Physics and control of Edge Localized Modes (ELMs)

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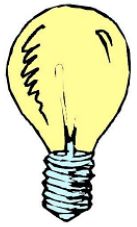
Outline

- Motivation
- Physics of ELMs
  - The trigger physics
  - ELM size and filament physics
  - Nonlinear behaviour of ELM
  - MHD modelling of ELMs
- Control of ELMs
  - Pellets
  - Gas puffing
  - Vertical kicks
  - Resonant Magnetic Perturbations
- Summary

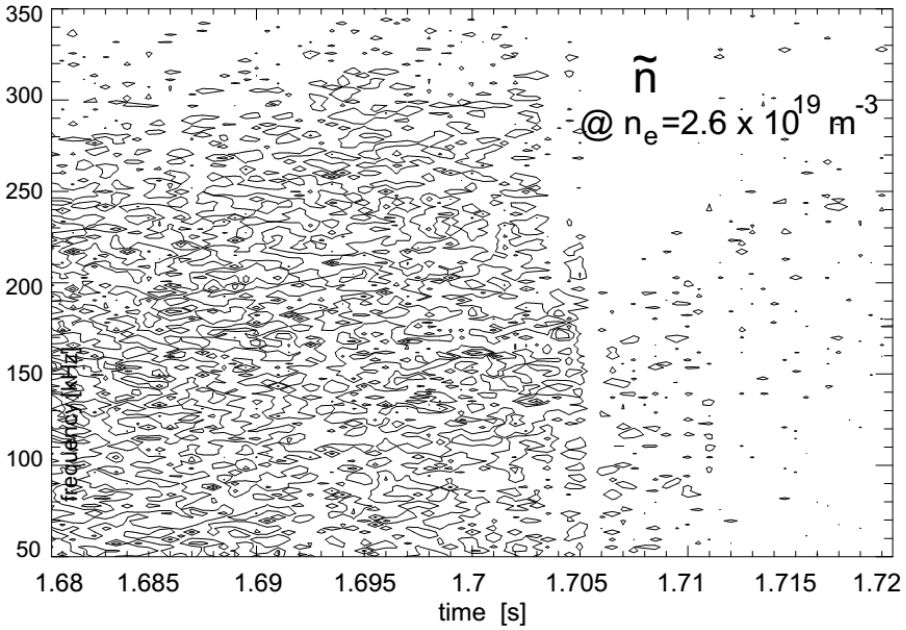
H-mode: reduction of the turbulent transport



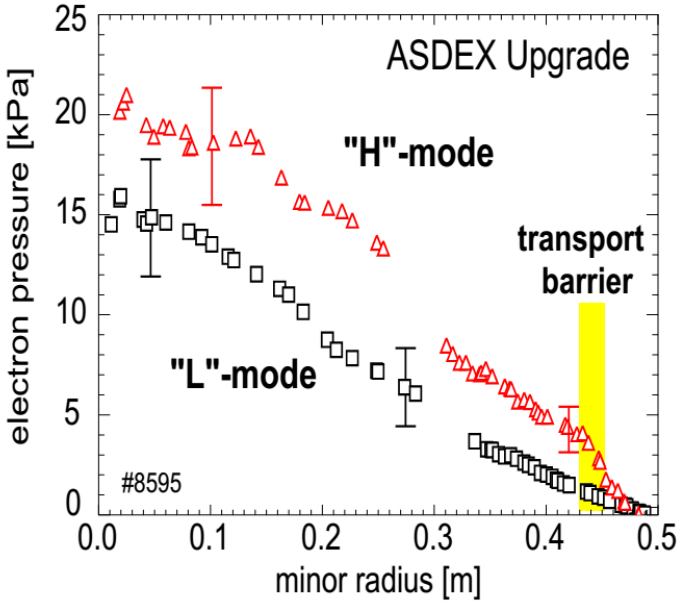
Phase transition to high confinement regime (ASDEX 1984)

Reduced density fluctuation level

„L-mode“ „H-mode“



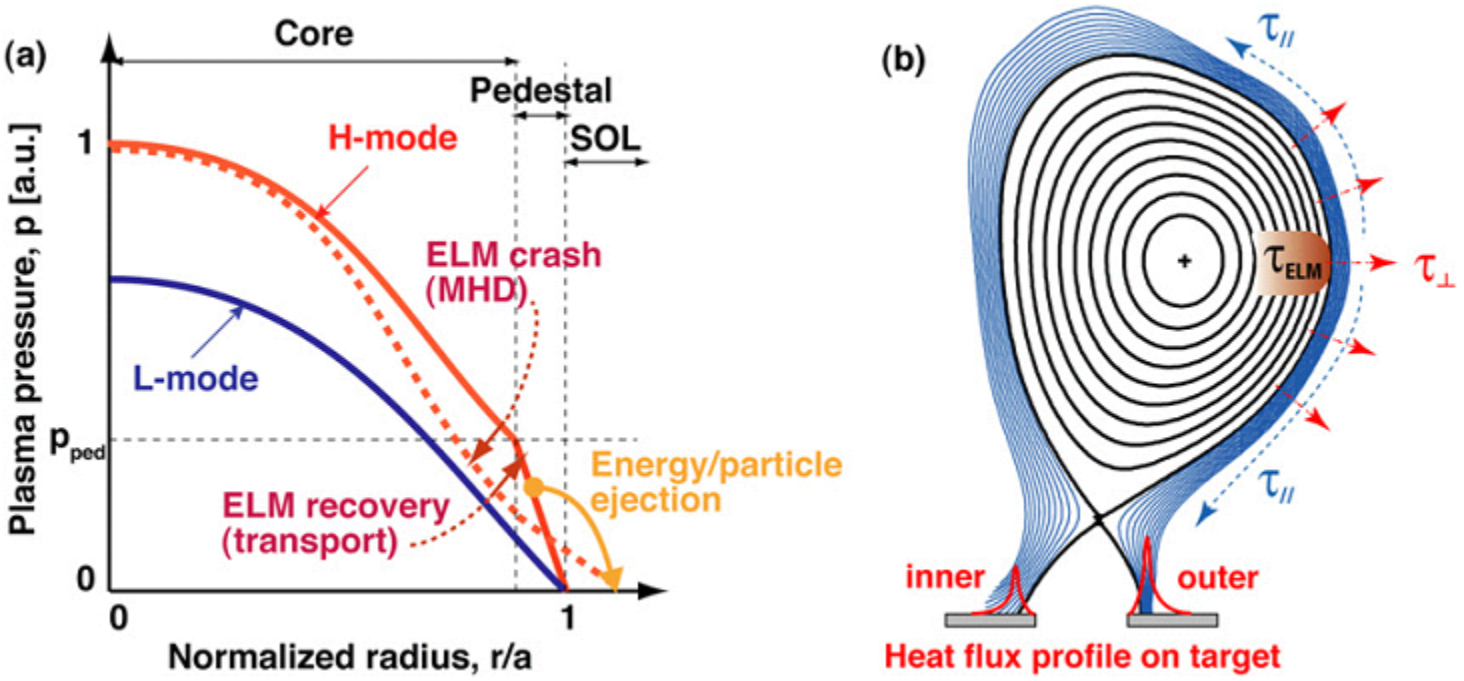
Reduced radial diffusivity
⇒ stronger pressure gradient



Typical H-mode signature is Edge Localized Modes (ELMs)

Schematic representation of the ELM cycle

Kamiya, PPCF, 2007



ELM crash, ejecting plasma energy/particle towards Scrape-Off-Layer (SOL)

Why is ELM control urgent for ITER?

Tungsten Erosion

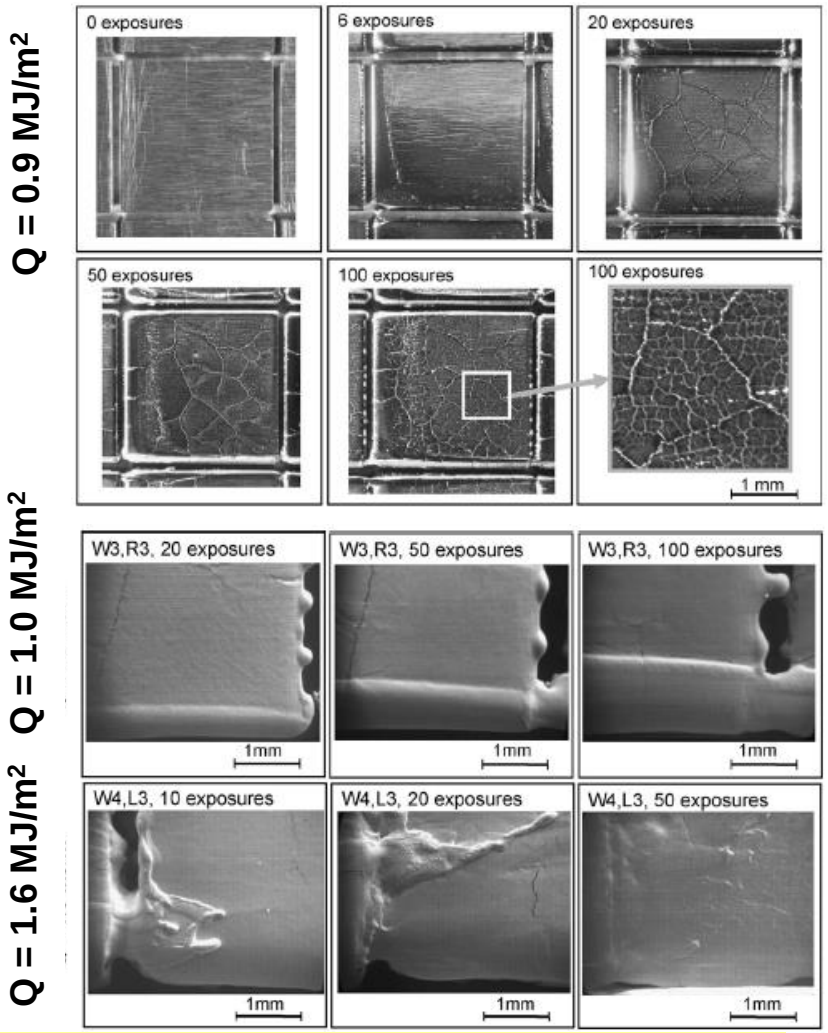
Tungsten melting, droplets, surface cracks if W_{ELM}>1MJ.

... but predicted for large ELMs: W_{ELM},ITER~30MJ!

(ITER divertor life-time = only few shots with big ELMs!)

This requires a decrease in the 'natural' ELM size by **a factor of ~ 30**

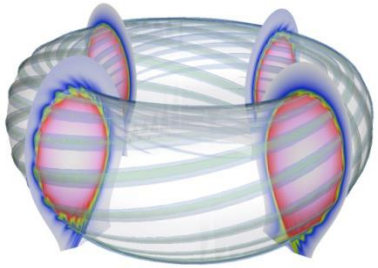
Zhitlukhin JNM 2007



ELM suppression/control is required for a steady state operation of ITER!

Physics of ELMs

Drives for instabilities in MHD are current and pressure profile gradients



Linearization:
$A = A_0 + A_1$
0 – equilibrium
1 - perturbation

$$\delta W = \frac{1}{2}\int_{plasma}\left(\underbrace{\gamma p_0\left(\nabla\cdot\vec{\xi}\right)^2}_{>0} + \left(\vec{\xi}\cdot\nabla p_0\right)\nabla\cdot\vec{\xi} + \underbrace{\frac{B_1^2}{\mu_0}}_{>0} - \vec{j}_0\cdot\left(\vec{B}_1\times\vec{\xi}\right)\right)d\tau + \underbrace{\int_{vacuum}\frac{B_{vac}^2}{2\mu_0}d\tau}_{>0}$$

Pressure driven instabilities

Current driven instabilities

Unstable only if $\delta W < 0$

Wesson, Tokamaks, 3rd Edition
Freidberg, Ideal MHD

ELM trigger: ideal MHD

- It is widely believed that ideal MHD instabilities provide the trigger for the ELM
- Theoretically, the instability properties can be understood from δW for radial displacement, X, at large toroidal mode number, n:

$$\delta W = \pi \int_0^{\psi_a} d\psi \oint d\theta \left\{ \frac{JB^2}{R^2 B_p^2} \left| k_\parallel X \right|^2 + \frac{R^2 B_p^2}{JB^2} \left| \frac{1}{n} \frac{\partial}{\partial \psi} \left(JBk_\parallel X \right) \right|^2 \right.$$

Field-line bending: strongly stabilising unless $k_\parallel$ is small

$$\frac{-2J}{B^2} \frac{dp}{d\psi} \left[\left| X \right|^2 \frac{\partial}{\partial \psi} \left(p + \frac{B^2}{2} \right) - \frac{i}{2} \frac{f}{JB^2} \frac{\partial B^2}{\partial \theta} \frac{X^*}{n} \frac{\partial X}{\partial \psi} \right]$$

Pressure gradient/curvature drive: destabilising if average curvature is “bad”

$$- \frac{X^*}{n} JBk_\parallel \left(\frac{\partial \sigma}{\partial \psi} X \right) + \frac{\partial}{\partial \psi} \left[\frac{\sigma}{n} XJBk_\parallel^* X^* \right]$$

Current density gradient/edge current drives kink/peeling modes

σ=normalised current density

- Must ensure field-aligned perturbations or field line bending will suppress the instability: ideal MHD naturally produces filamentary structures

Kink or peeling modes

- A single, resonant Fourier mode

$$\delta W = \pi \int_0^{\psi_a} d\psi \oint d\theta \left\{ \frac{JB^2}{R^2 B_p^2} \left| k_\parallel X \right|^2 + \frac{R^2 B_p^2}{JB^2} \left| \frac{1}{n} \frac{\partial}{\partial \psi} \left(JBk_\parallel X \right) \right|^2 \right.$$

$$\left. - \frac{-2J}{B^2} \frac{dp}{d\psi} \left[|X|^2 \frac{\partial}{\partial \psi} \left(p + \frac{B^2}{2} \right) - \frac{i}{2} \frac{f}{JB^2} \frac{\partial B^2}{\partial \theta} \frac{X^*}{n} \frac{\partial X}{\partial \psi} \right] \right.$$

$$\left. - \frac{X^*}{n} JBk_\parallel \left(\frac{\partial \sigma}{\partial \psi} X \right) + \frac{\partial}{\partial \psi} \left[\frac{\sigma}{n} XJBk_\parallel^* X^* \right] \right\}$$

Single Fourier mode, highly localised at rational surface eliminates field line bending

$|X|^2$ constant around poloidal plane, so experiences "good" average curvature

$\Rightarrow$ Pressure gradient is stabilising

Driven unstable by current gradient at modest n: kink mode

Or edge current density at large n: peeling mode

- Peeling and kink modes are essentially the same thing
  - Driven by current density gradient, stabilised by pressure gradient
  - Highly localised

Ballooning modes

- Multiple Fourier modes couple to tap free energy of pressure gradient

$$\delta W = \pi \int_0^{\psi_a} d\psi \oint d\theta \left\{ \frac{JB^2}{R^2 B_p^2} \left| k_\parallel X \right|^2 + \frac{R^2 B_p^2}{JB^2} \left| \frac{1}{n} \frac{\partial}{\partial \psi} \left(JBk_\parallel X \right) \right|^2 \right.$$

$$\left. \frac{-2J}{B^2} \frac{dp}{d\psi} \left[|X|^2 \frac{\partial}{\partial \psi} \left(p + \frac{B^2}{2} \right) - \frac{i}{2} \frac{f}{JB^2} \frac{\partial B^2}{\partial \theta} \frac{X^*}{n} \frac{\partial X}{\partial \psi} \right] \right.$$

$$\left. - \frac{X^*}{n} JBk_\parallel \left(\frac{\partial \sigma}{\partial \psi} X \right) + \frac{\partial}{\partial \psi} \left[\frac{\sigma}{n} XJBk_\parallel^* X^* \right] \right\}$$

To couple, each Fourier mode must extend across multiple rational surfaces:
Field line bending is minimised, but not eliminated

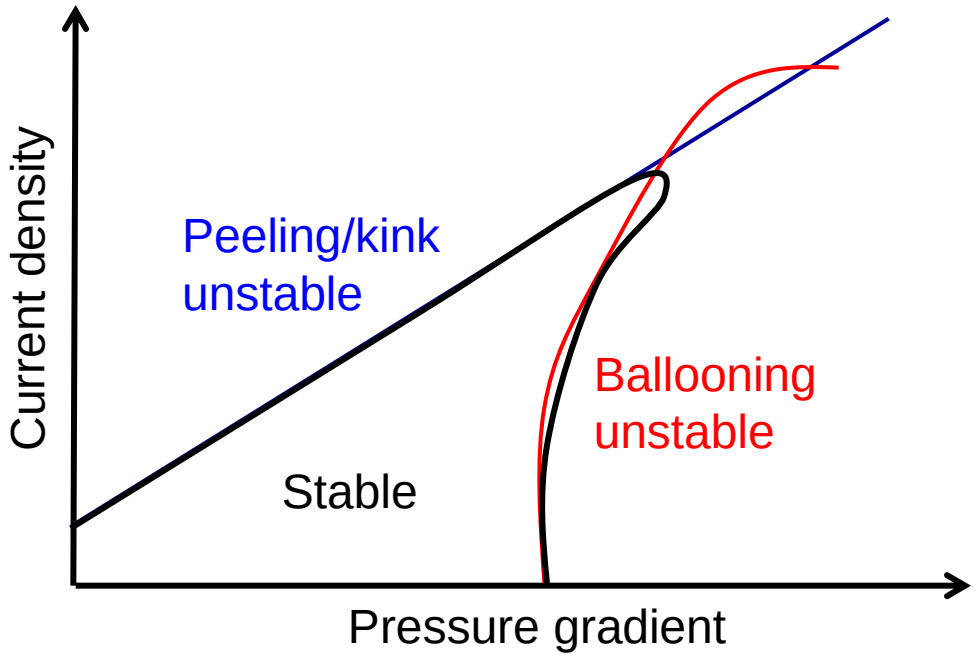
Multiple Fourier modes couple to constructively interfere in bad curvature region: $|X|^2$ is maximum on outboard side

Current gradient does not play a role at large n; edge current can influence mode

- Ballooning mode is unstable when the curvature exceeds field line bending
  - Critical $dp/d\psi$ is required (depends on shear, and therefore current)
  - Many coupled Fourier modes $\Rightarrow$ radially extended mode structure

Ideal MHD stability diagram

- The peeling-ballooning mode stability diagram

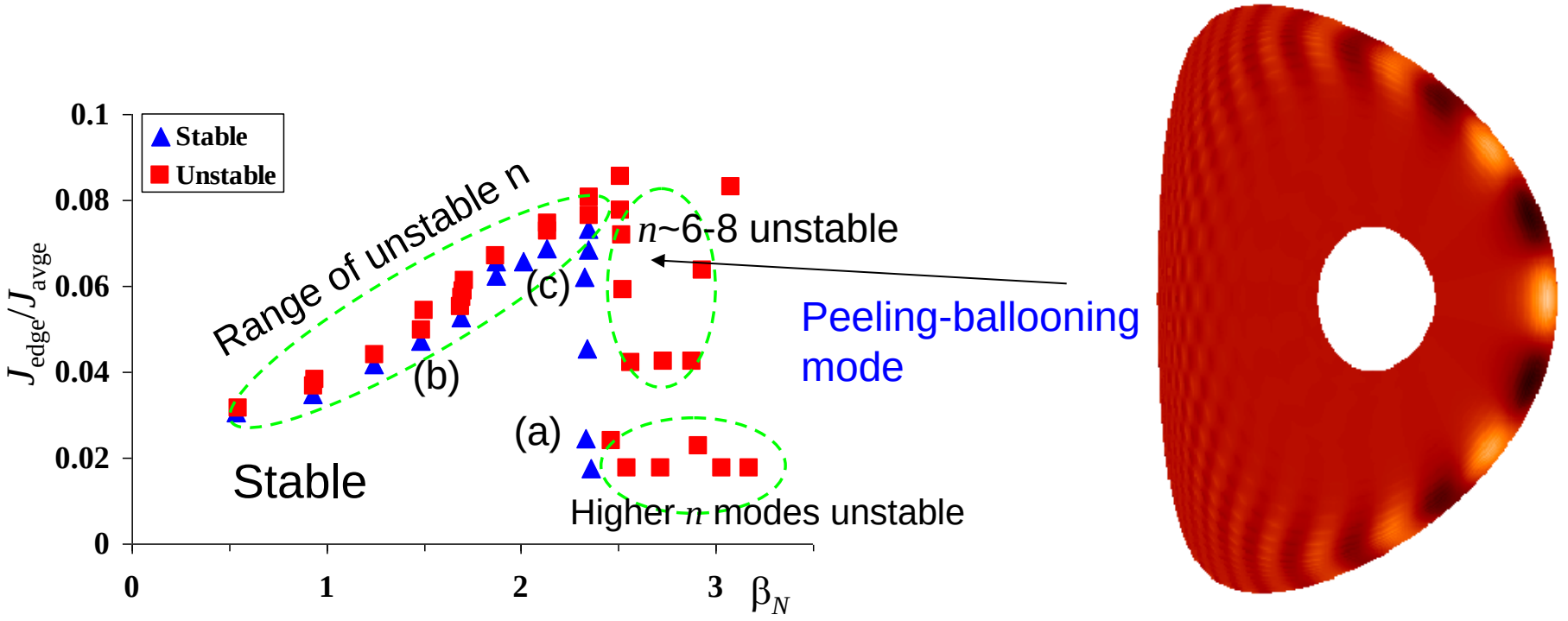


Important (slightly subtle) point

- Although stability diagrams are shown in terms of local dp/dr and J, profile effects cannot be neglected (when n is finite)
- Higher pressure gradient can be achieved for a narrower pedestal $\Rightarrow$ care when interpreting experimental pedestal profiles

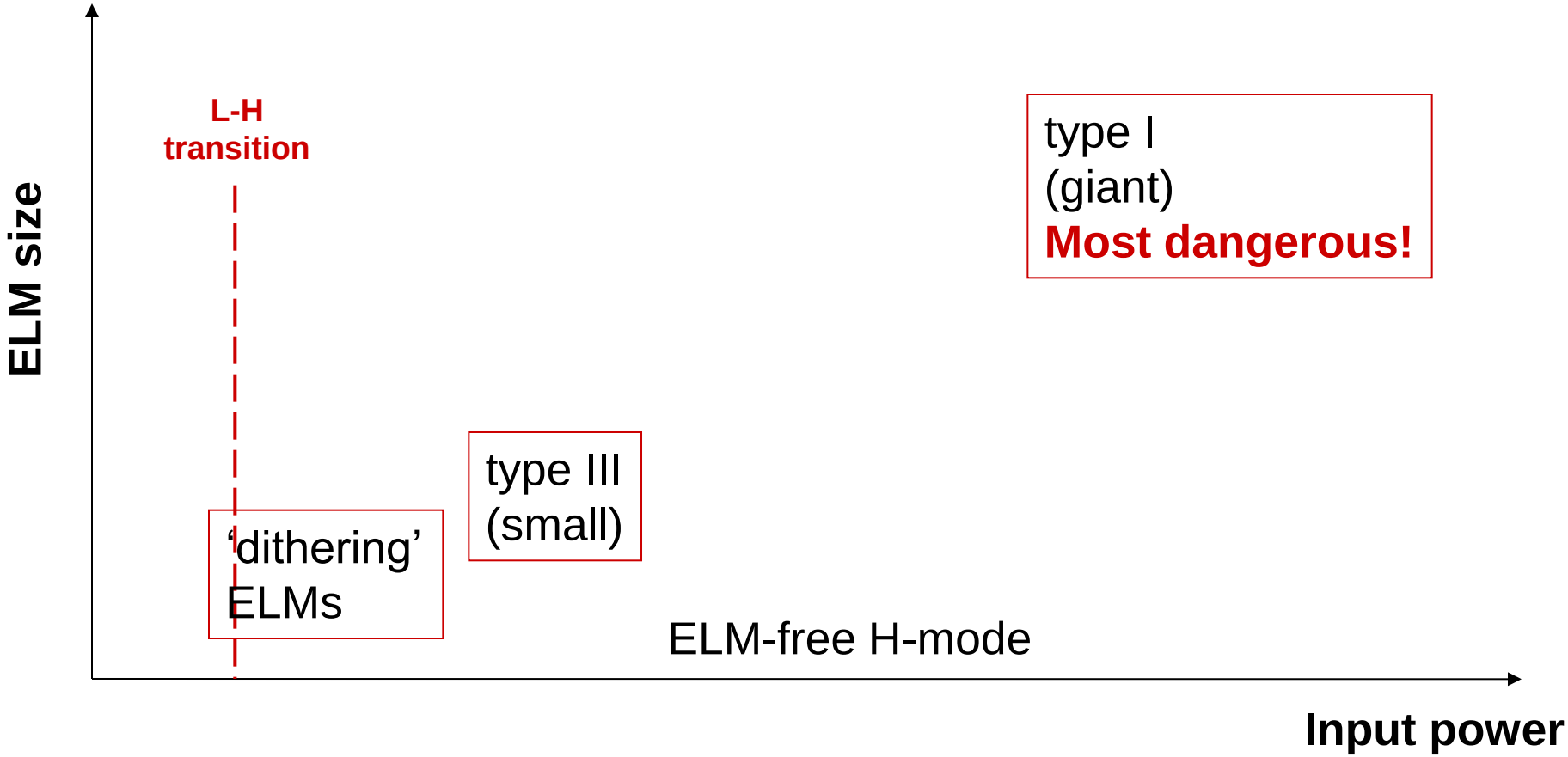
Ideal MHD stability diagram

- Typical ELITE stability diagram (model JET-like equilibrium)



Types of ELMs

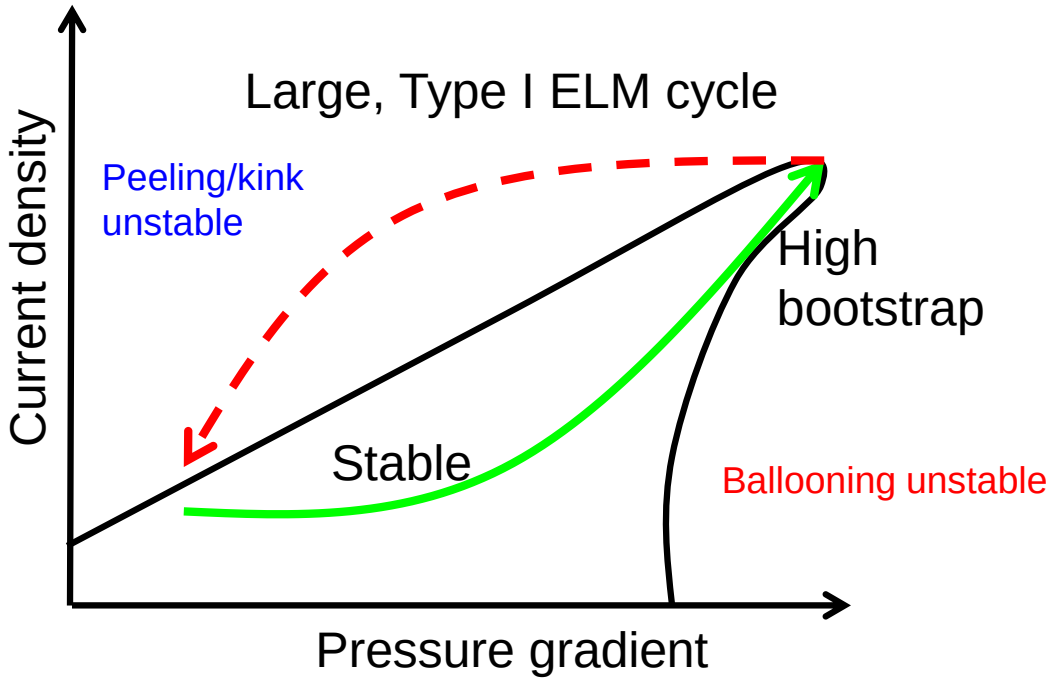
Definitions from Connor, PPCF, 98



type II (or, sometimes, 'grassy') are associated with strongly-shaped tokamaks at high edge pressure when there is access to the second stability at the plasma edge

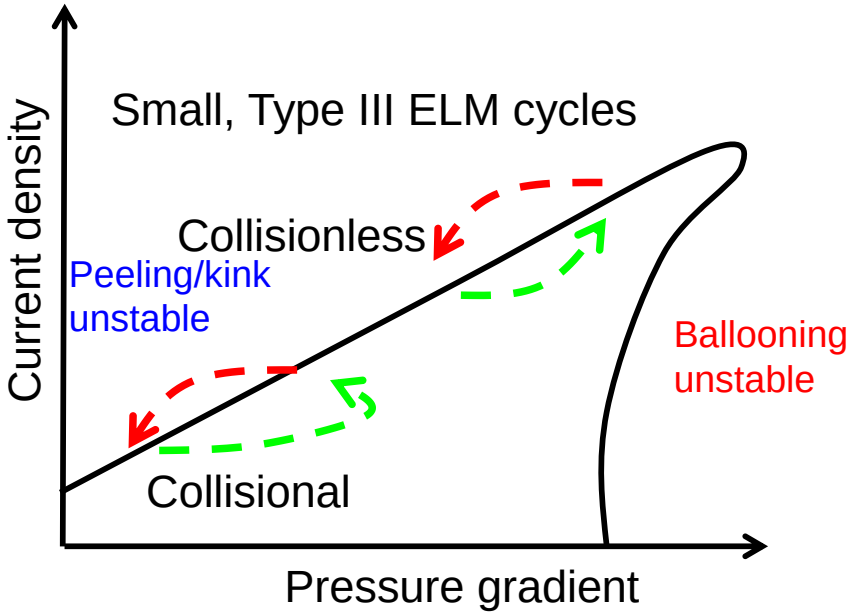
The ELM cycle: Type I

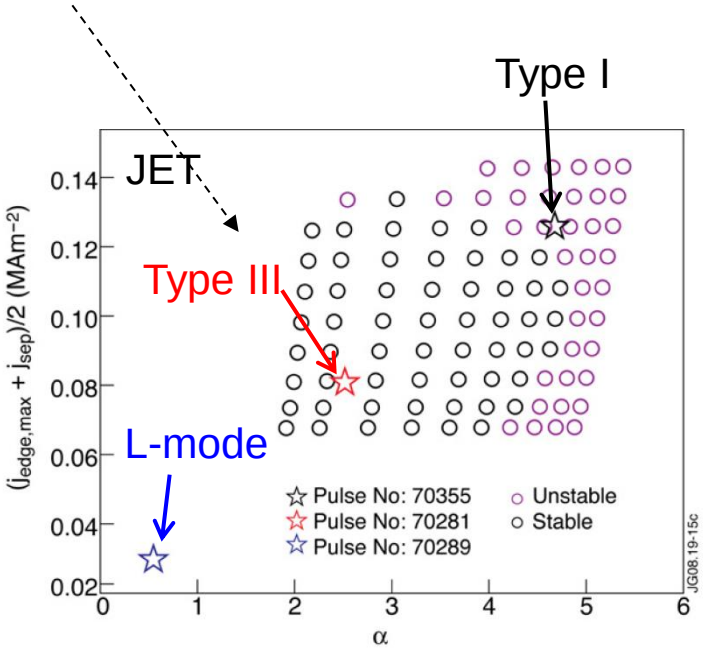
- Initial models: Type I ELM cycle
  - High pressure gradient in pedestal (so good performance)
  - Low collisionality, and strong bootstrap current
  - Extended linear mode across pedestal region
  - Anticipate a substantial crash



The ELM cycle: Type III

- Initial models: Type III ELMs (more speculative?)
  - Either highly collisional edge, destabilising resistive ballooning, driving pedestal to lower gradient and crossing peeling stability boundary
  - Or at higher temperatures, higher current pushes pedestal directly across peeling stability boundary
  - However, data seems to suggest Type III are stable to ideal modes (but uncertainty over edge current)

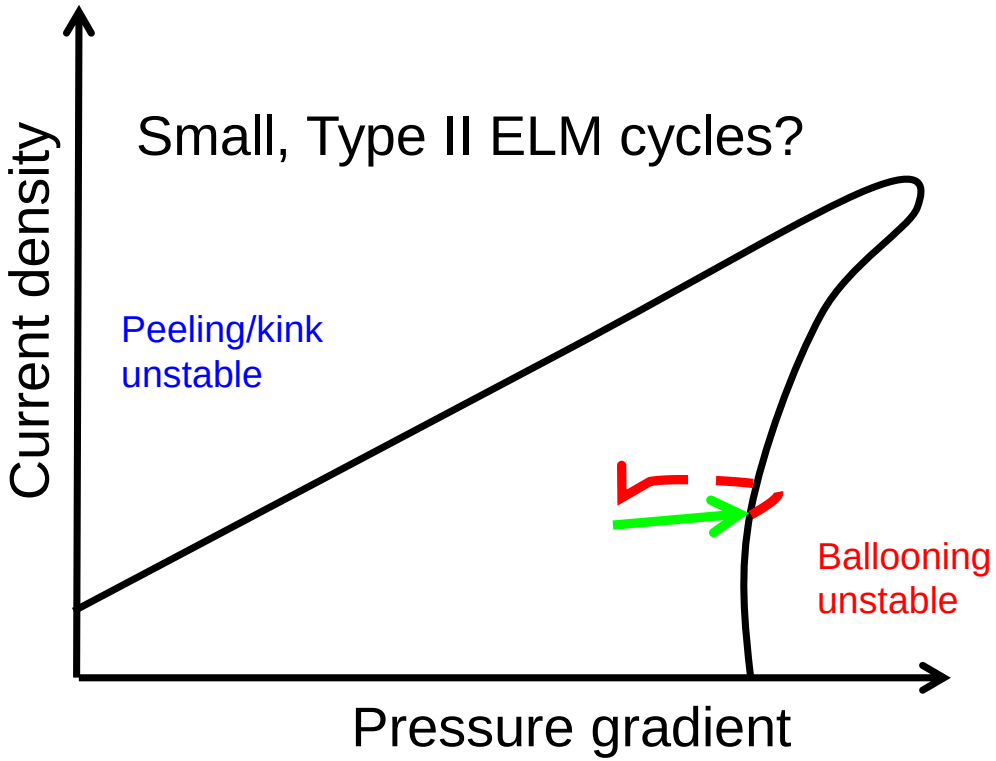




Saarelma, PPCF, 2009

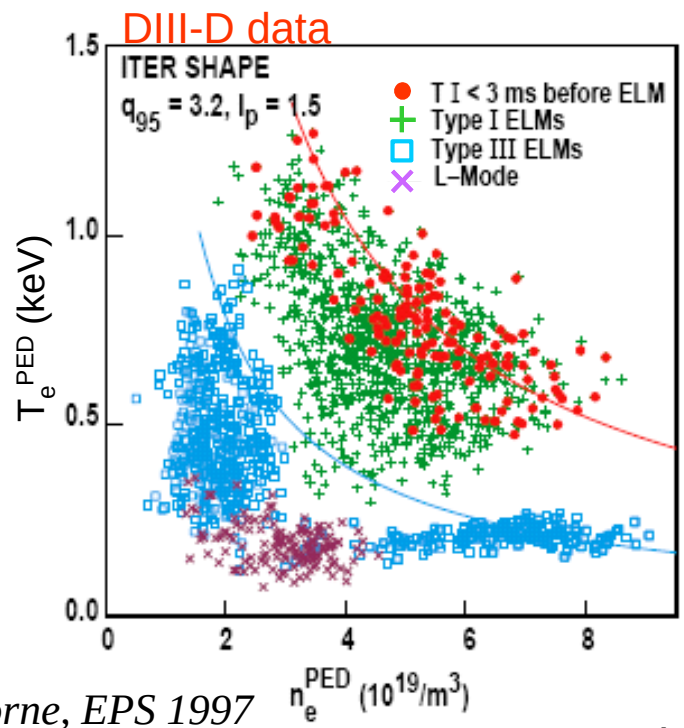
The ELM cycle: Type II

- Initial models: Type II ELMs (speculative, again)
  - Higher collisionality would help to suppress bootstrap current
  - Strong shaping can also push peeling boundary to high current density
  - Removes role of peeling mode, providing a pure ballooning mode

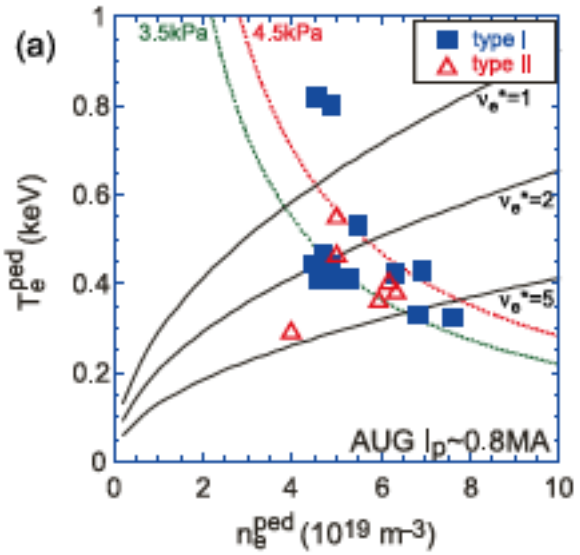


ELM Types: experiment

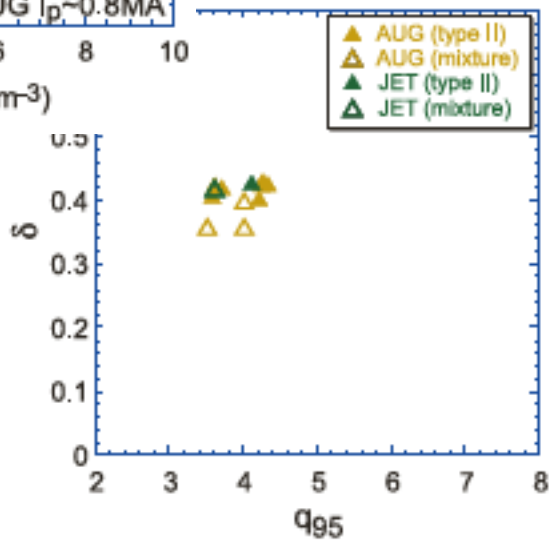
- The positions of Type I ELMs on an edge stability diagram are consistent with this picture:



T Osborne, EPS 1997



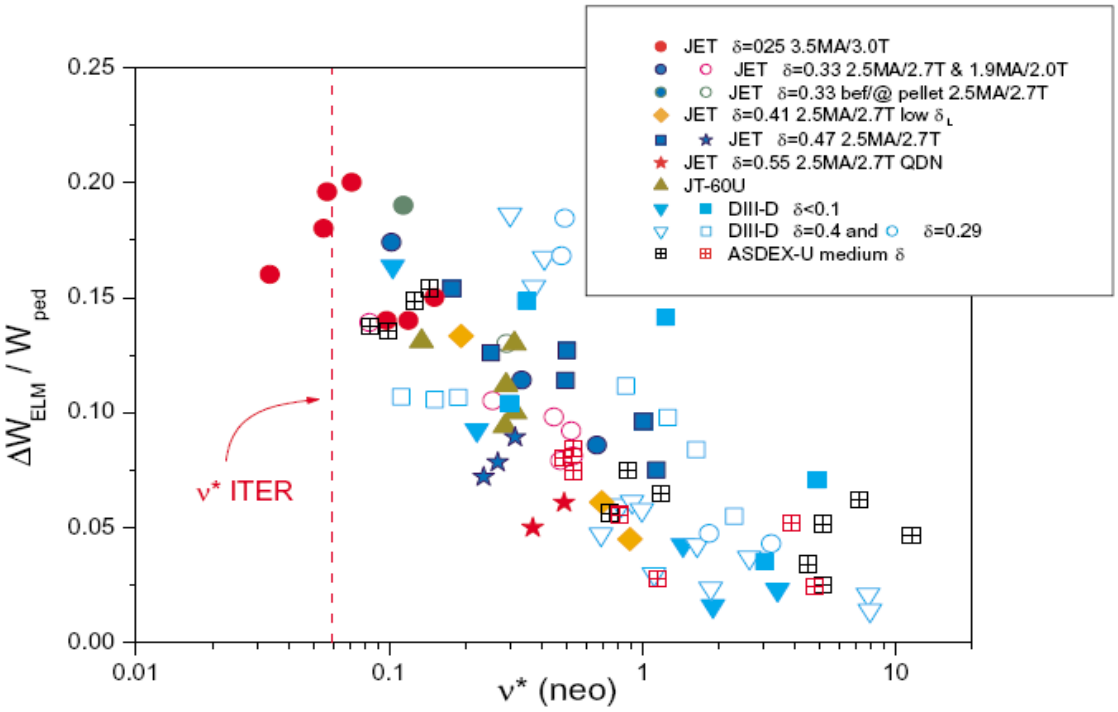
Oyama, PPCF 2006



Existence space for Type II ELMs on JET and AUG is consistent also

Understanding ELM size requires understanding transport processes

- ELM size shows a strong dependence on collisionality
  - Cause for concern on ITER
  - Must identify the origin of the collisionality scaling



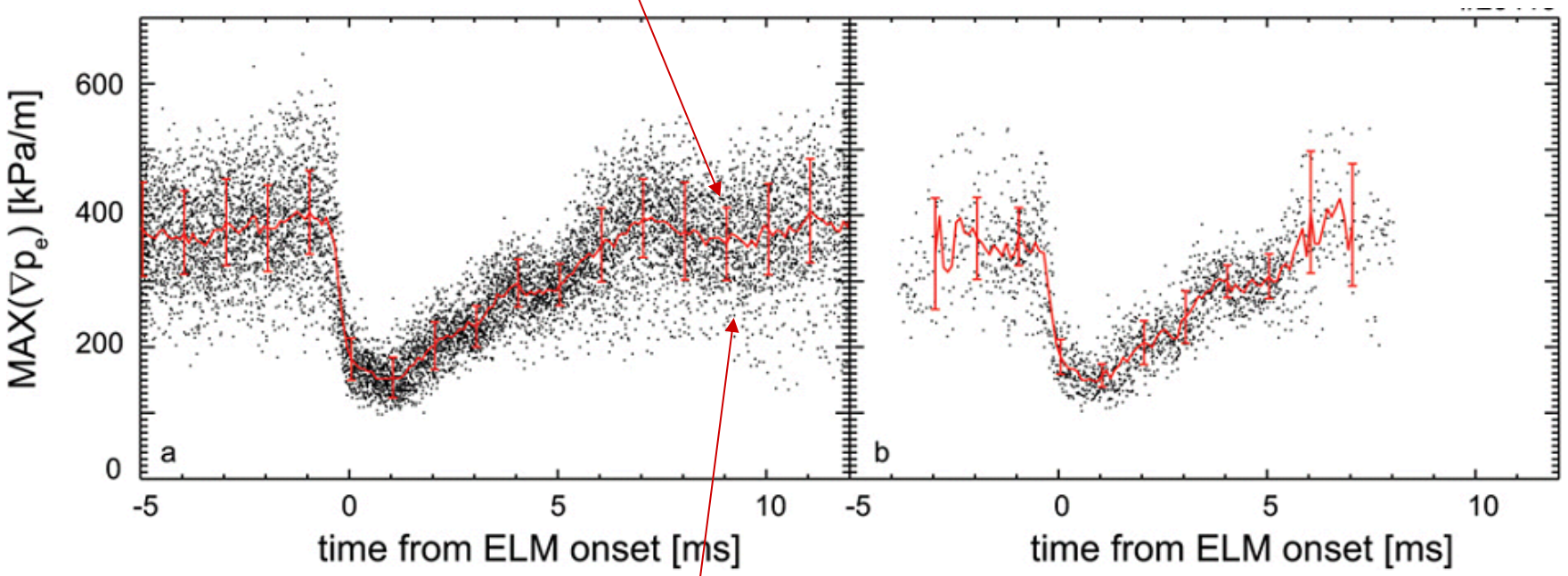
Loarte (PPCF 2003)

- Likely nonlinear physics

Behaviour of the pressure gradient

Saturated gradient, non-linear phase!

ASDEX Upgrade



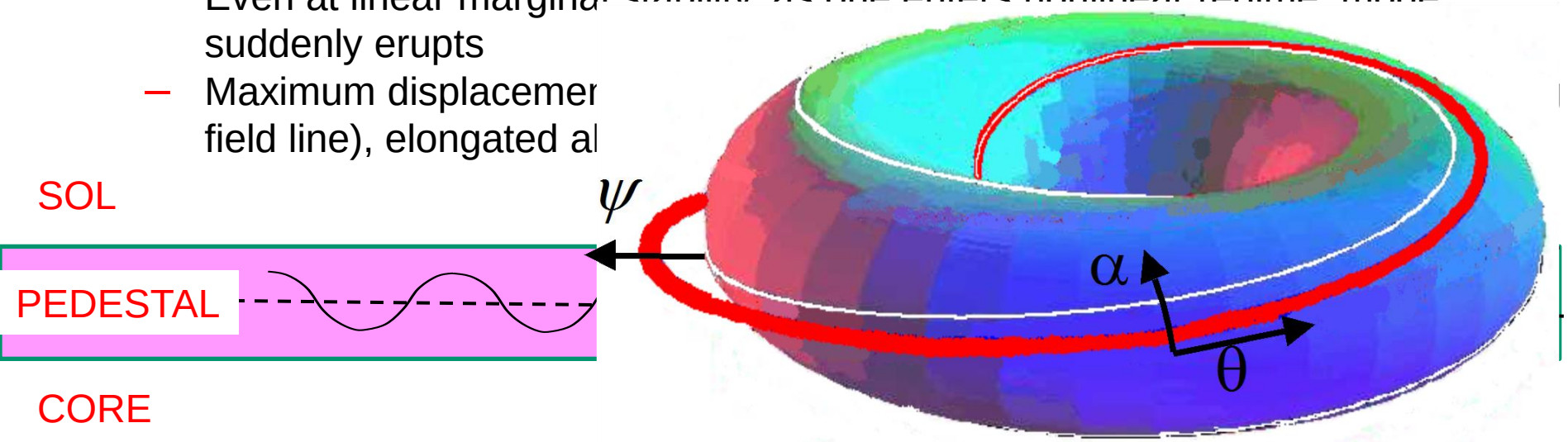
Burckhart, PPCF, 2010

Figure 7. ELM-synchronized maximal ∇p_e of (a) the slow and (b) the fast ELM cycles in discharge

Non-linear physics is important!

Nonlinear ballooning Theory

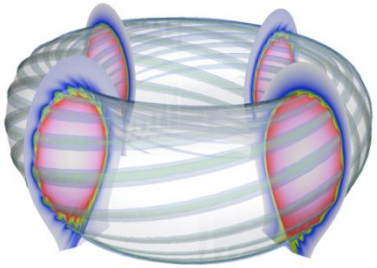
- Progress can be made analytically for the early nonlinear evolution (Wilson, Cowley PRL 2004)
- Predictions are
  - Initially sinusoidal mode narrows in direction across field lines, in flux surface
  - Mode tends to broaden radially, forming field-aligned filamentary structures
  - Even at linear marginal stability, as one enters nonlinear regime, mode suddenly erupts
  - Maximum displacemer field line), elongated al



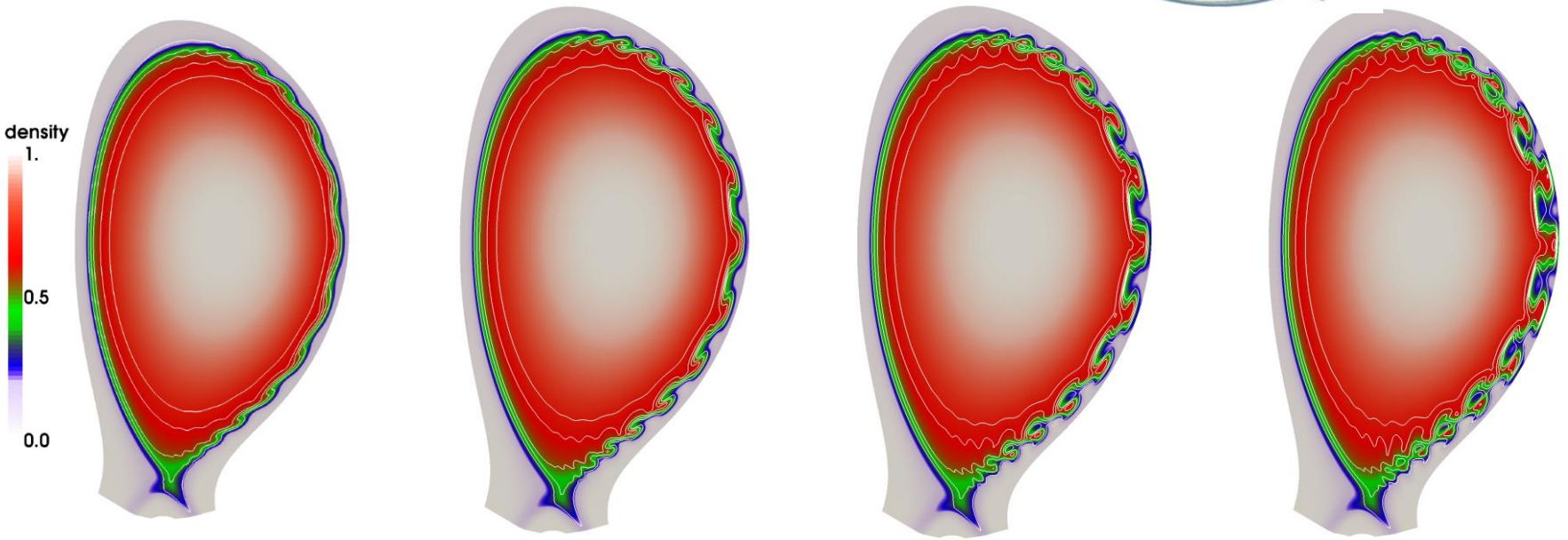
- Filament could strike material surface on outboard side while remaining connected to pedestal on inboard
  - Potential damage to plasma-facing components, especially on ITER

Non-linear simulations of ELMs

Non-linear MHD code JOREK solves the time evolution of the reduced MHD equations in general toroidal geometry



Density



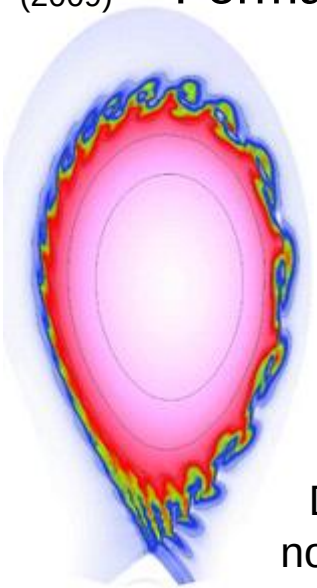
time

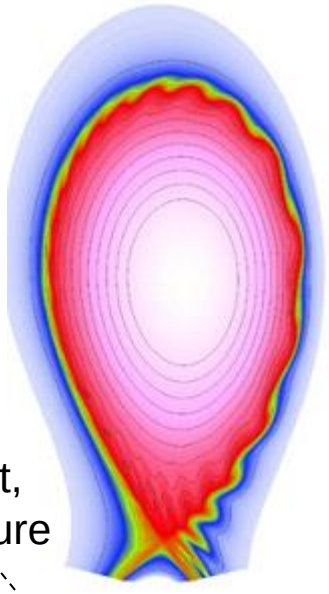
Hyusmans PPCF (2009)

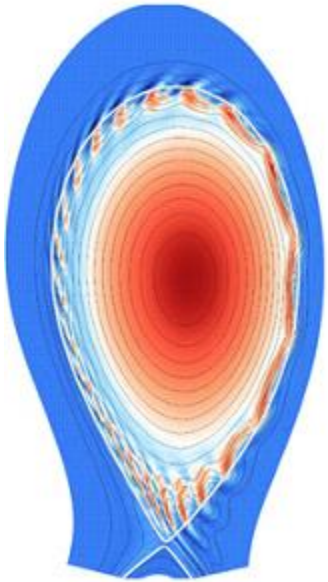
Non-linear simulations of ELMs

Hyusmans PPCF (2009)

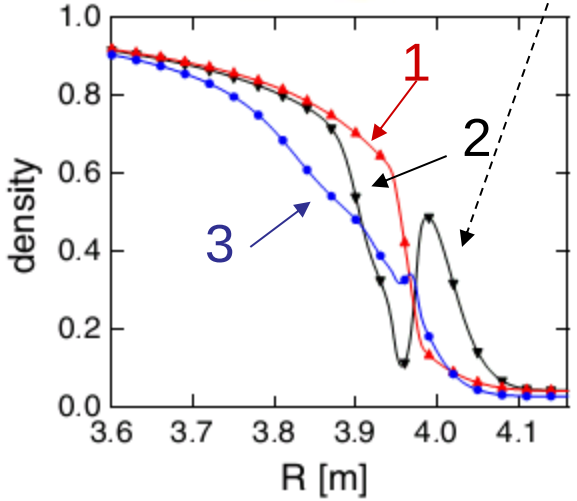
Formation of density filaments expelled across the separatrix.

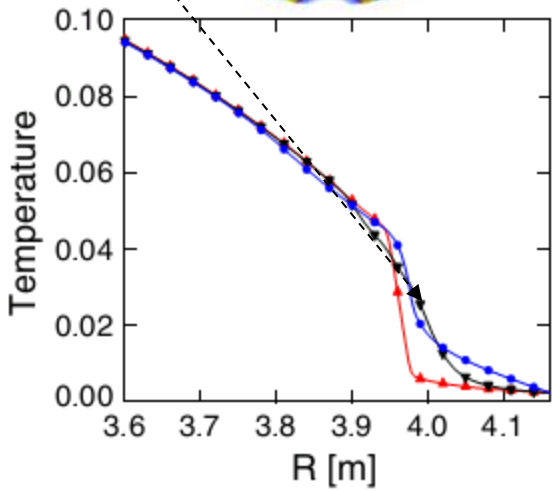


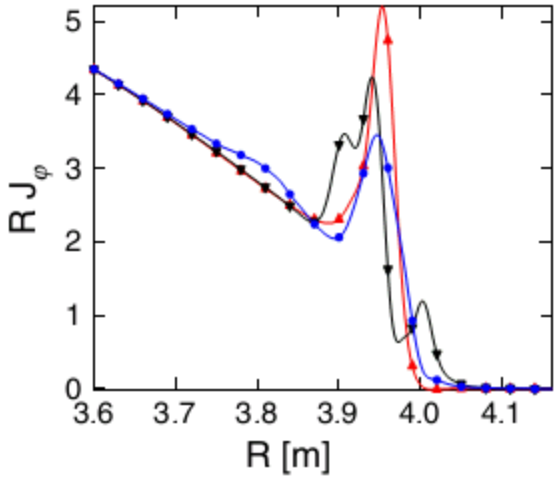




Density filament,
not the temperature

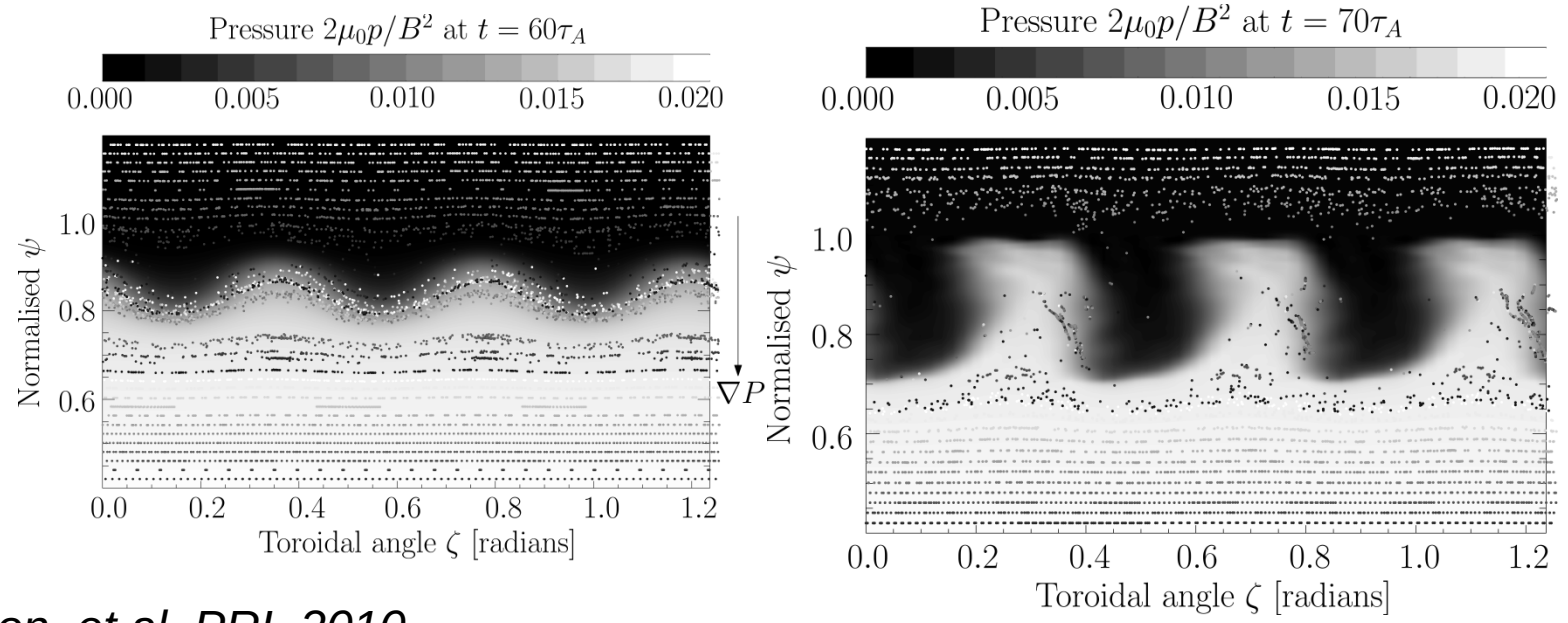






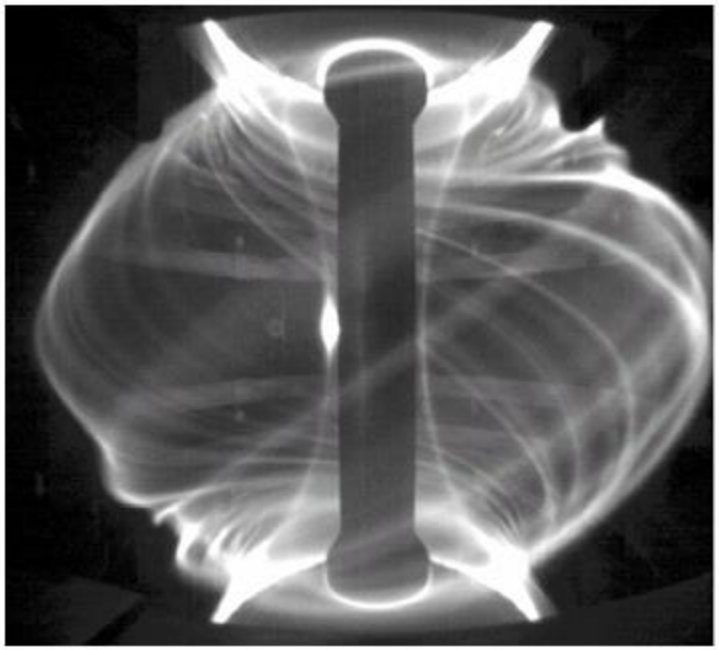
Nonlinear MHD modelling: Transport processes

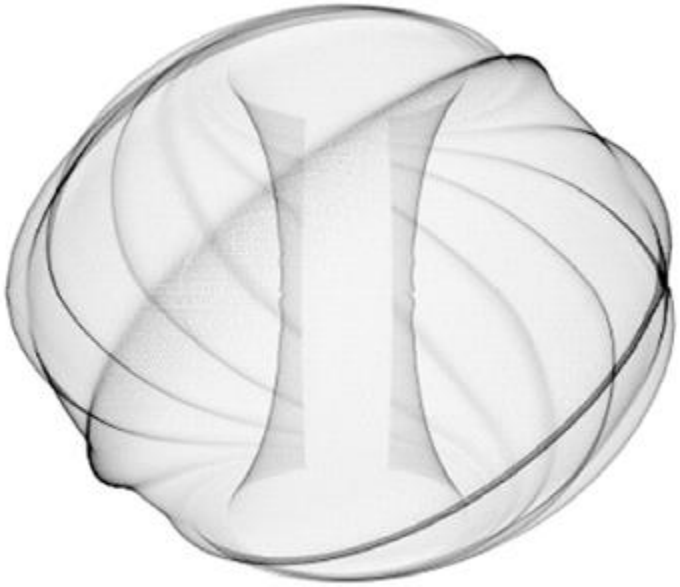
- Nonlinear MHD codes can probe the transport processes during the ELM
  - JOREK: electron heat transport dominated by parallel conductivity; density is convected into SOL; ion heat is a mixture
  - BOUT++ and JOREK observe stochastic magnetic field at the edge, which seems to play a role in the transport



Xu, Dudson, et al, PRL 2010

ELM Filament Observations.Fast cameras (eg MAST)

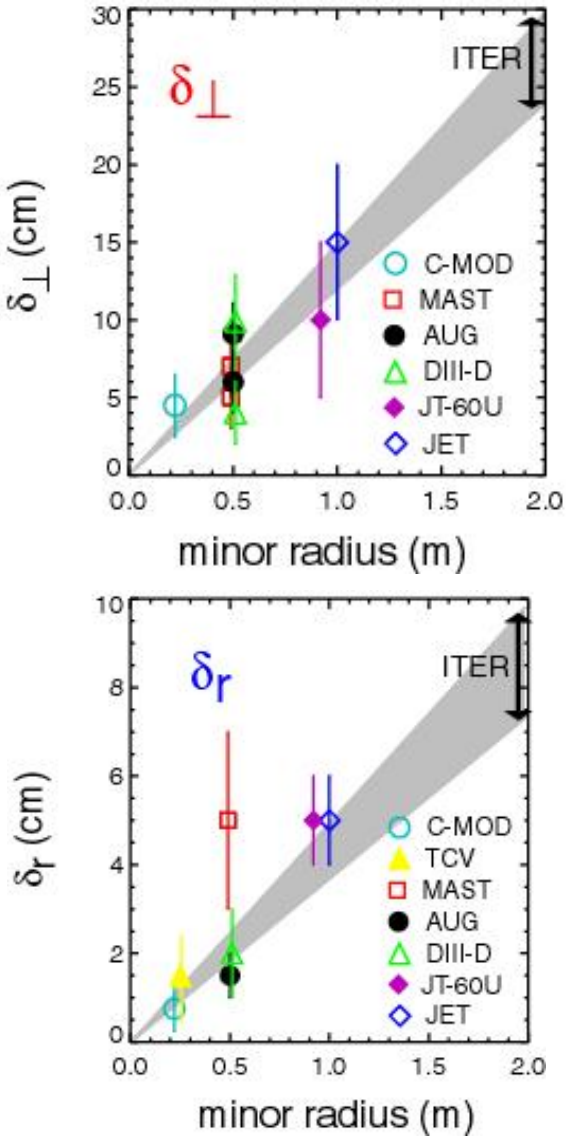




High-speed video image of the MAST plasma obtained at the start of an ELM

The predicted structure of an ELM in theMAST tokamak plasma geometry, based on the nonlinear
ballooning mode theory

ELM Filament Observations

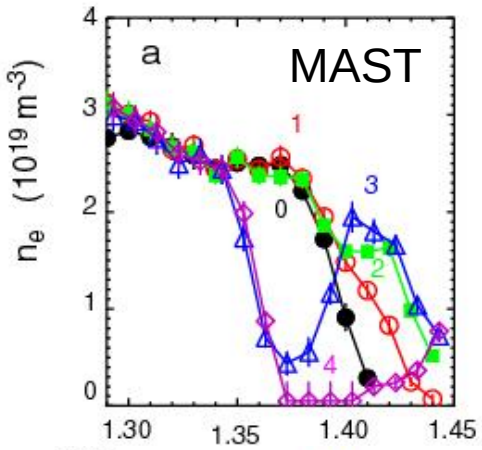


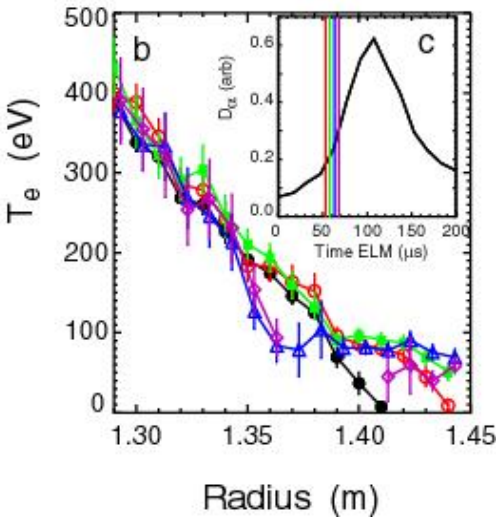
A Kirk JNM 2009

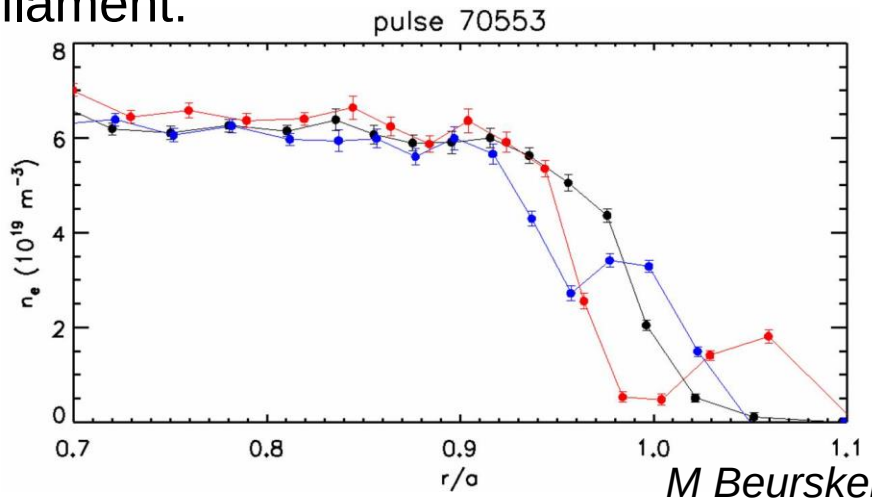
- Fast cameras provide the most direct observation of filaments
- They twist to align with magnetic field lines as they erupt
- One can measure their ejection velocity: clear acceleration on MAST, but constant velocity on AUG
- Filaments scale with machine size, and are oval: ⊥ extent more in flux surface than radial

ELM filament observation: Thomson scattering

- TS measurements of filaments on MAST and JET provide a measure of the thermal energy stored in a filament:







JET

M Beurskens, PPCF 2007

- Assuming Ti=Te, stored energy in filament~2.5% ELM energy loss
- 10 filaments only account for ~25% of the loss
- Another mechanism operates (filament syphoning energy from pedestal, or something else?)

A Kirk, PRL 2006

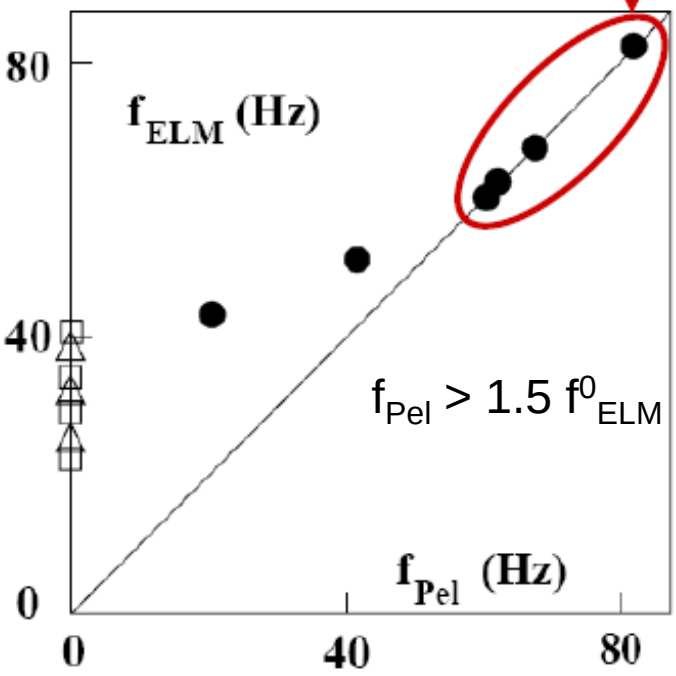
Control of ELMs

ELM size reduction by pellet injection

Type-I ELM frequency can be increased by injection of small deuterium pellets, provided that pellet freq. > 1.5 natural ELM freq. (results from AUG)

Can the effects of plasma fuelling and ELM pacing be decoupled?

Only here we have **suitable pacing**, elsewhere it is just triggering



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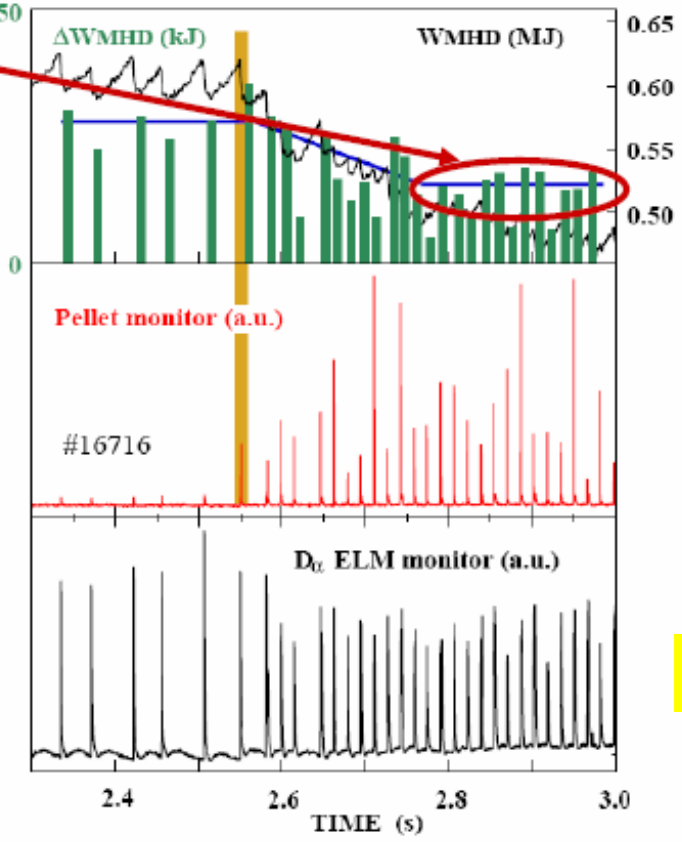
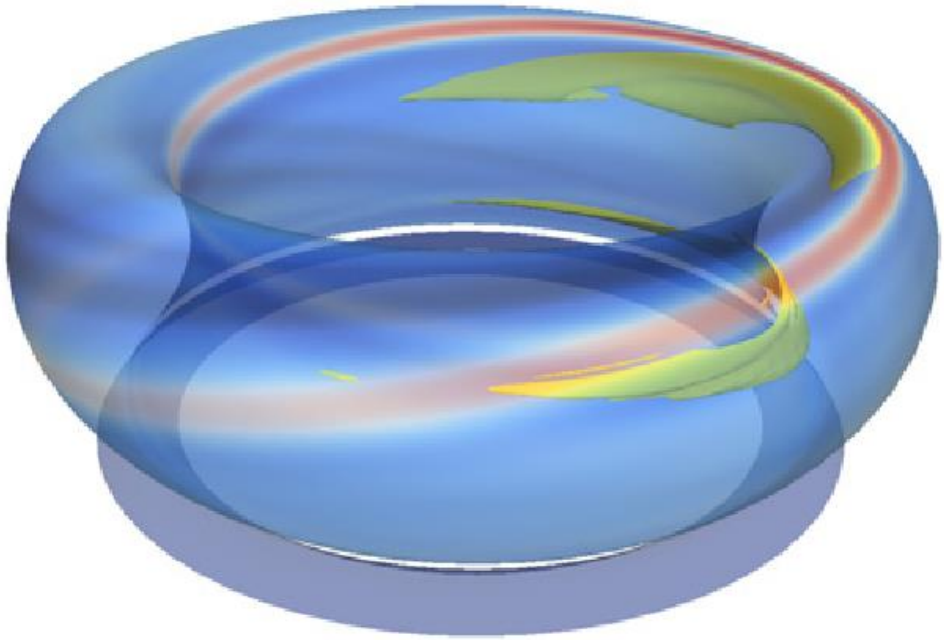


P T Lang, et al., Plasma Phys. Control. Fusion ***46*** *(2004) L31–L39*

AUG

Non-linear MHD simulations of pellets injected in the H-mode pedestal

JOREK

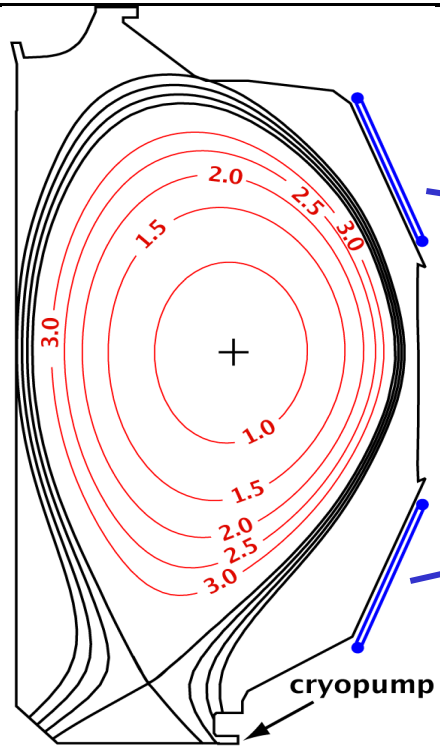


G T A Huysmans, PPCF 51 (2009)

- A strong pressure develops in the high density plasmoid, in this case the maximum pressure is aprox. 5 times the pressure on axis.
- There is a strong initial growth of the low-*n* modes followed by a growth phase of the higher-*n* modes ballooning like modes.
- The coupled toroidal harmonics lead to one single helical perturbation centred on the field line of the original pellet position.

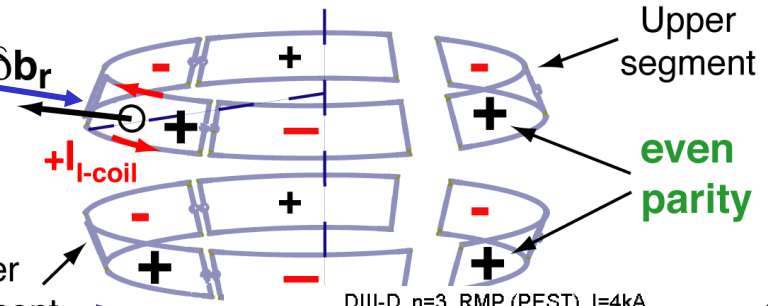
Simulations of pellets injected in the H-mode pedestal show that pellet perturbation can drive the plasma unstable to ballooning modes.

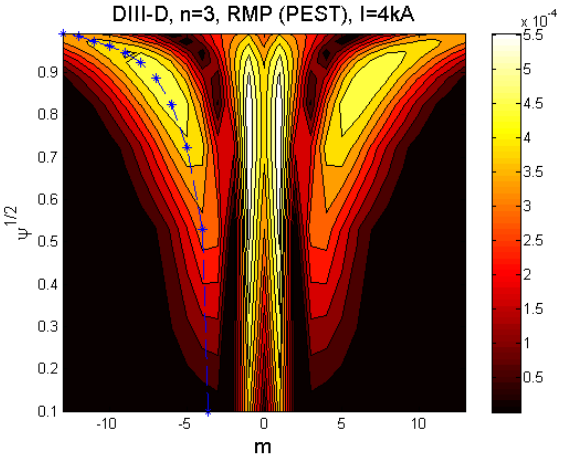
Experiments of Active Control of ELMs with a RMP on DIII-D Tokamak

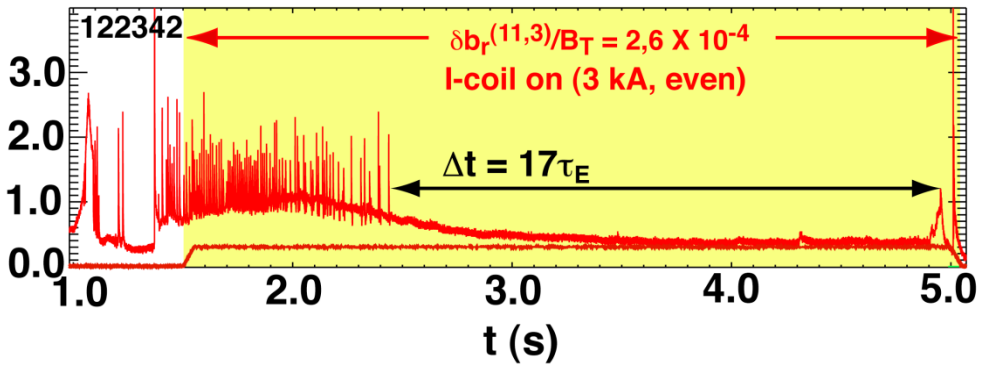


Internal coil (I-coil)

n=3 I-coil configuration
(strong RMP - even parity)







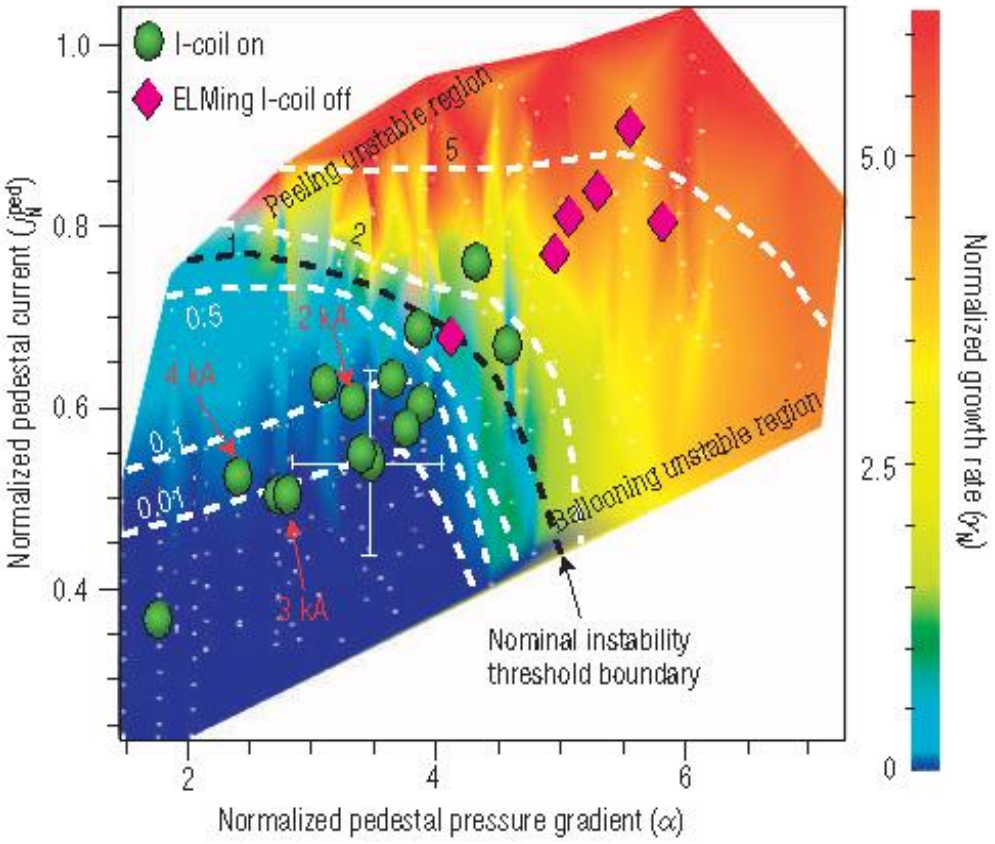
T. E. Evans,et al., PRL, 92, 235003 (2004)

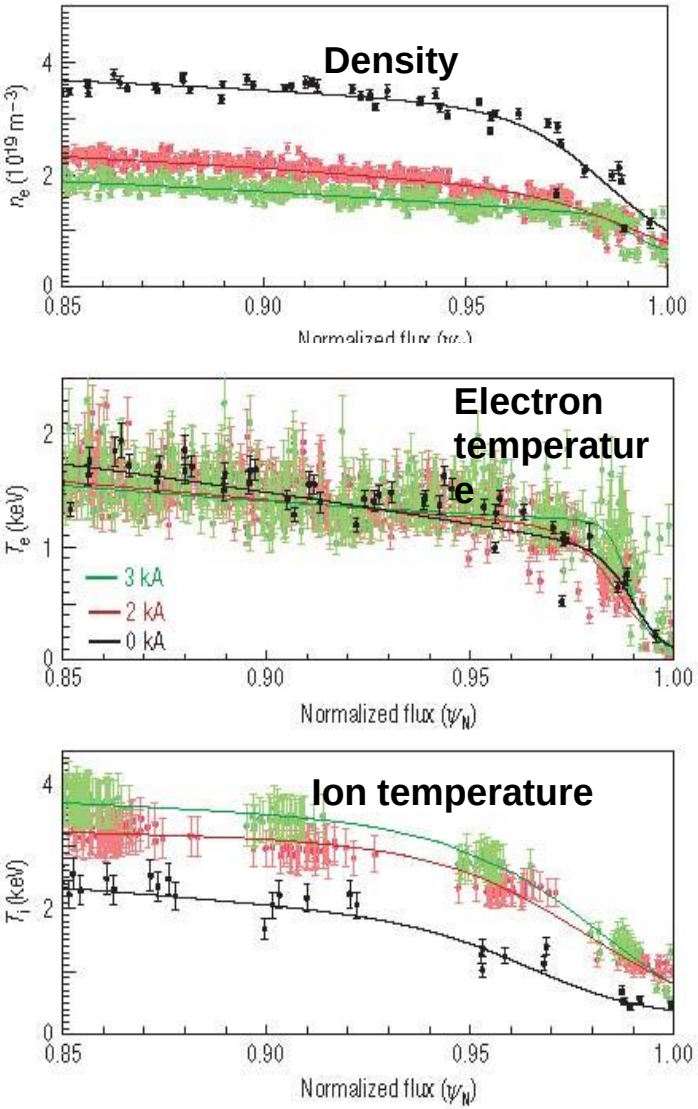
T. E. Evans,et al., Nature physics, Vol. 2, p419, June 2006

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

Dominant mechanism of ELM suppression

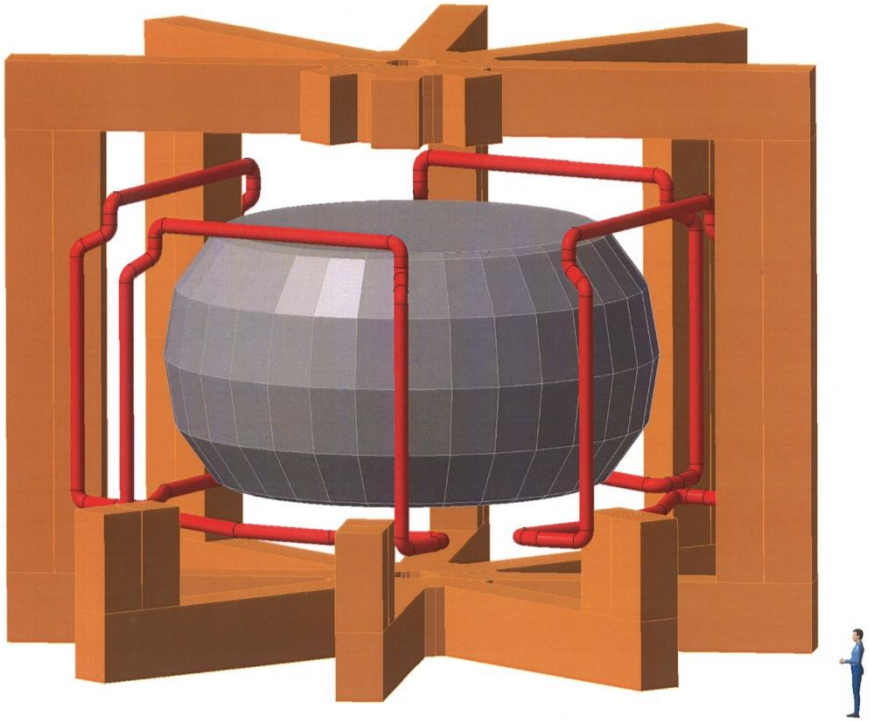
T. E. Evans,et al., Nature physics, Vol. 2, p419, June 2006



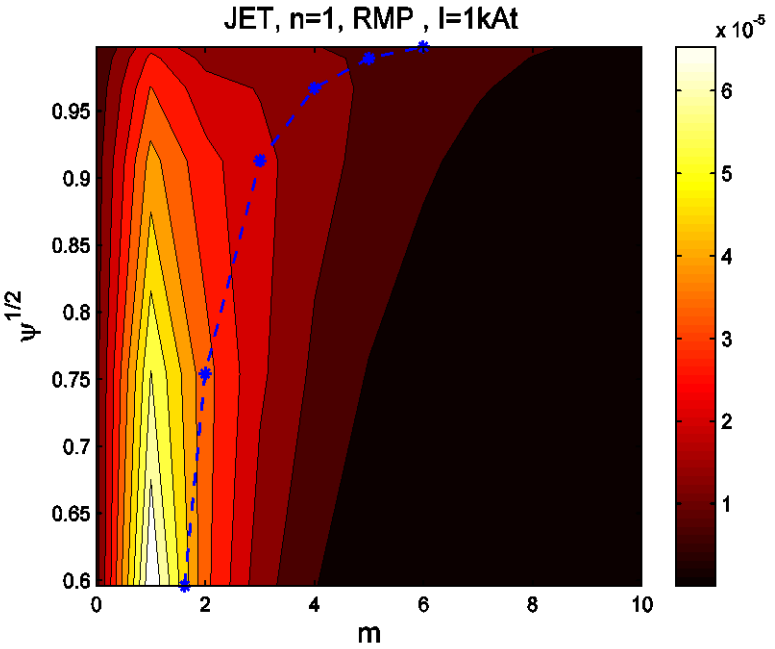


Reduction of edge pressure below instability threshold

Error field correct coils (EFCC) on JET



I_{EFCC} = 1 kAt; B_t= 1.84 T

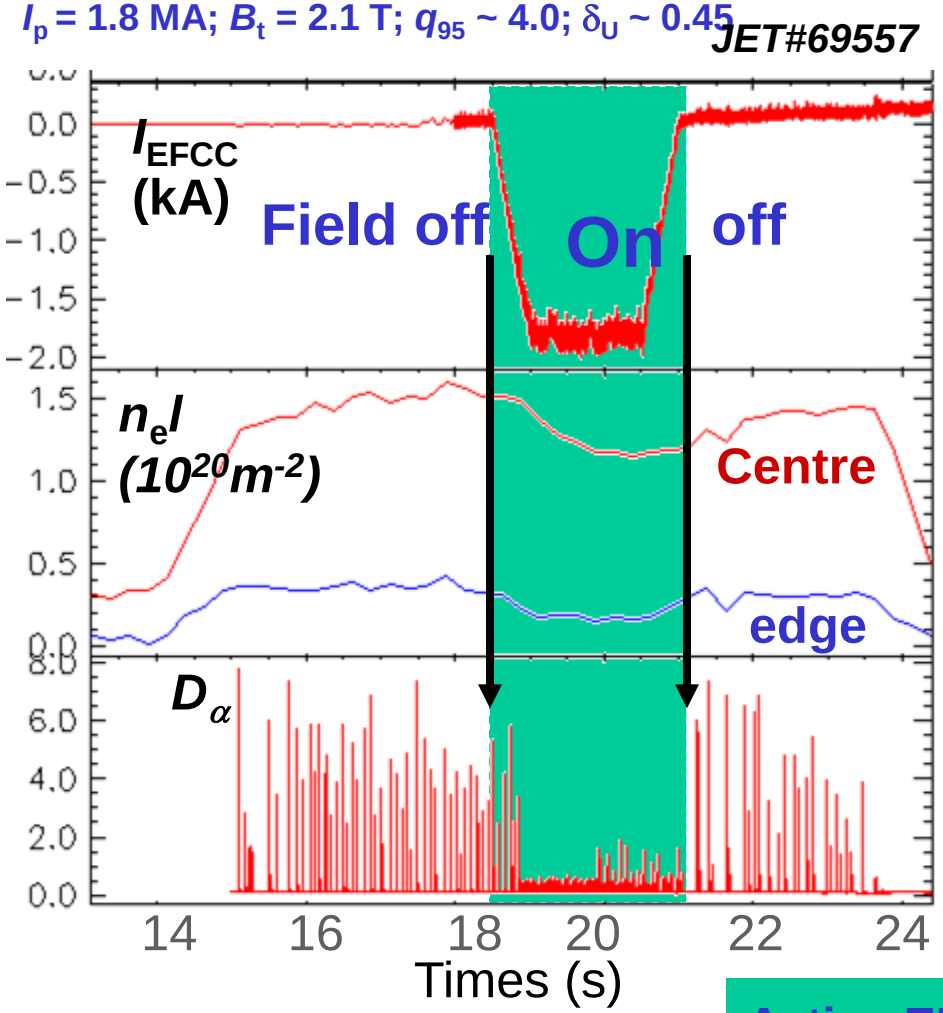


- Depending on the relative phasing of the currents in individual coils, either *n*=1 or *n*=2 fields can be generated
- I_{Coil} ≤ 3 kA x 16 turns (*n* = 1 *and* 2)
- *R* ~ 6 m; Size ~ 6 m * 6 m
- B_r at wall ~ 0.25 mT/kAt

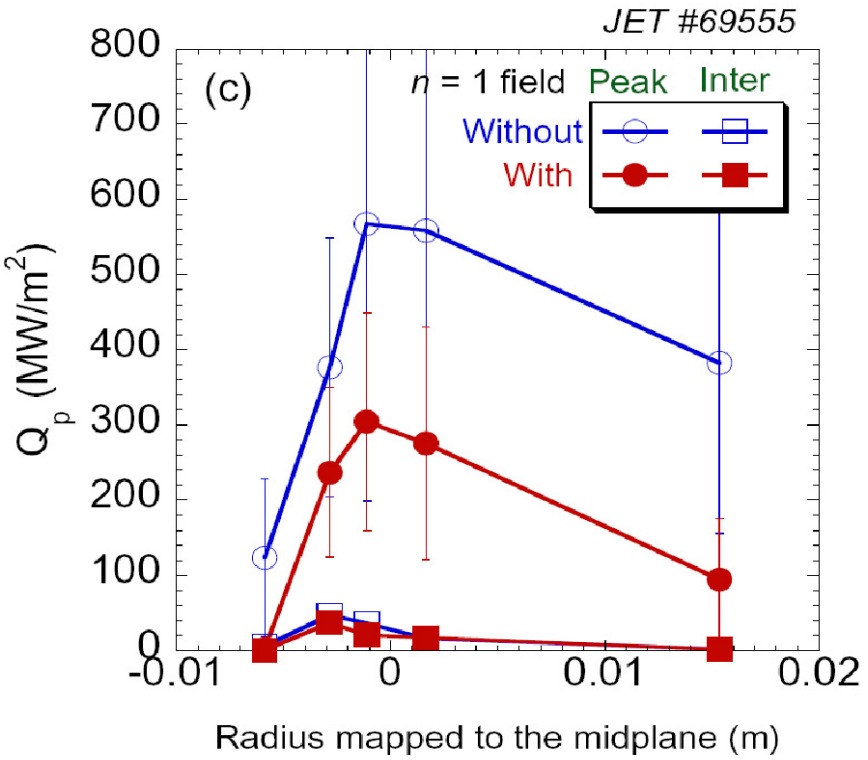
Y.Liang et al., PPCF 2007

Active ELM control with n = 1 magnetic perturbation field on JET

I_p = 1.8 MA; B_t = 2.1 T; q_{95} ~ 4.0; δ_U ~ 0.45



Heat flux onto the outer divertor

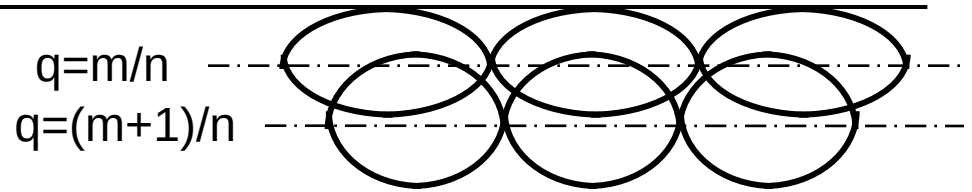


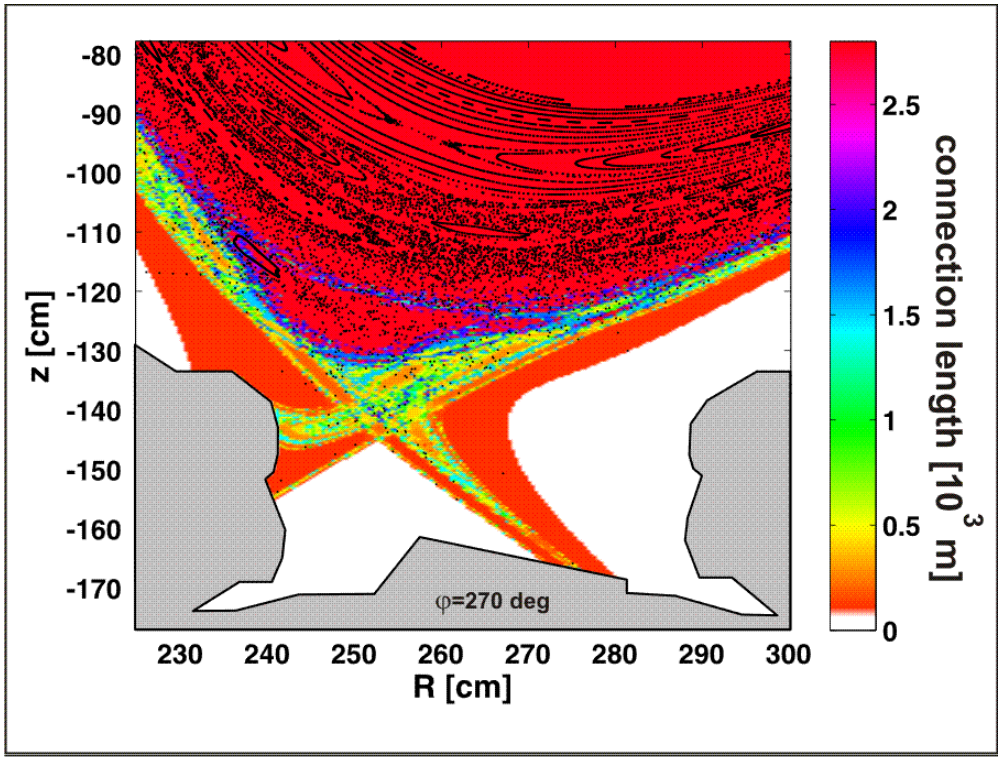
Y Liang, et al, PRL, 98, 265004 (2007)
Y Liang, et al, PPCF , 49, B581 (2007)
Y Liang et al, JNM, 390–391, 733–739 (2009)

Active ELM control (frequency/size) observed in a wide q_{95} window, but no ELM suppression

Edge ergodisation

Equilibrium Magnetic Field at Plasma Edge





Chirikov parameter

$$\sigma_{m,m+1} = \frac{w_{n,m} + w_{n,m+1}}{2\delta_{m,m+1}}$$

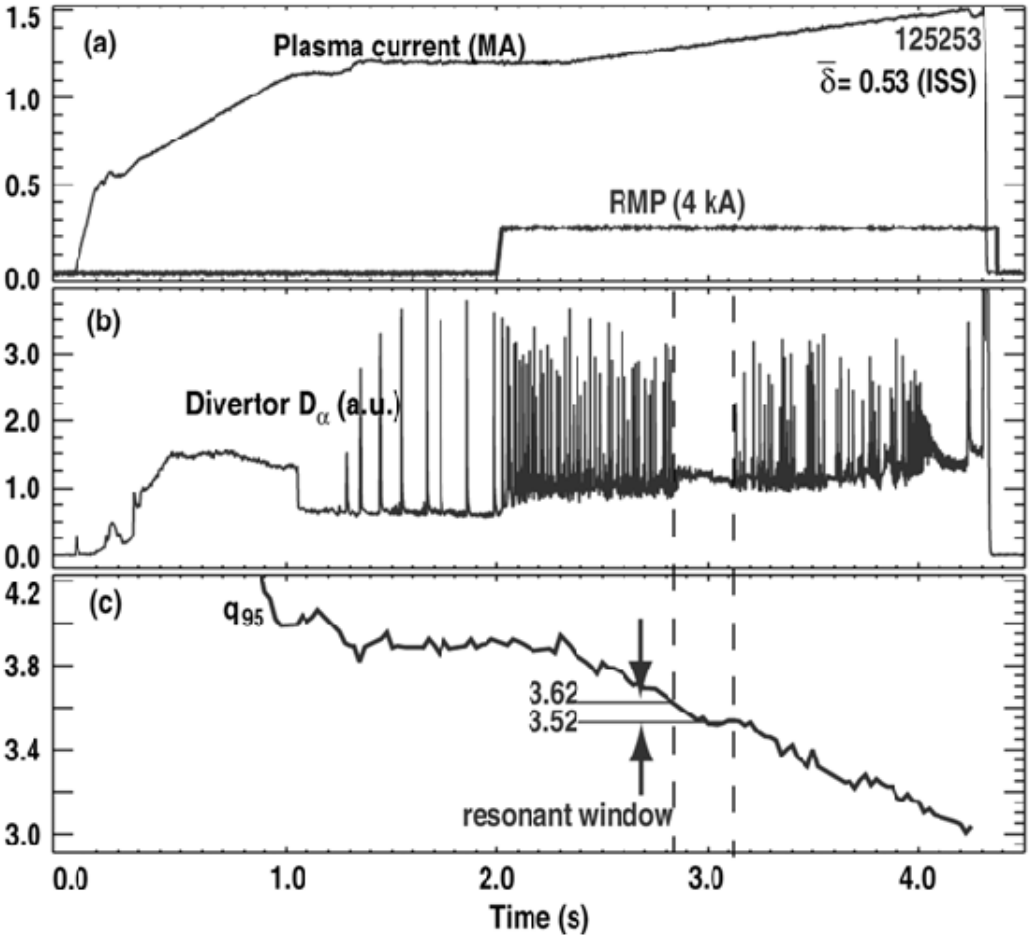
larger than 1

- Splitting of strike point
- Spin-up plasma rotation to co-current direction

Edge Ergodisation with a magnetic perturbation

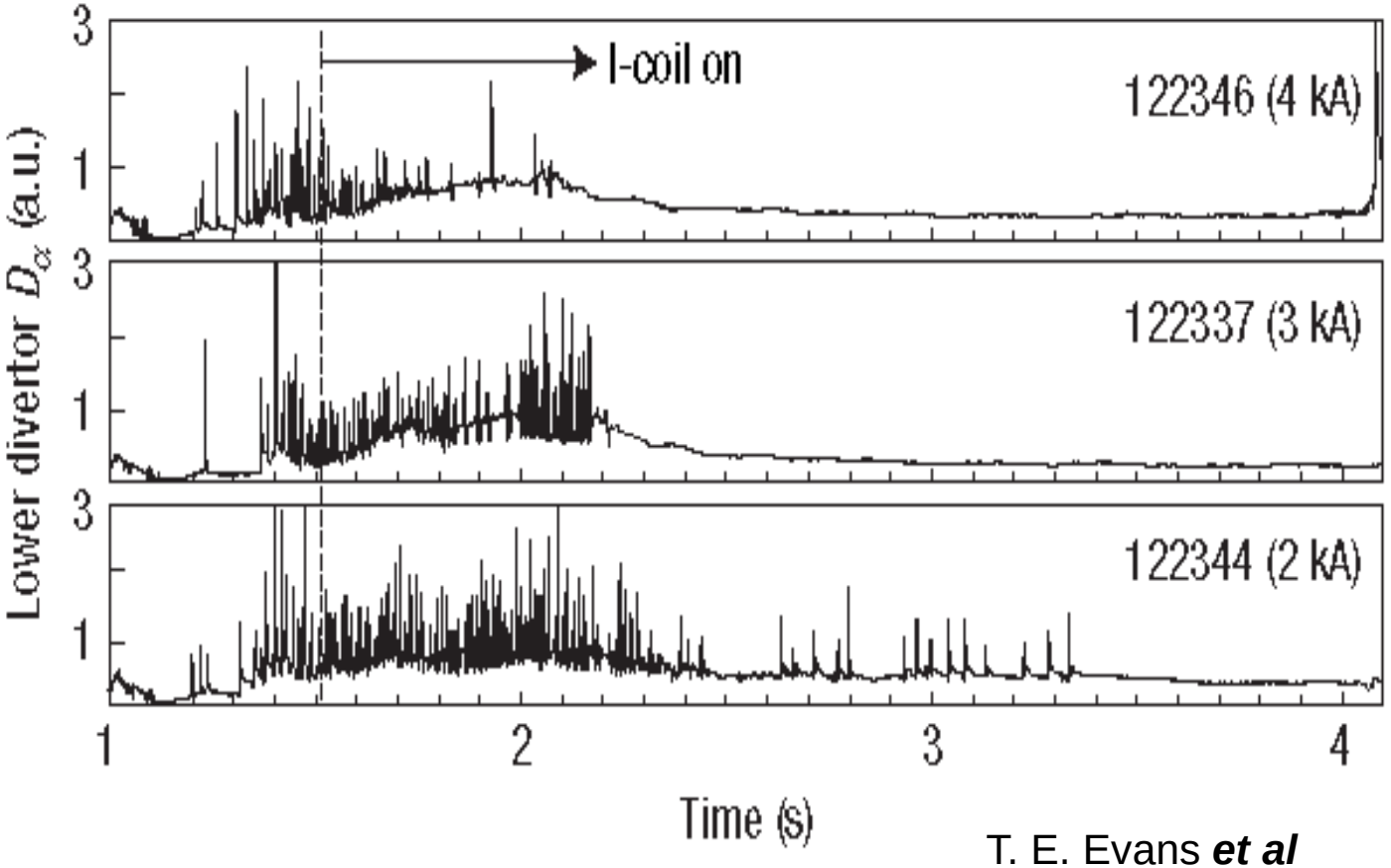
ELM suppression window on DIII-D

- ✓ ELM suppression achieved in a narrow q_{95} window on DIII-D with an *n*=3 field induced by the I-coils.
- ✓ q_{95} ELM suppression window can be enlarged slightly with a mixed *n*=1 and *n*=3 fileds.



T.E. Evans, et al., NF **48** (2008) 024002

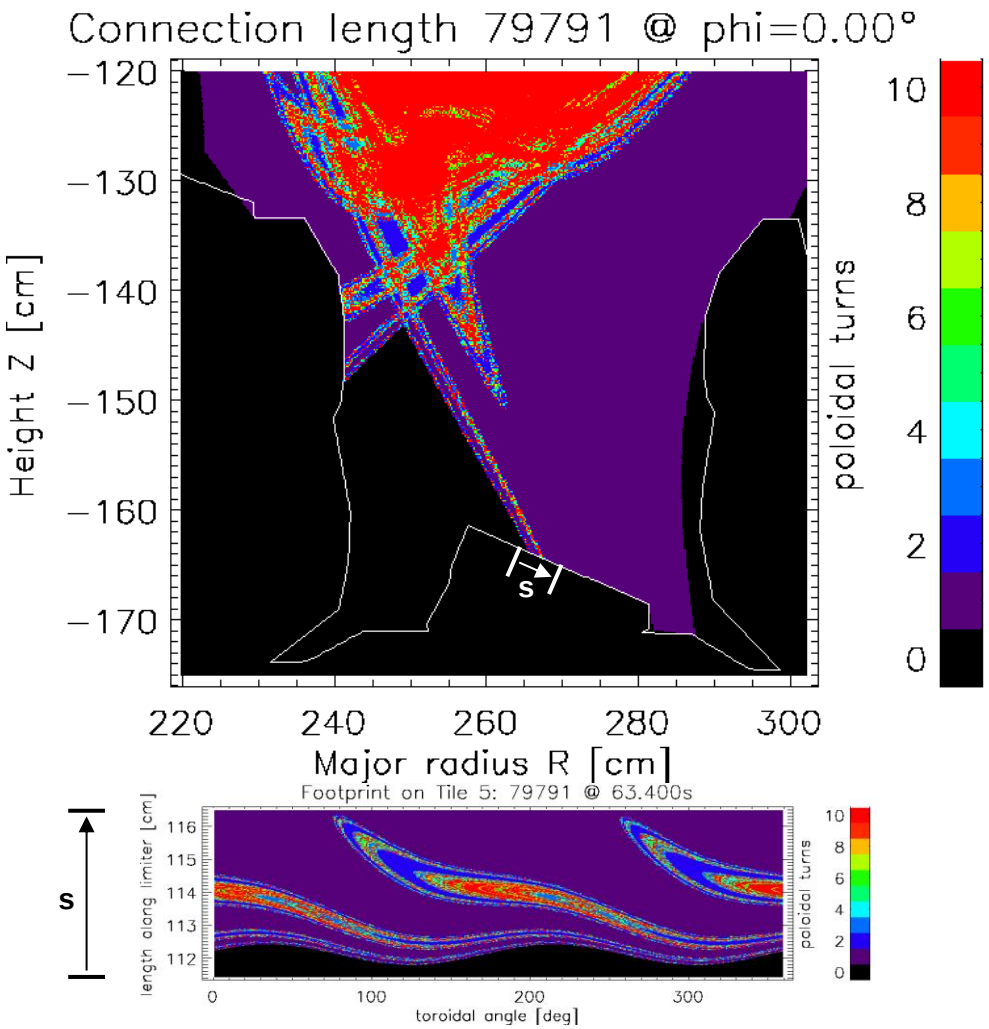
Threshold of ELM suppression



T. E. Evans ***et al***
Nature Physics 2 (2006) 419

There is a threshold of ELM suppression in the amplitude of the n = 3 field.

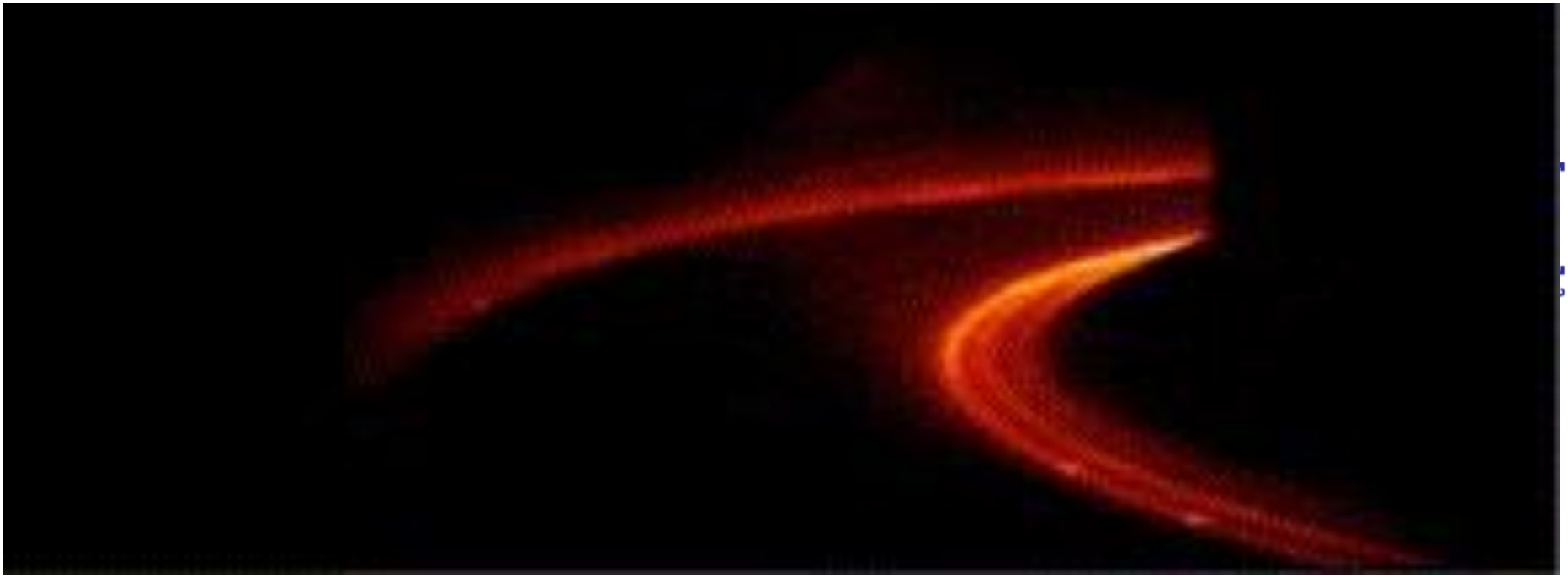
Toroidal evolution of strike point



- Field line tracing in vacuum approximation (superposition of equilibrium and perturbation field)
- No screening of RMP by poloidal rotation
- Ergodic field lines form lopes which generate multiple strike points on the divertor
- Strike point splitting depends on toroidal position
- Footprint represents N=2 symmetry of perturbation field

D. Harting, JET science meeting 2010

Strike point splitting on DIII-D



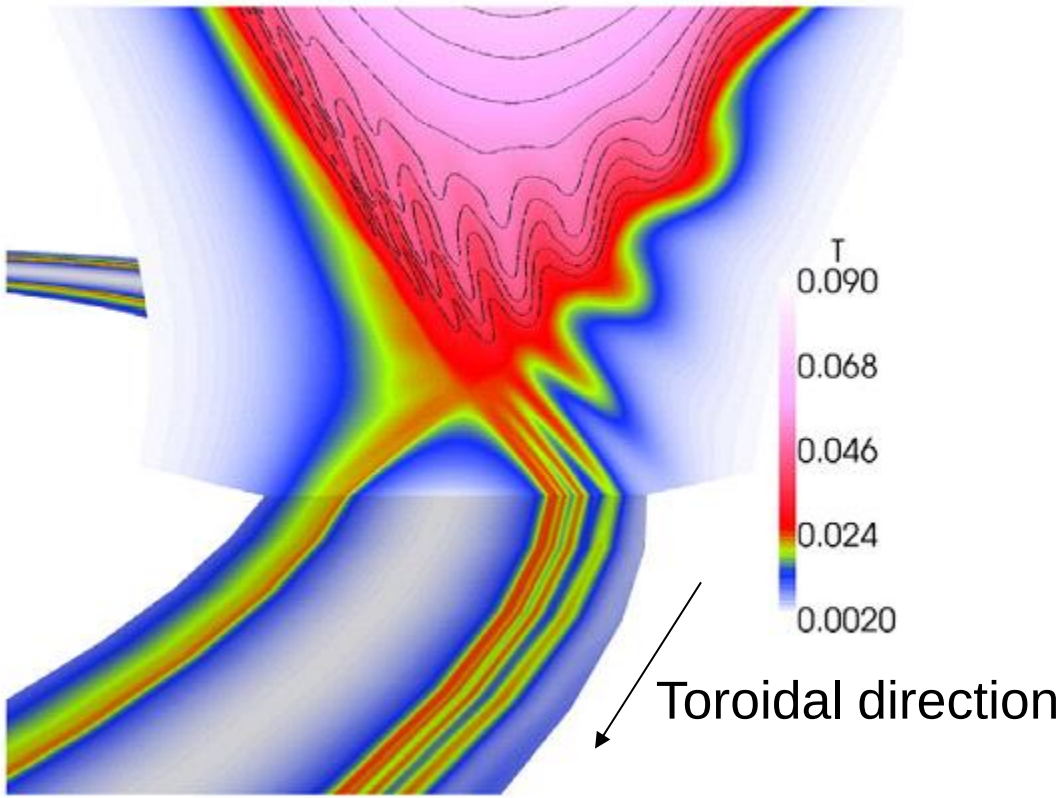
O. Schmitz, PPCF (2008)

I. Joseph JNM, 2007

Splitting of the inner strike-point has been observed during ELM suppression with an n = 3 field on DIII-D.

Nonlinear simulations of ELMs

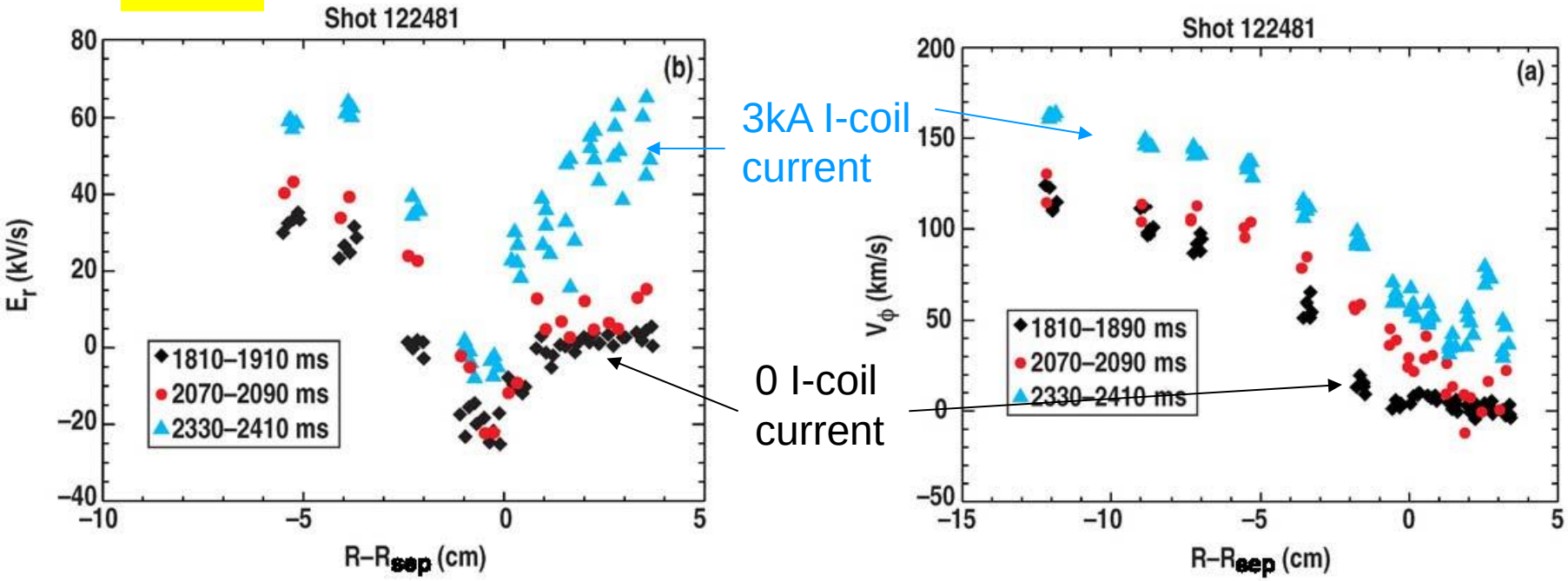
Hyusmans PPCF (2009)



A poloidal and toroidal cut of the plasma temperature

Influence of magnetic perturbation on the Edge Electric field and rotation

DIII-D



K. Burrell, PPCF 47, B37, 2005

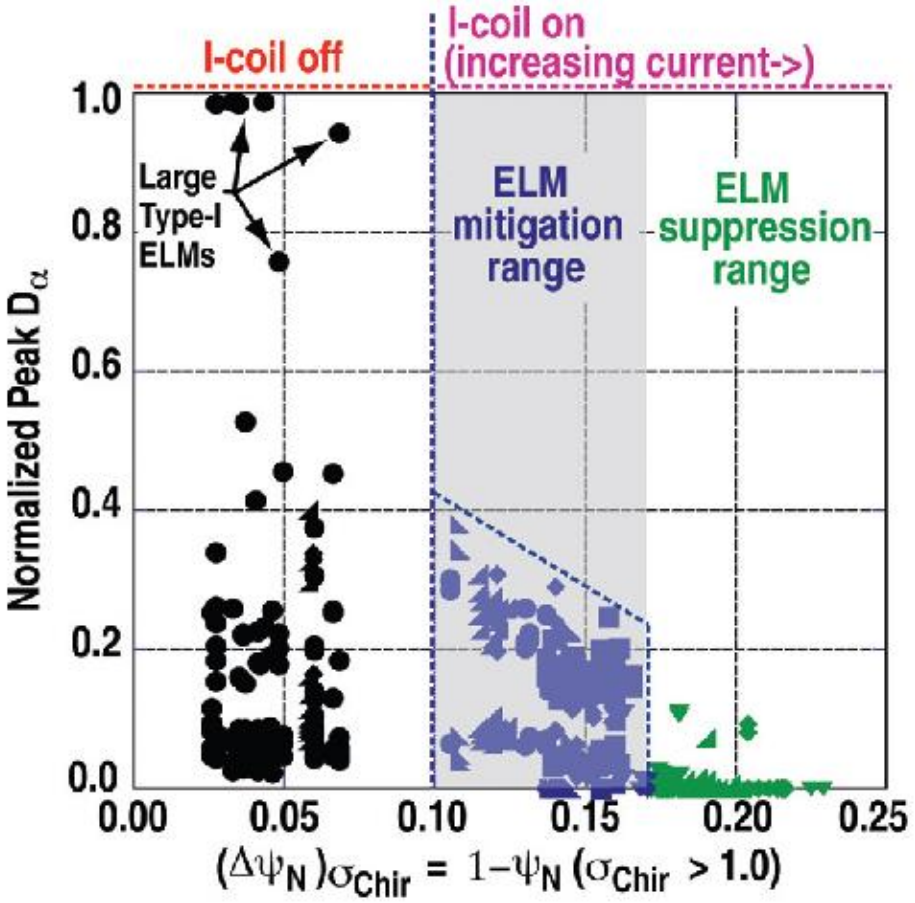
With an *n* = 3 field applied,

edge Er → more positive;

spin-up plasma rotation in co-current direction,

A large enhancement of the electron losses rather than ions by reason of the edge ergodisation.

Criterion for ELM suppression with RMPs



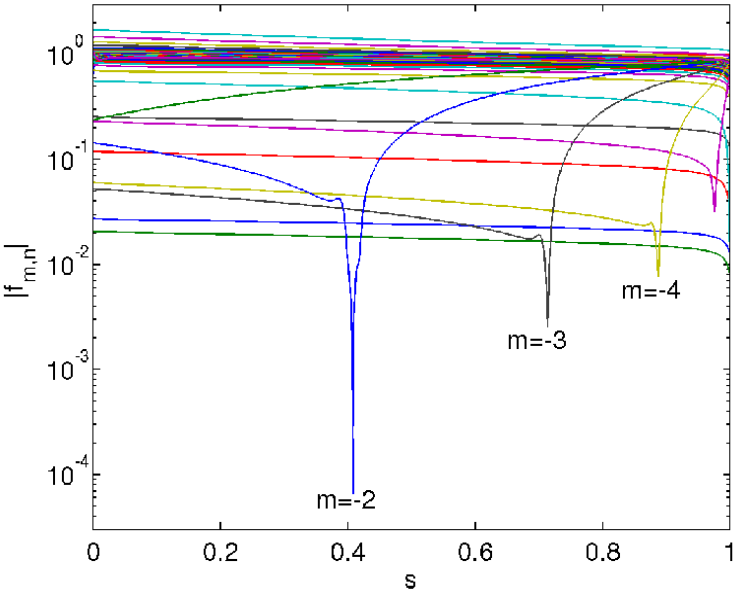
M.J. Schaffer, et al., IEEE (2009); NF (2008)

✓Chrikov parameter number larger than 1 in the edge layer (sqrt(ψ) >0.925).

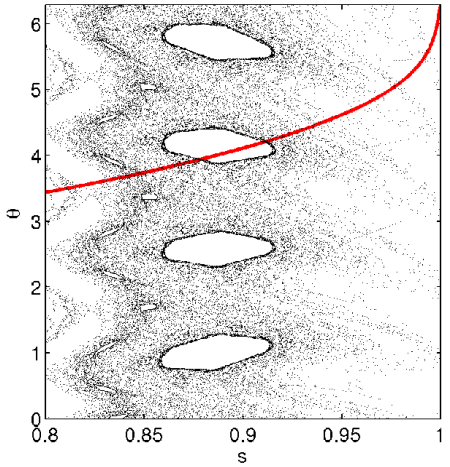
Effect of plasma shielding of the RMP

M. Heyn, JET science meeting, 2010

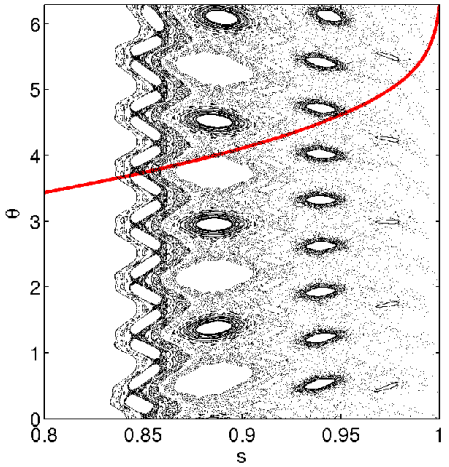
$$f_{mn} = B_{r,mn}^{(\mathrm{plas})} / B_{r,mn}^{(\mathrm{vac})}$$



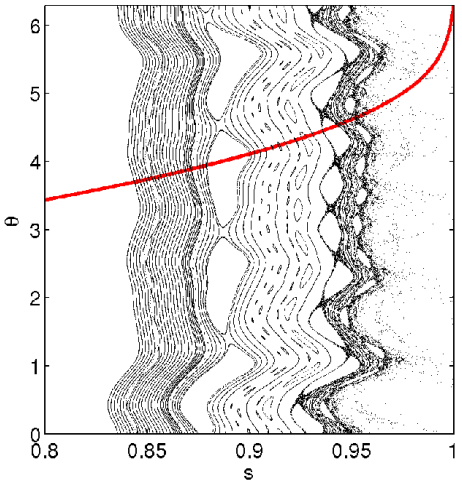
✓The resonant perturbation is shielded due to plasma rotation and the magnetic field topology in the plasma core is not affected by RMP's.



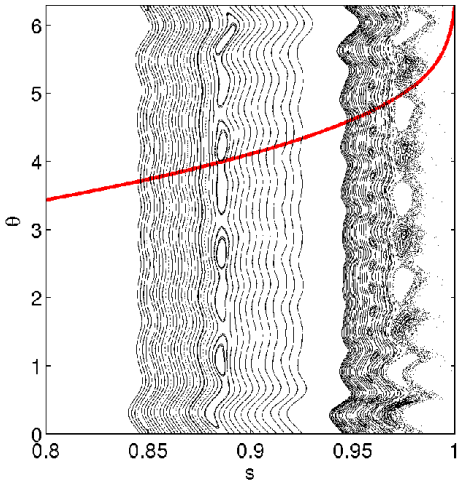
vacuum, $n = 1$



vacuum, $n = 2$



plasma, $n = 1$

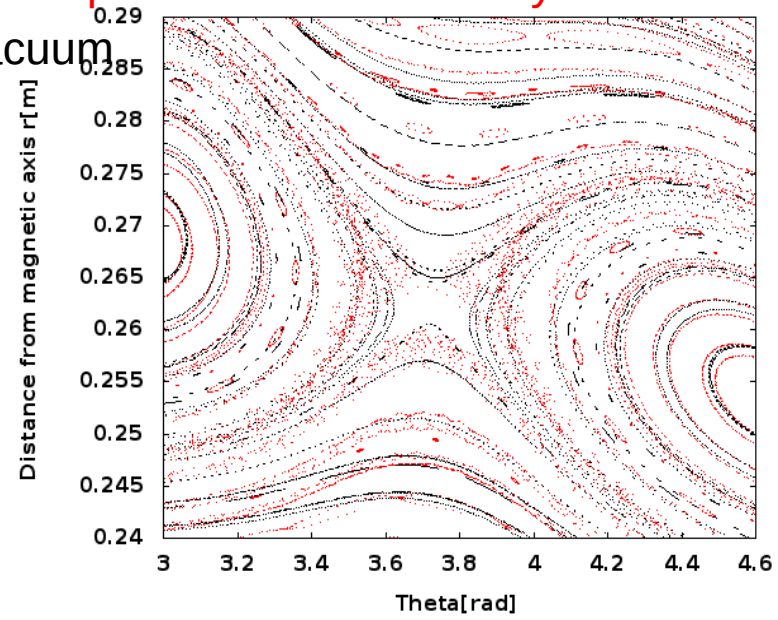


plasma, $n = 2$

Influence of magnetic perturbation on X-point

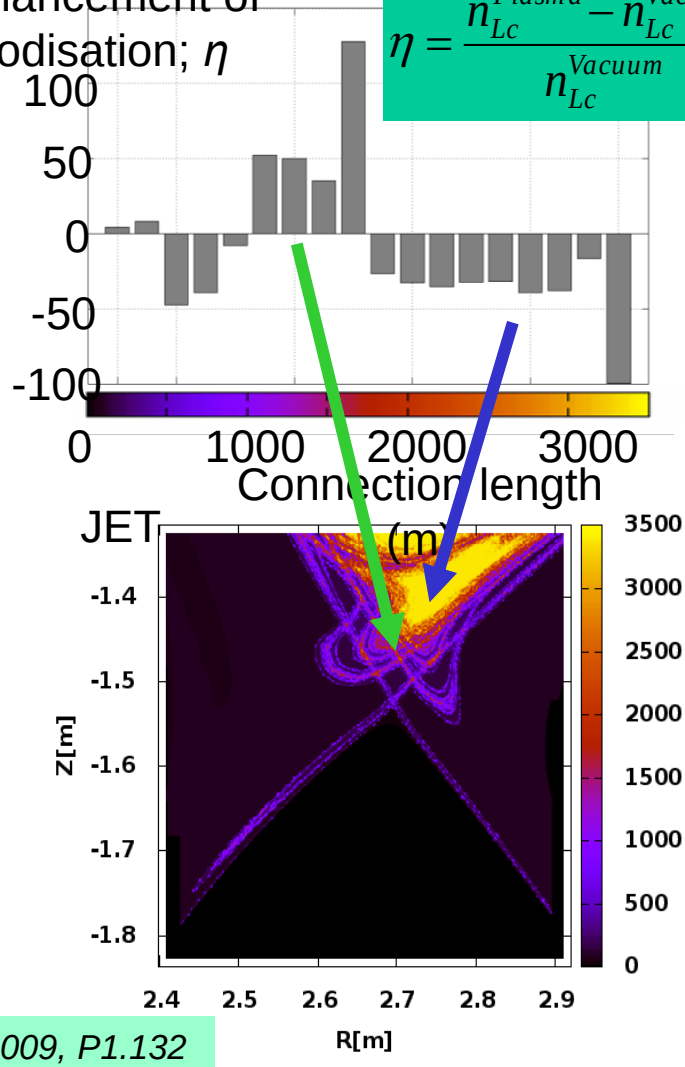
3-D Equilibrium calculation by HINT2 Code

Vacuum



Enhancement of ergodisation; η (%)

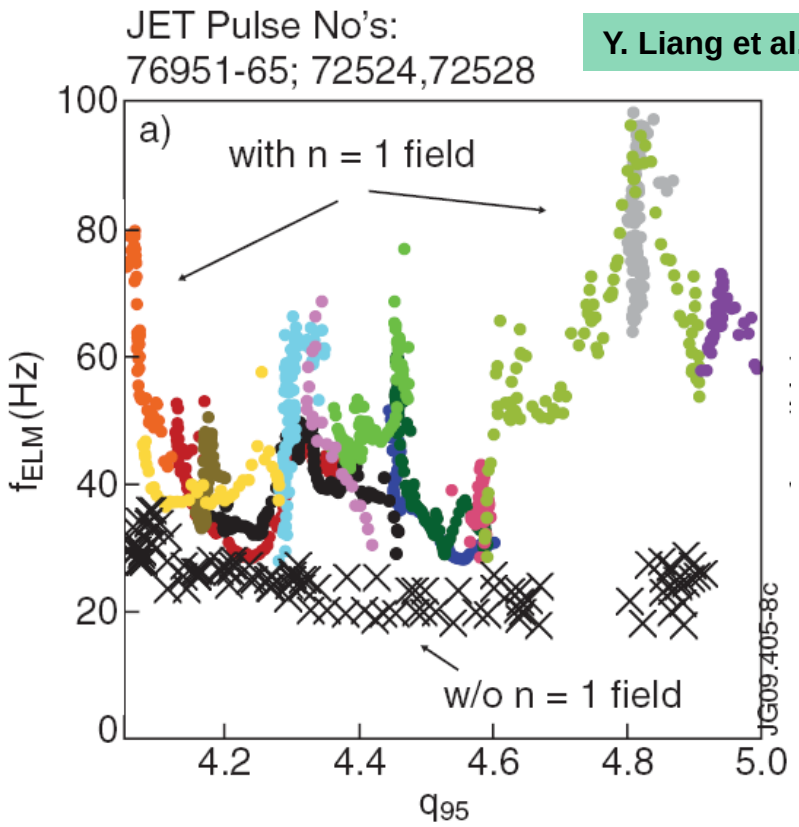
$$\eta = \frac{n_{Lc}^{Plasma} - n_{Lc}^{Vacuum}}{n_{Lc}^{Vacuum}}$$



- Flattening of *j* and *p* at the islands leads to an ergodisation at the island X-points
- Strong enhancement of ergodisation at the X-point region due to plasma response may explain the density pump-out seen already at a small amplitude of the pertubation field

C. Wiegmann, et al, EPS2009, P1.132

Observations of Multi-Resonance Effect in ELM Control with Perturbation Fields on the JET



Y. Liang et al., PRL 105, 065001 (2010)

A model in which the ELM width is determined by a localized relaxation to a profile which is stable to peeling modes can qualitatively predict this multi-resonance effect with a low n field. The dominant unstable peeling mode number and ELM frequency depends on the amplitude of the normalized edge currents as well as q_{95}.

- Multiple resonances in f_{ELM} vs q_{95} have been observed with n = 1 and 2 fields
- The mechanism of edge ergodisation, can not explain the multi-resonance effect observed with the low n fields on JET.
- Possible explanation in terms of ideal peeling mode model by *Gimblett,PRL,2006*.

ELM control coils on AUG

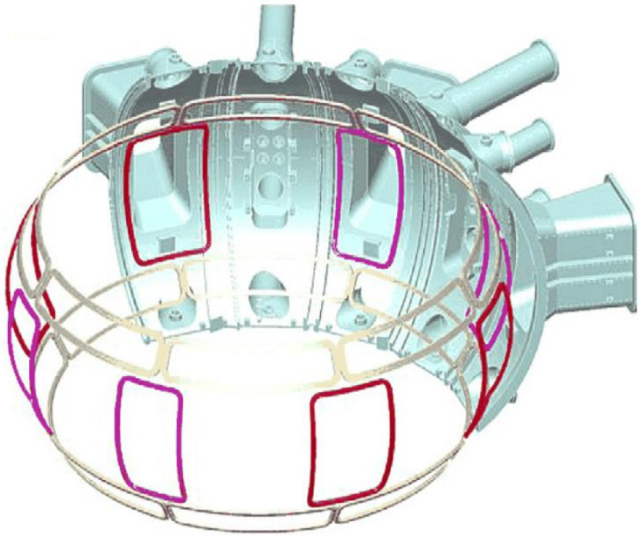
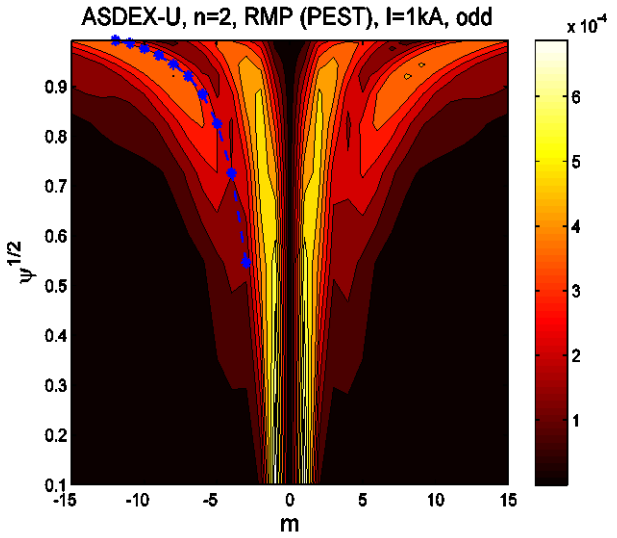
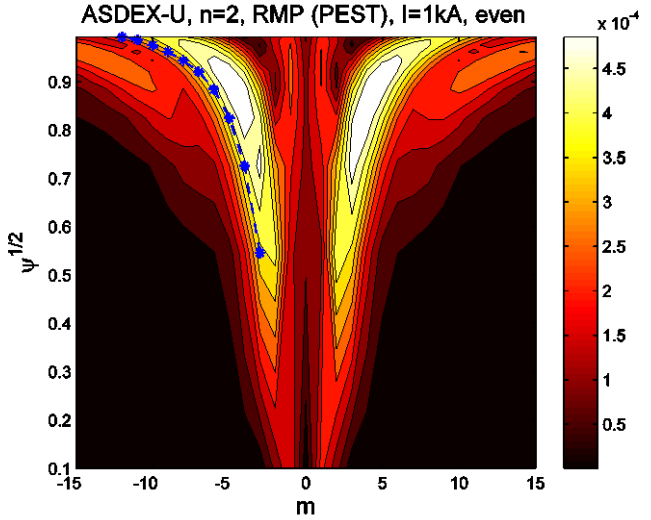


Fig. 1. 3D view of active in-vessel coils.

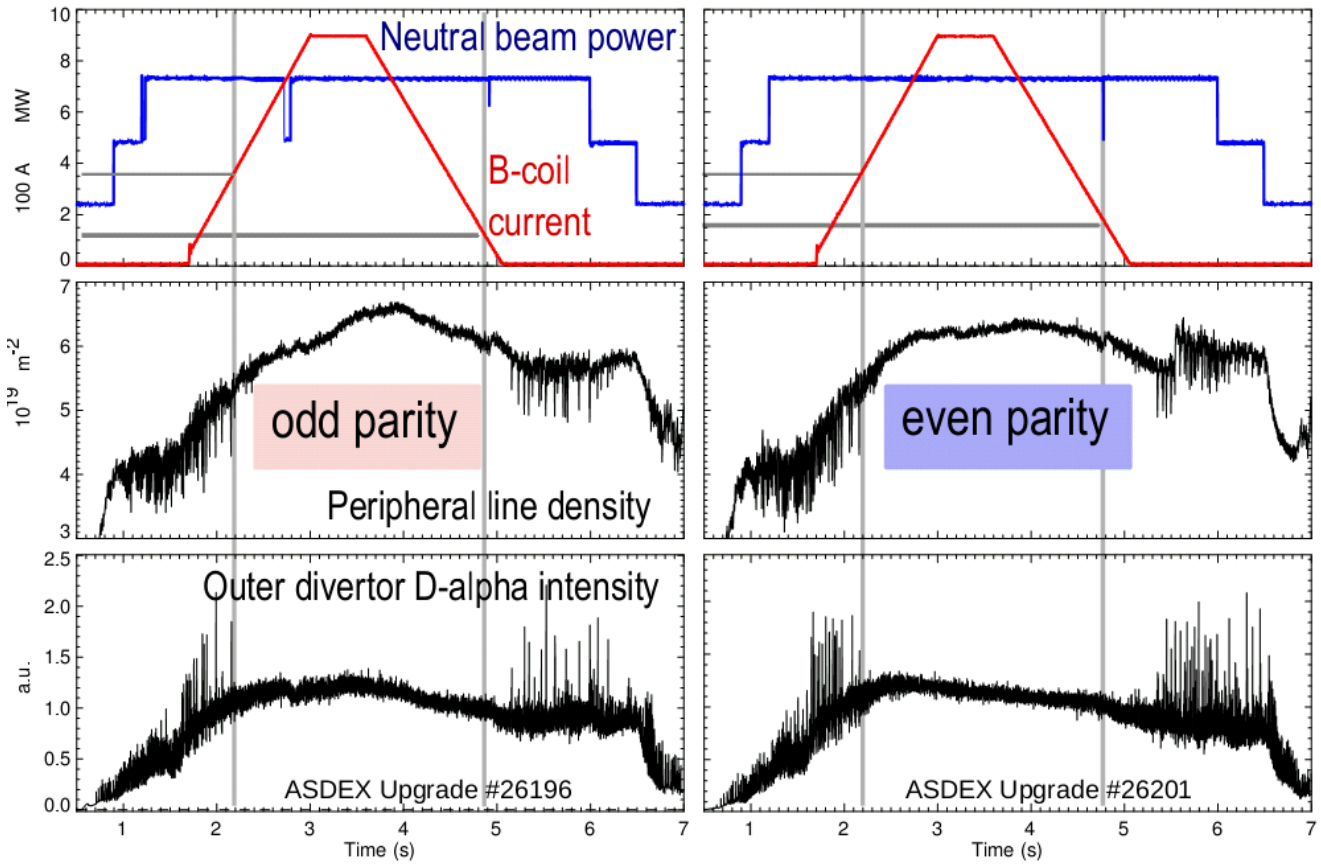
W Suttrop, Fusion Engineering and Design 84 (2009) 290

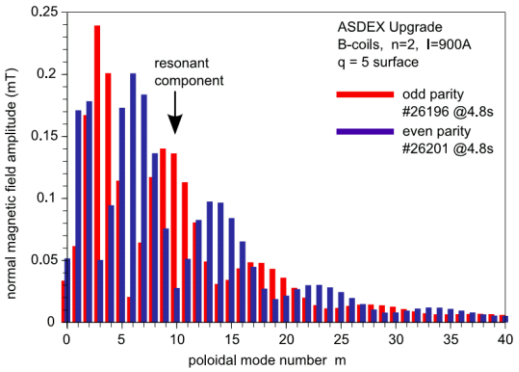
In 2011: Two rows ×4 toroidally distributed coils (n = 2).
Single DC supply (all coils in series / anti-series).





ELM mitigation on AUG





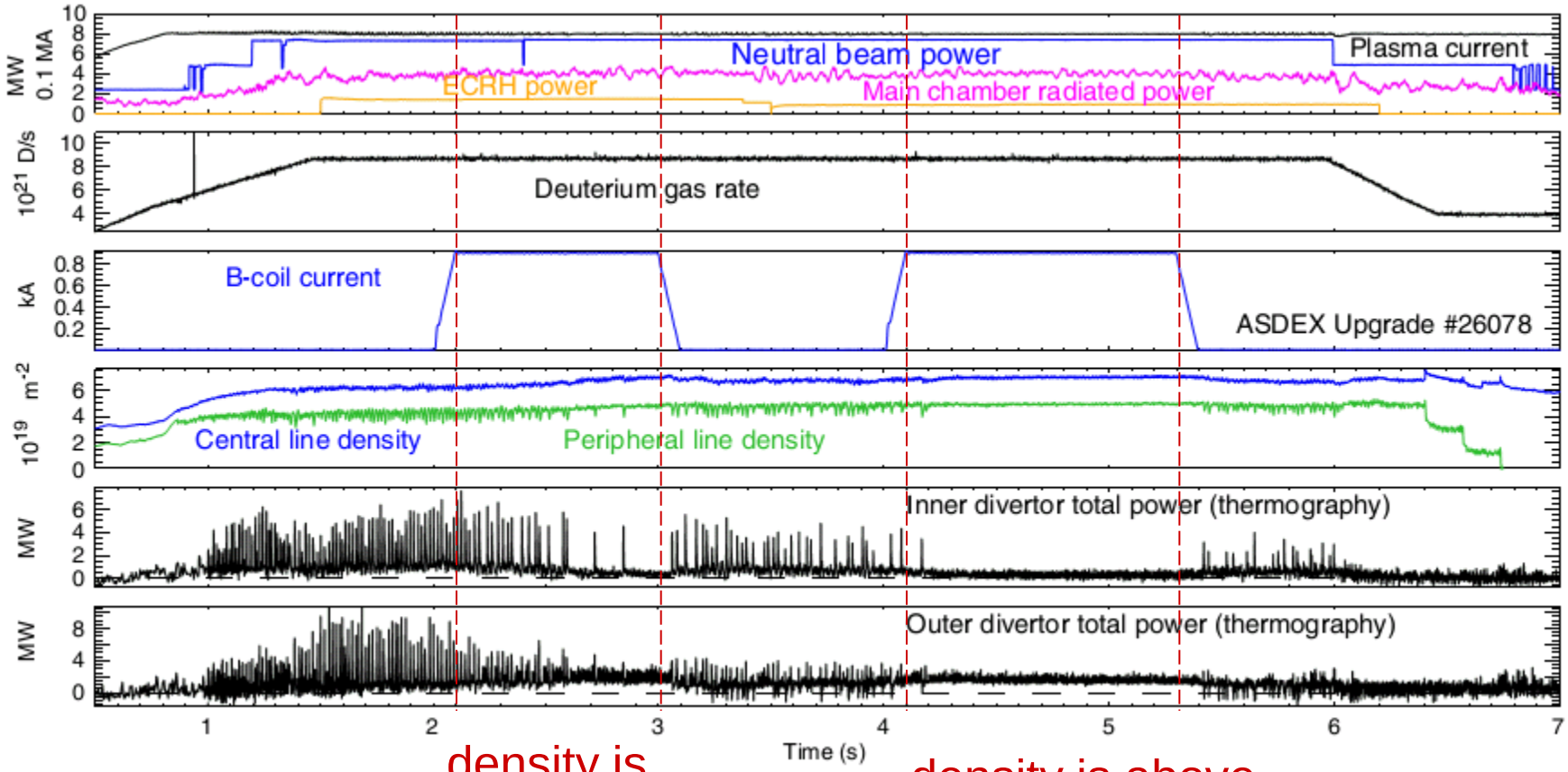
Resonant and non-resonant variants work in the same way!

… which is in contradiction to stochastic hypothesis…

Hysteresis: $I_{\mathrm{coil}} = 350$ A to and ≈ 150 A from ELM-mitigated state

W Suttrop, PRL (2010)

ELM mitigation on AUG

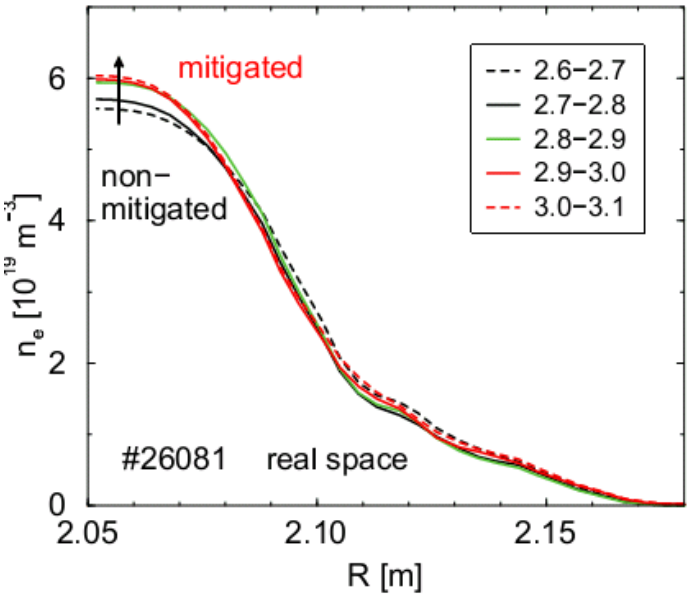


density is around the threshold

density is above the threshold (mitigation)

ELM control in AUG

- Type-I ELMs replaced by frequent small ELMs (not a gradual evolution of ELM losses)
- Particle confinement, pedestal density increase (no “pump-out”)
- Energy confinement (stored energy) $\approx$ unchanged W concentration, Z_{eff} not increased
- Minimum density for ELM mitigation
  Empirical “scaling”: $n_{\mathrm{edge.min}} = 0.65\, n_{\mathrm{GW}}$
  Universal? Physical meaning?
- ELM mitigation apparently insensitive to resonance condition
  Demonstrated at $q_{95} = 5.5$, but true for all q ?



Summary of ELM suppression/control with RMP

DIII-D *n* = 3, I-coils

→ ELM suppression in a narrow range of q_{95}

→ ELM mitigation in a wide range of q_{95}

JET *n* = 1, 2 EFCC

→ ELM mitigation

global effect in a wide range of q_{95}

multi-resonance effect in multiple narrow q_{95} windows

MAST *n* = 1, 2 EFCC; n=3 i=coils

→ ELM mitigation (q_{95} dependence)

AUG *n* = 2 B-coils

→ ELM mitigation in a relative wide range of q_{95}

→ Thresholds for RMP ELM mitigation

Summary of ELM suppression/control with RMP

- Is the amplitude of the effective RMP important? → **Yes**
  - → Plasma Rotational screening effect

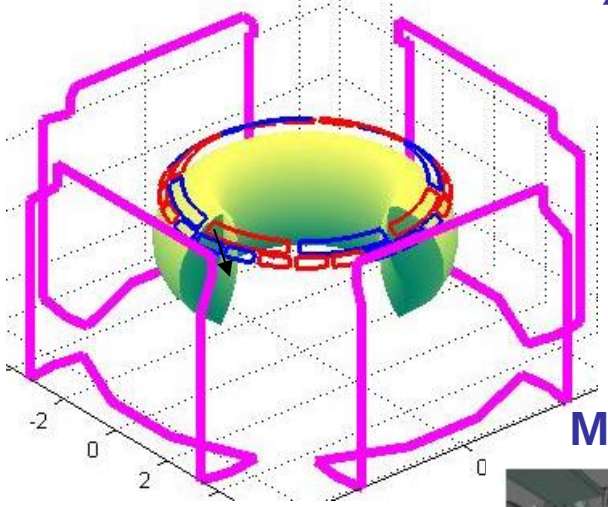
    Field penetration → **Yes, but how deep the RMP field have to penetrate into a plasma for ELM suppression?**

- Is the target plasma itself important? → **Yes**
  - → Operation regime (ELM stability) → **Unknown**
  - → Plasma shaping (ELM stability) → not very important
  - → Collisionality (depending on the device; → **Unknown**)
  - → q_{95} → **Yes**
  - → Beta dependence? (→ **DIII-D Yes**)

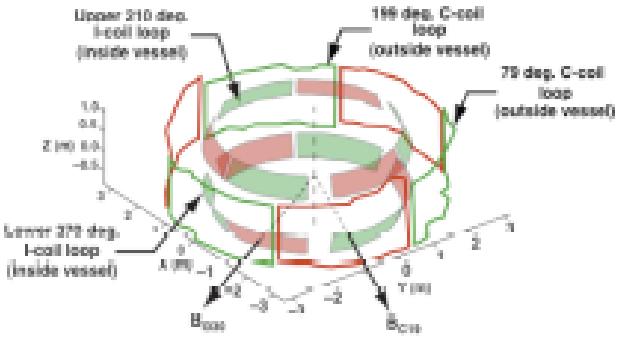
RMP ELM control Experiments

JET EFCC

& In-vessel coils (planned)



DIII-D existing



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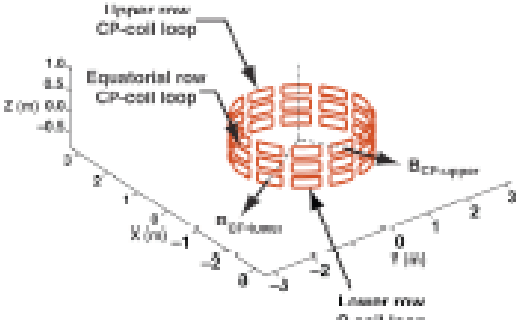
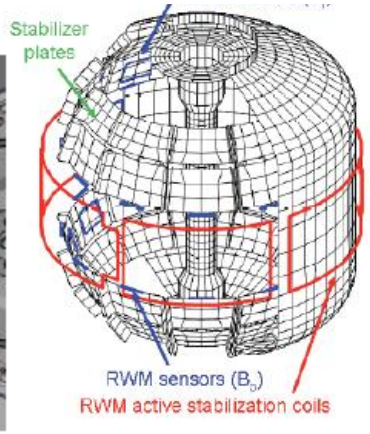
DIII-D planned

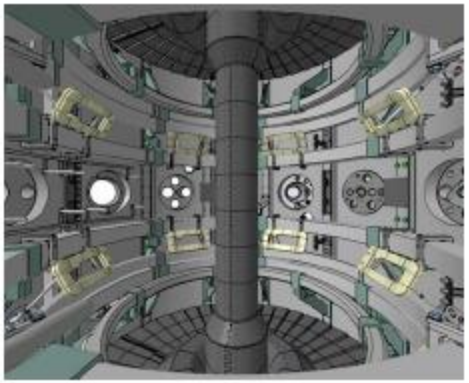


ASDEX-U

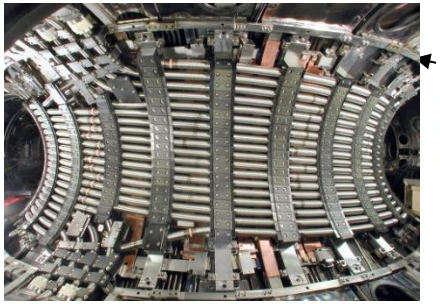
NSTX



MAST



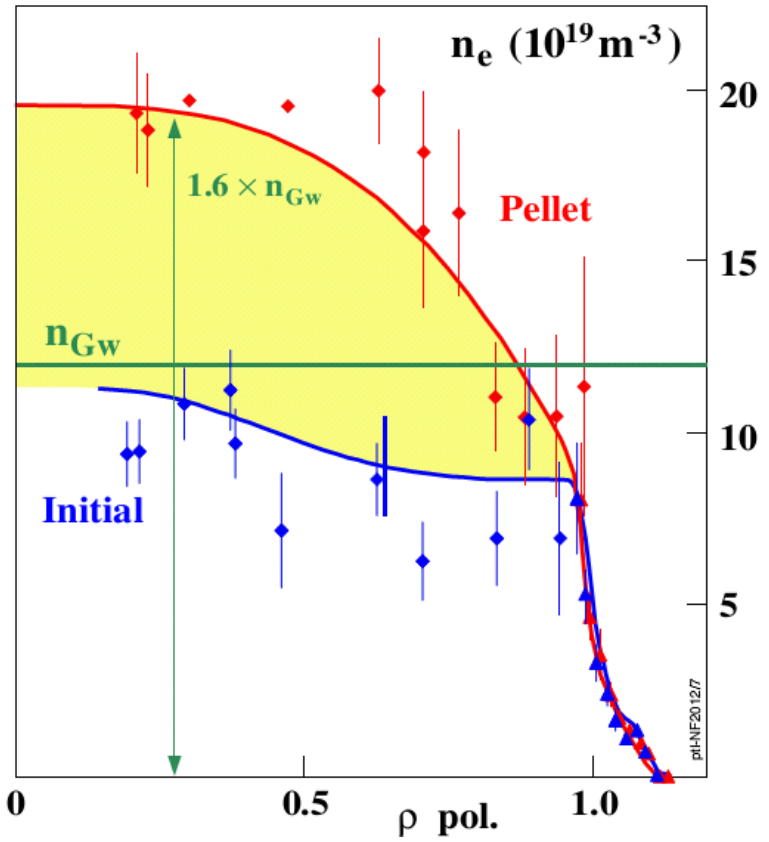
TEXTOR



+ EAST

…… providing input to modelling for ITER.

ASDEX Upgrade



External coils + pellets

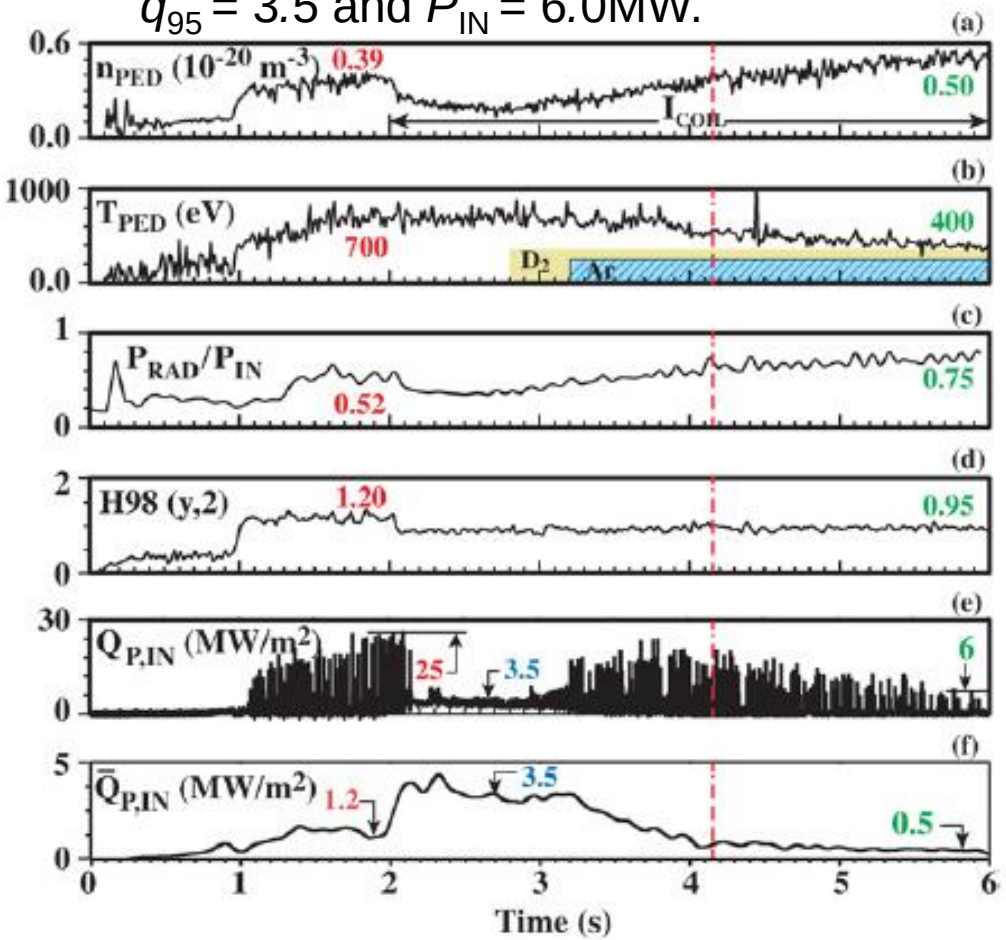
Central density could be increased up to $n \approx 1.6 n_G$

Recent result $n > 2 n_G$!!

Lang Nucl. Fusion 52(2012) 023017

Results from radiating divertor experiments with RMP ELM suppression/control on DIII-D

Plasma parameters: I_p = 1.43 MA, q_{95} = 3.5 and P_{IN} = 6.0MW.



*T.W. Petrie, et al, Nucl. Fusion **51** (2011) 073003*

- ✓ Under RMP ELM-suppressed conditions, divertor peak heat flux could be reduced by the addition of deuterium and argon gas puffing.
- ✓ The 'cost' in doing so, however, was triggering the return of ELMs, although these ELMs produced lower peak heat flux on divertor than that observed prior to the application of RMP.

Summary

- ✓**ITER needs ELM control/suppression of Type I ELMs**
- ✓**Linear stability boundaries are relatively well detected**
- ✓**Nonlinear behaviour is important**
- ✓**Possible control options**
  - ✓ ***Radiating divertors (type-III ELM)***, successful ELM control and full H-mode confinement have still to be demonstrated.
  - ✓ ***Magnetic triggering*** (“vertical kicks”) need in-vessel coils.
  - ✓ ***Pellet pacing*** can typically achieve a factor of two reduction in the energy per ELM – this is not enough.
  - ✓ ***External magnetic perturbation*** Very promising results up to now but physics is not clear
  - ✓ ***Combine methods*** have good future

Edge localized modes: recent experimental findings and related issues

Plasma Phys. Control. Fusion **49** (2007) S43–S62

K Kamiya[1], N Asakura[1], J Boedo[2], T Eich[3], G Federici[4], M Fenstermacher[5], K Finken[6], A Herrmann[3], J Terry[7], A kirk[8], B Koch[3], A Loarte[9], R Maingi[10], R Maqueda[11], E Nardon[12], N Oyama[1] and R Sartori[9]

+ recent publications for control with external coils

Substantial amount of the material for this lecture was taken from the talks given by Yunfeng Liang and Howard Wilson on 480th Wilhelm and Else Heraeus Seminar on „Active Control of Instabilities in Hot Plasmas” (16-18 June, Bad Honnef, 2011)

Questions to the lecture

1) We can not tolerate ELMs because ….

2) If we see ELMs we are in ….

3) Peeling and kink modes are essentially the same thing
   - Driven by ….. density gradient, stabilised by ….. gradient

3) Ballooning mode is unstable when critical …. gradient is sustained.

4) ELM control techniques are:

   …..

   …..