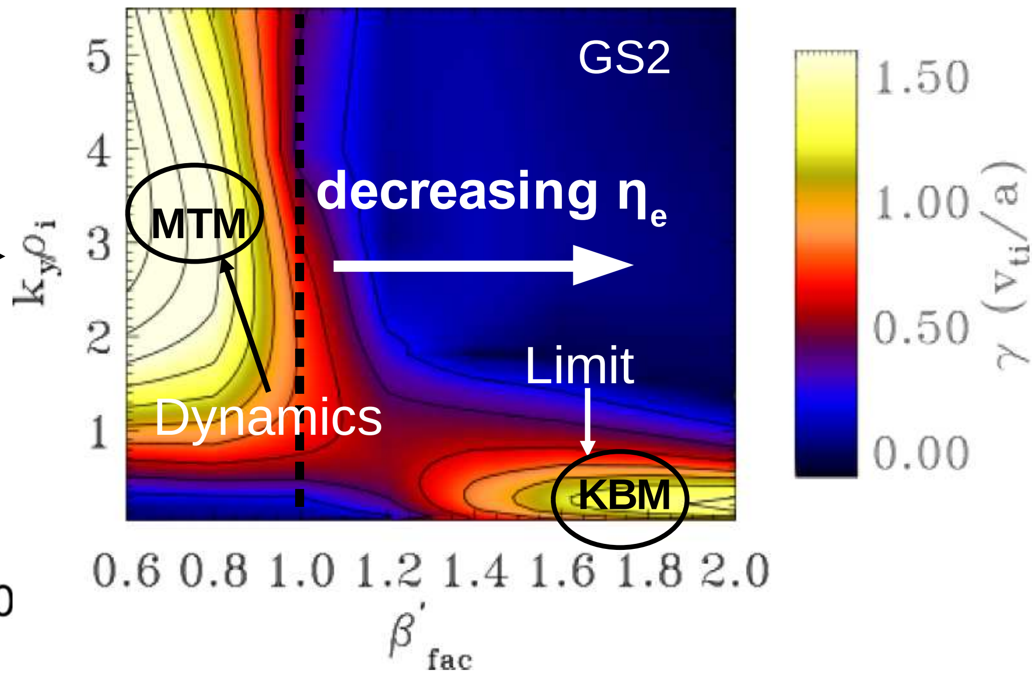


D. Dickinson, et al, PPCF 2011
D. Dickinson, et al, PRL 2012

A model for pedestal formation

- Simulations suggest the following model:
  - The pedestal gradients are initially held low by the micro-tearing mode
  - This mode is initially stabilised close to the plasma edge, allowing the pressure gradient to build until the KBM is destabilised
  - As the MTM is progressively stabilised, the pedestal widens into the core





D. Dickinson, et al, PPCF 2011
D. Dickinson, et al, PRL 2012

Background: Pedestal physics

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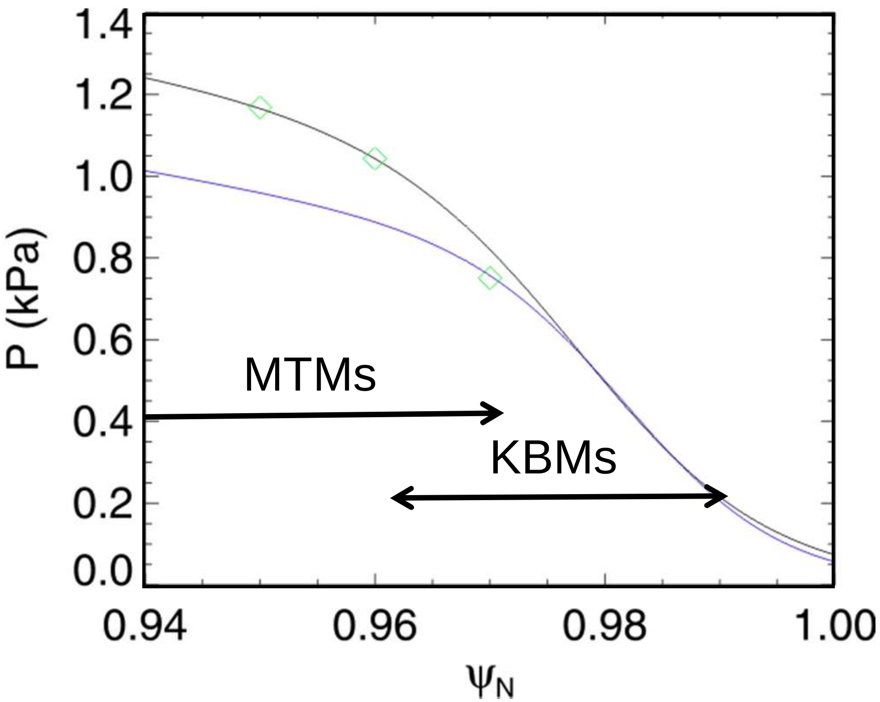
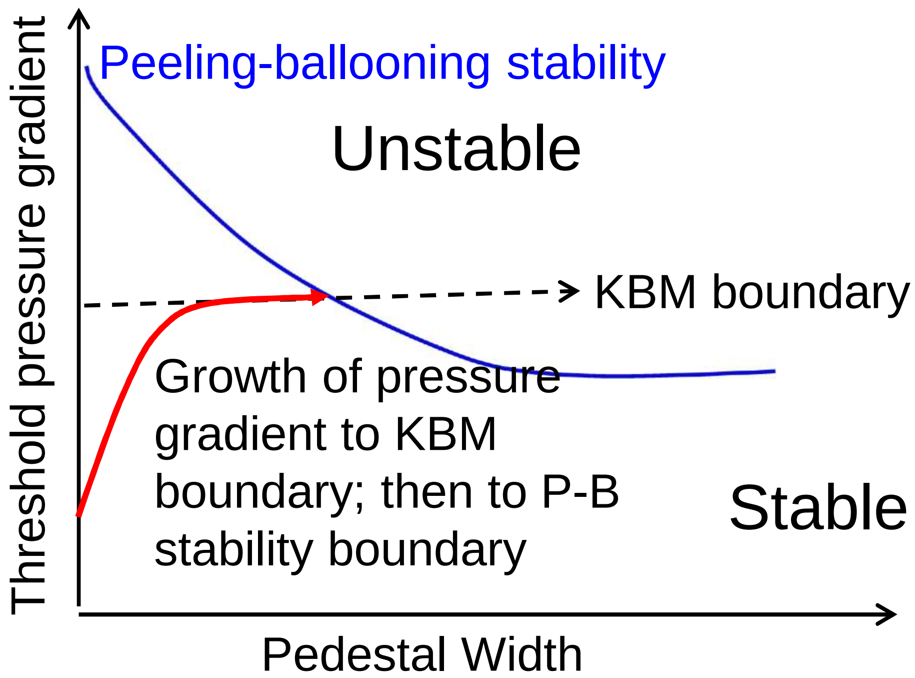
So what limits the extent of the pedestal penetration?

- The more the pedestal penetrates, the greater the pedestal width and the higher the core pressure
  - So what limits the pedestal width?
- It is actually the peeling-ballooning stability limit
  - A wider pedestal has a lower threshold for instability





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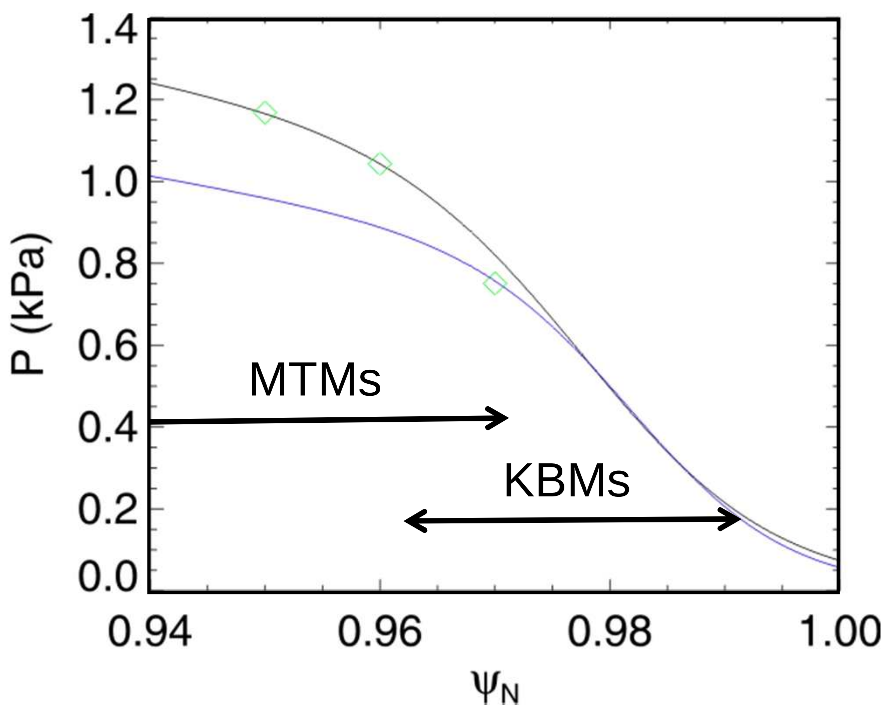
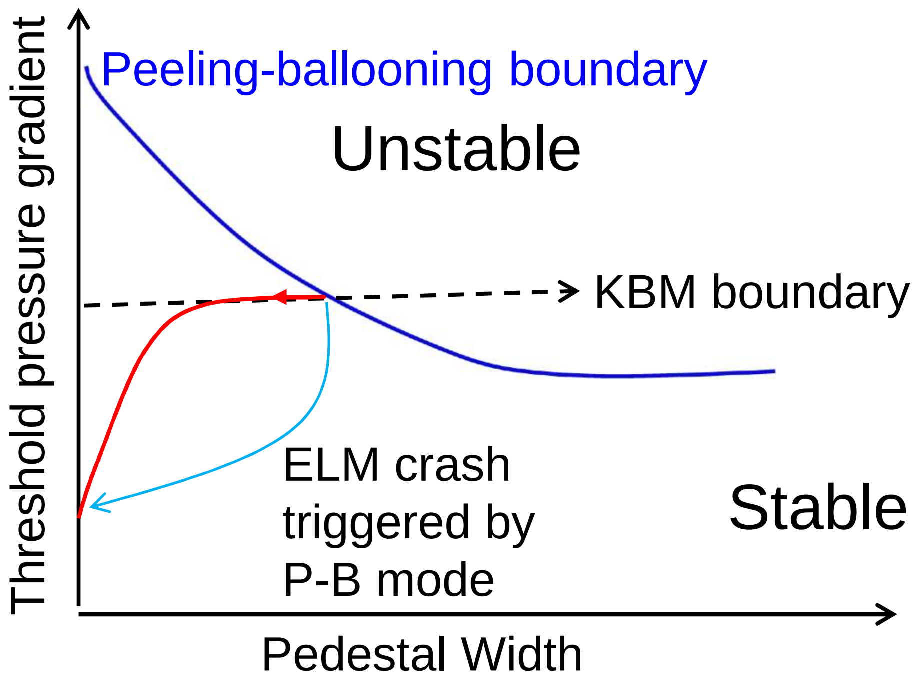
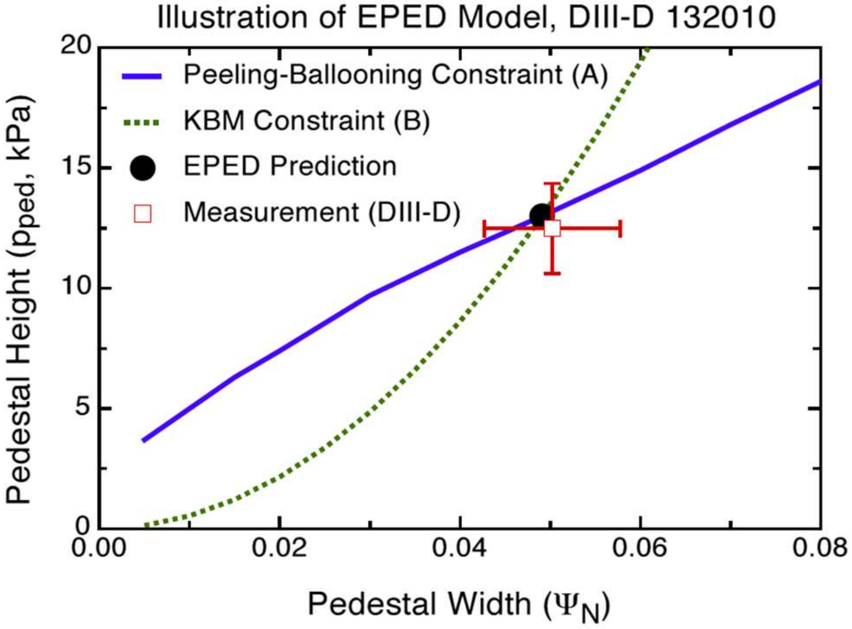
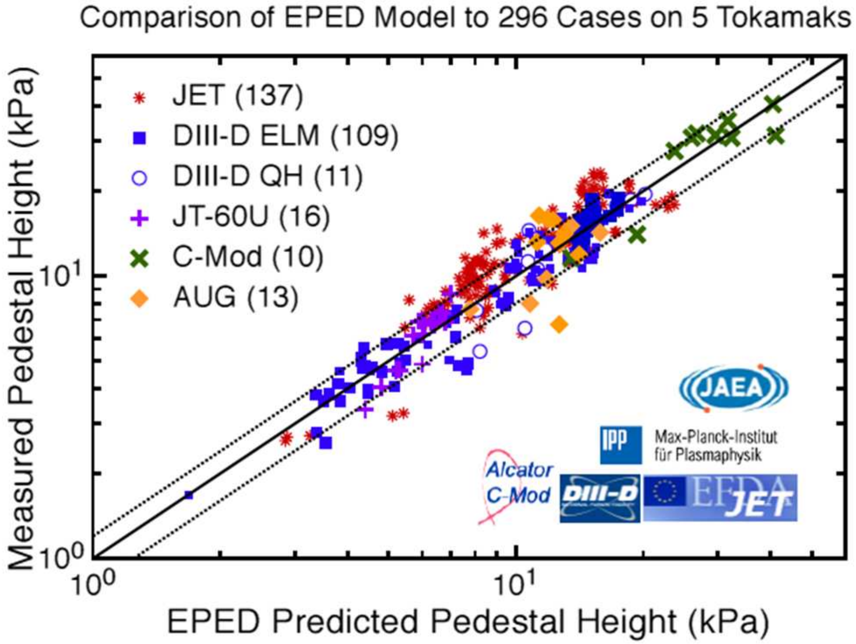




EPED model: a predictive model for the pedestal pressure

- Locally, we expect $\Delta \sim \beta_p$ from KBM constraint
- Experimentally, pedestal width, $\Delta \sim \beta_p^{0.4}$
  - EPED accounts for variation of shear as width increased:
    - averaging over this yields the EPED model: $\Delta \sim \beta_p^{1/2}$
  - A proxy is that the KBM limit is the n=∞ ballooning limit

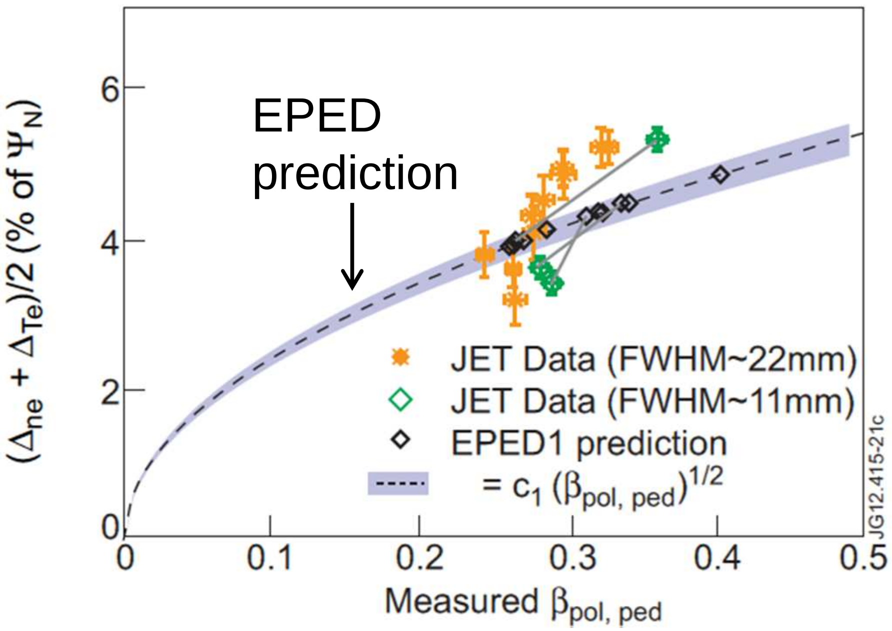


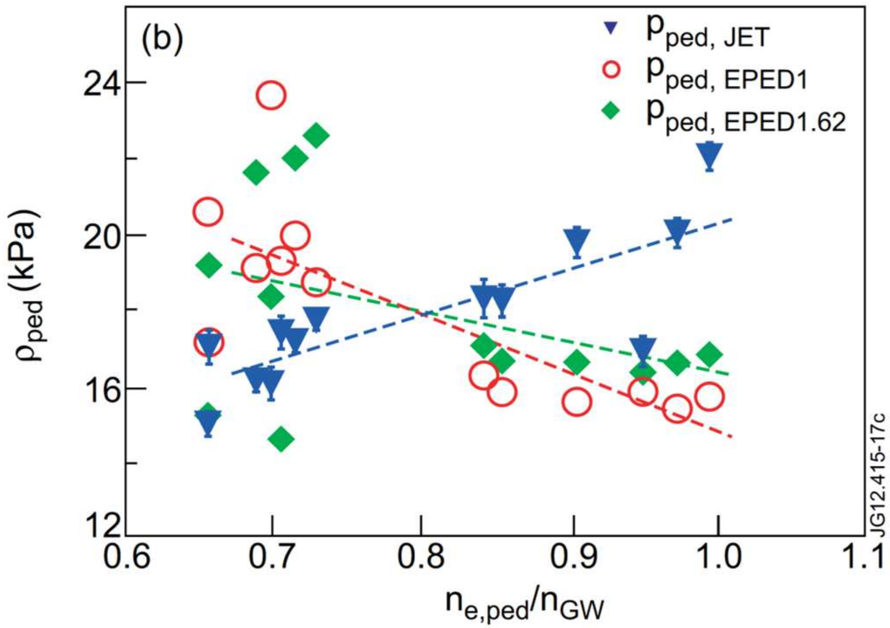


P.B. Snyder et al Phys Plas ***16*** *056118 (2009), NF* ***51*** *103016 (2011)*

EPED model: A major advance, but not the full picture

- While EPED broadly predicts pedestal width, there are differences in trends
- Recent analysis from JET, for example:





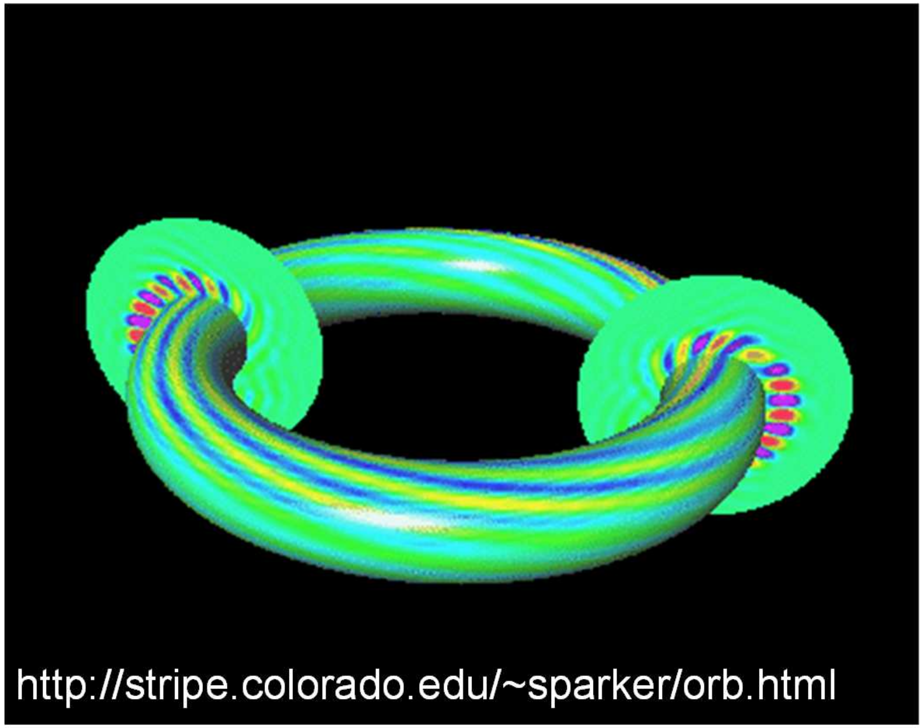
M Leyland, et al, Nucl Fusion 2013

- Also on JET, the pedestal appears to narrow into the ELM cycle, rather than broaden – a challenge for the model (but there are ideas)

Local vs Global Calculations of Micro-instabilities
A speculative model for Grassy ELMs

Local vs Global approach

- Micro-instabilities have a short wavelength across magnetic field lines, but long wavelength along



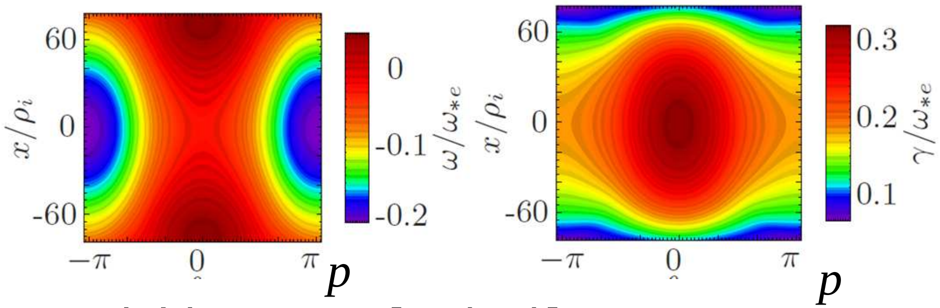
- A global code solves for the full mode structure
- A local code exploits this small ratio of wavelengths
  - Determines the stability of a given flux tube – "local complex mode frequency: $\Omega_0(x, p)$
- The leading order provides the behaviour (e.g for ϕ) along field lines (a "flux tube") and $\Omega_0(x, p)$
- Higher order theory determines
  1. The poloidal localisation
  2. How to build up the radial profile
  3. The true growth rate from the local one

Two types of toroidal mode structure: "Isolated" and "General" Modes

Isolated modes: Most dangerous, but rare

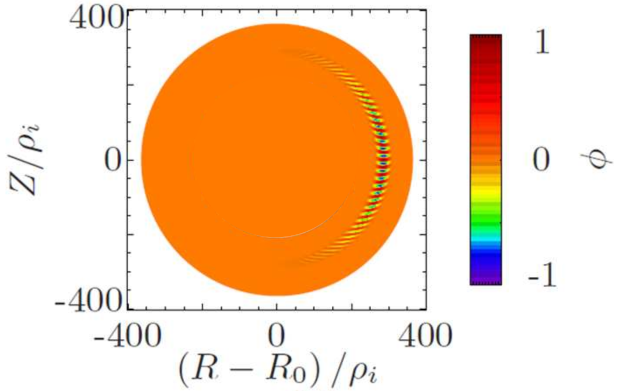
– Peak in ITG instability drive profile, $\eta_i(x)$

– $\Omega_0(x,p)$ has a stationary point



– Yields Ω=Max[$\Omega_0(x,p)$]

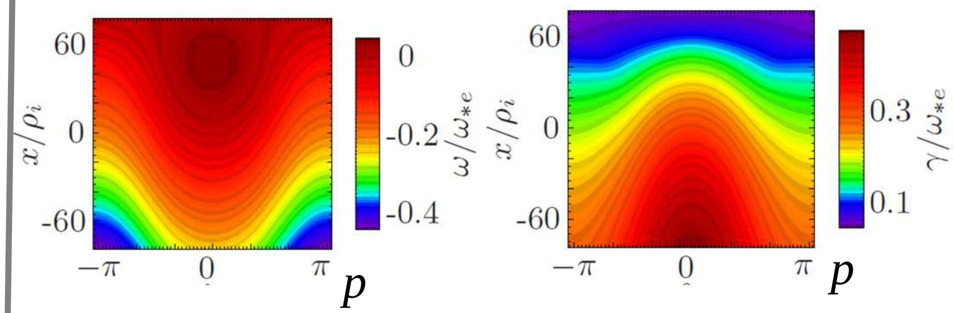
– Mode balloons on outboard side



General modes: Less dangerous, but common

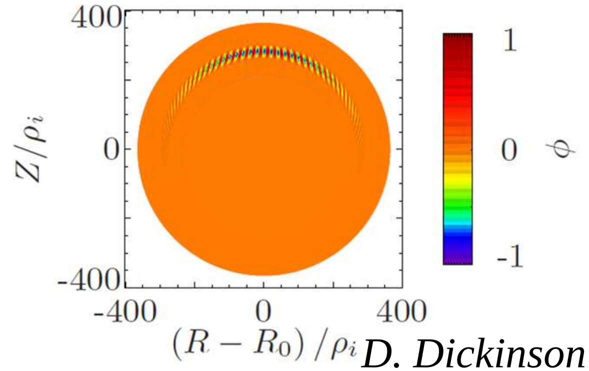
– Linear ITG instability drive profile, $\eta_i(x)$

– $\Omega_0(x,p)$ is linear in x



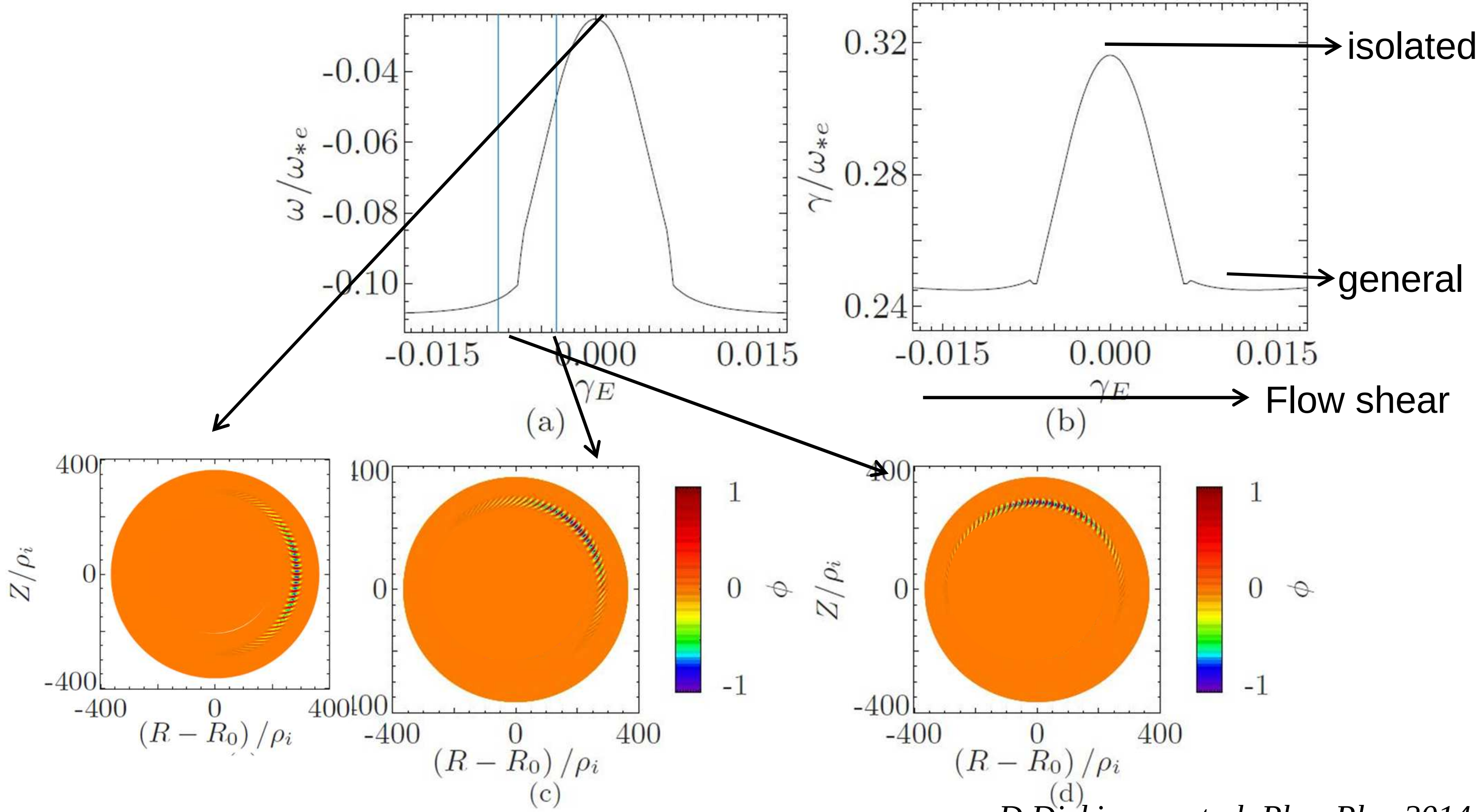
– Yields Ω=Average[$\Omega_0(x=0,p)$]

– Mode balloons at top or bottom



D. Dickinson, et al PoP 2014

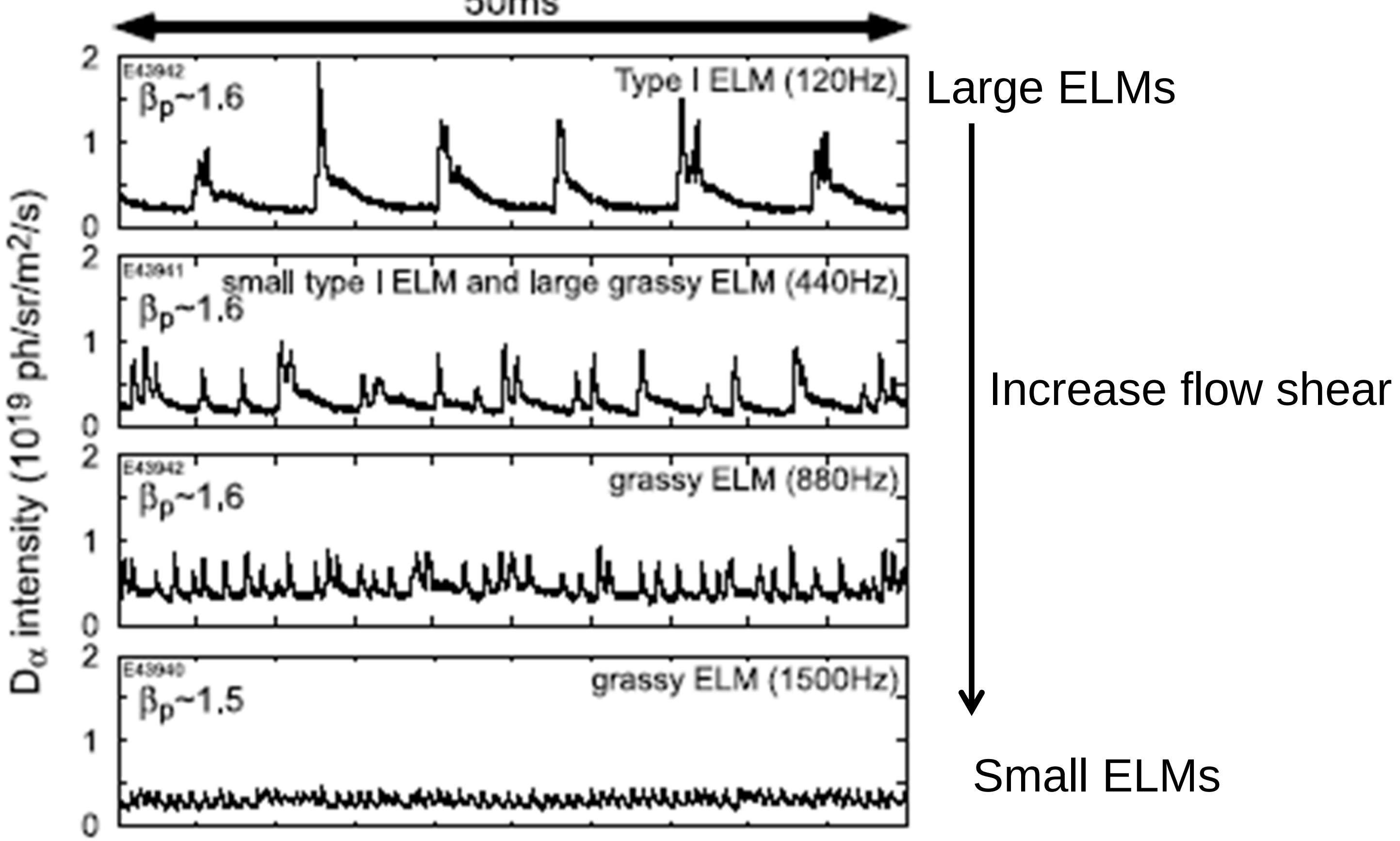
Flow shear provides a control knob: Transition between mode types



D Dickinson, et al, Phys Plas 2014

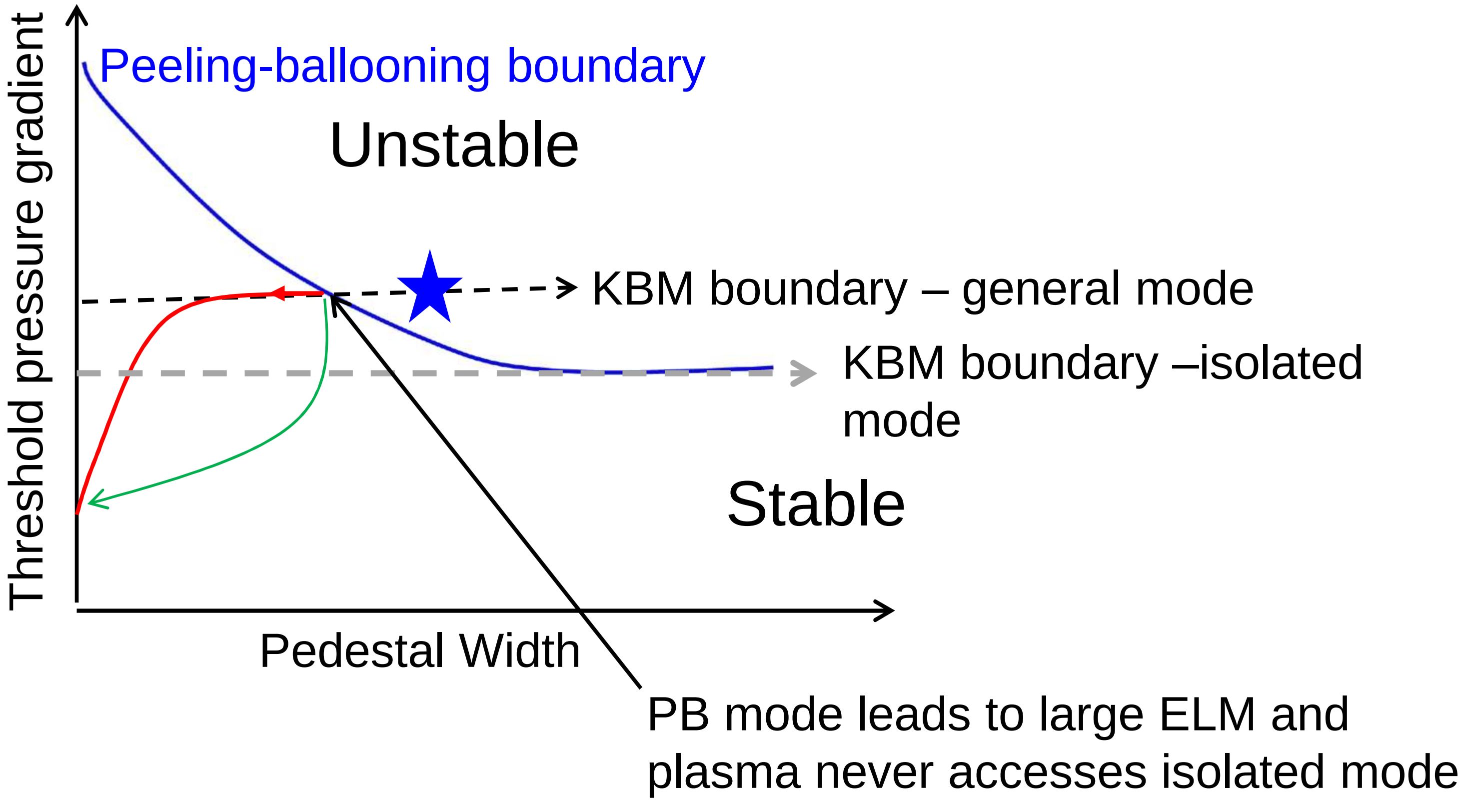
Could this be an ingredient for small ELM regimes?

JT-60U *Oyama 2005*



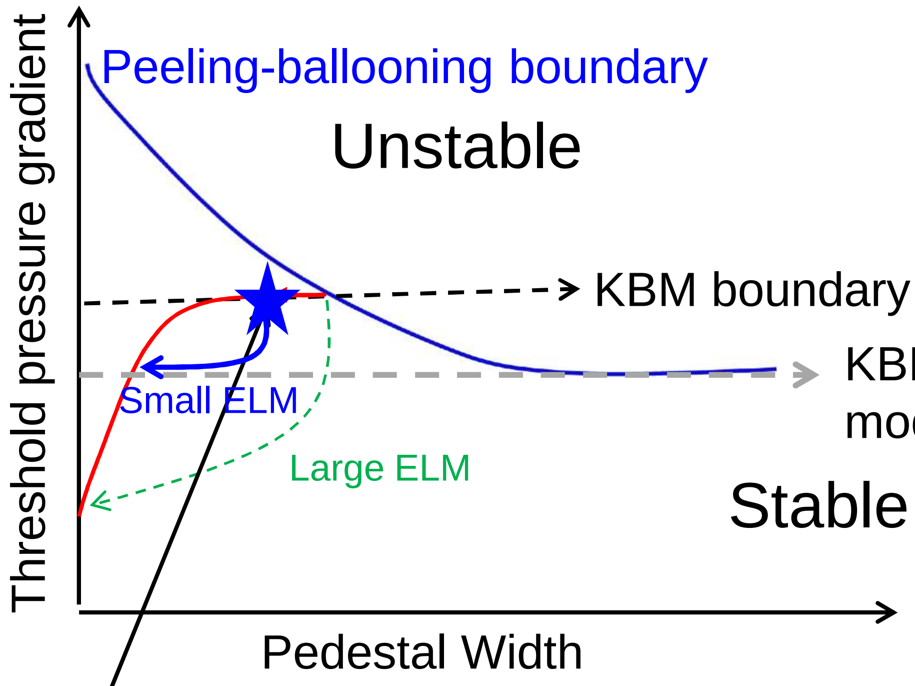
Towards a model for small (Grassy?) ELMs

- Let us return to our pedestal evolution model
- Assume at some point ★ the conditions are right for the isolated mode
- Large ELM situation ★ beyond ideal MHD boundary



Towards a model for small (Grassy?) ELMs

- Let us return to our pedestal evolution model
- Assume at some point ★ the conditions are right for the isolated mode
- Small ELM situation ★ is encountered before large scale MHD event



If conditions for isolated mode are satisfied at ★ (as flow evolves), plasma suddenly unstable ⇒ small ELM crash

Summary

- The pedestal region is key for confinement in ITER and the requirements of the plasma exhaust system
- The pedestal properties are a consequence of an interaction between turbulence and stability
- Plasma eruptions called ELMs are potentially very damaging for ITER
  - The largest “Type I” ELMs are well-understood in terms of peeling-ballooning modes, and cannot be tolerated on ITER
  - A range of possible ELM control techniques will be available on ITER
  - Ideal MHD stability properties indicate that the no-ELM QH Mode may be accessible for ITER (edge flow shear may be key)
  - Small ELM regimes are more of a challenge – we have some ideas, but still great uncertainty whether they can be accessed on ITER
- Despite being a very small region, the pedestal is key to ITER performance and operation