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4TH ITER International Summer School,
"Magnetohydrodynamics and Plasma Control in Magnetic Fusion Devices“, Austin, Texas USA

JÜLICH
FORSCHUNGSZENTRUM

ELM Control in Tokamak Plasmas

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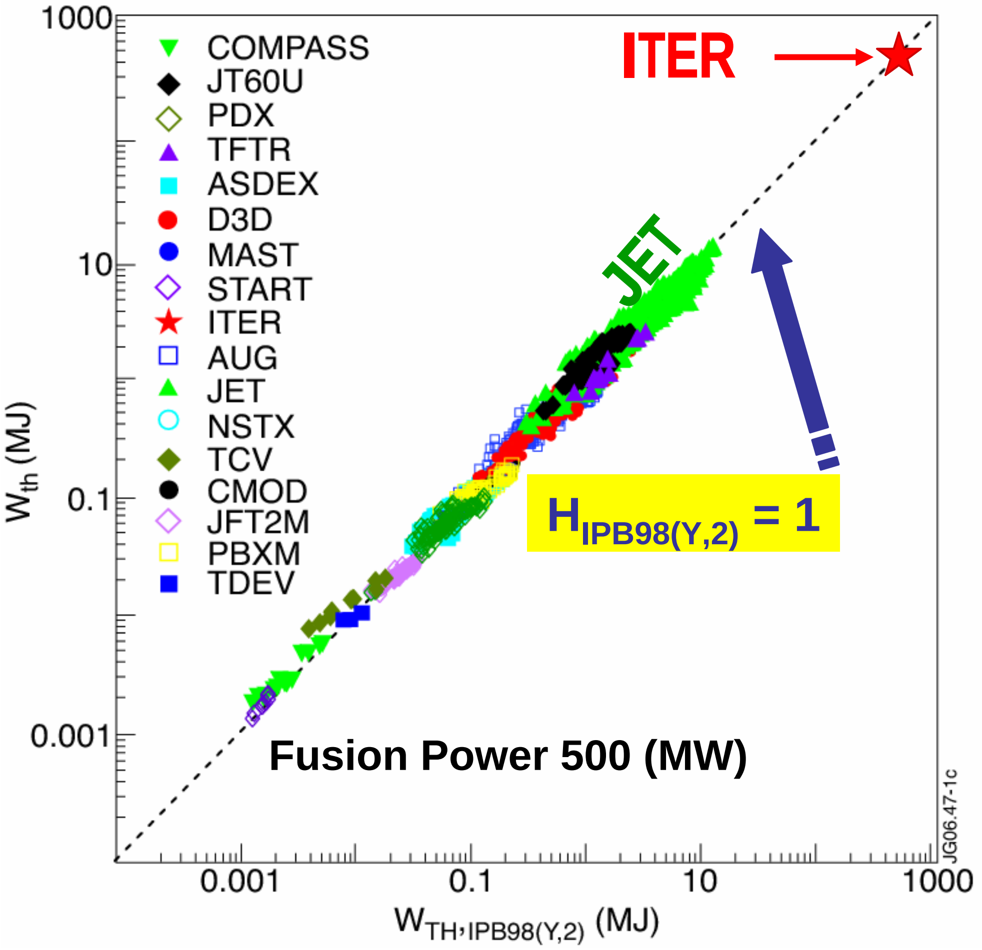
Stored energy vs 'scaling law'



$$\tau_{E,th}^{ELMy} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} n^{0.41} \times M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_a^{0.78}$$

- ❑The foreseen baseline operating scenario for ITER is the H-mode.
- ❑Edge Localized Modes are observed in H-mode plasmas

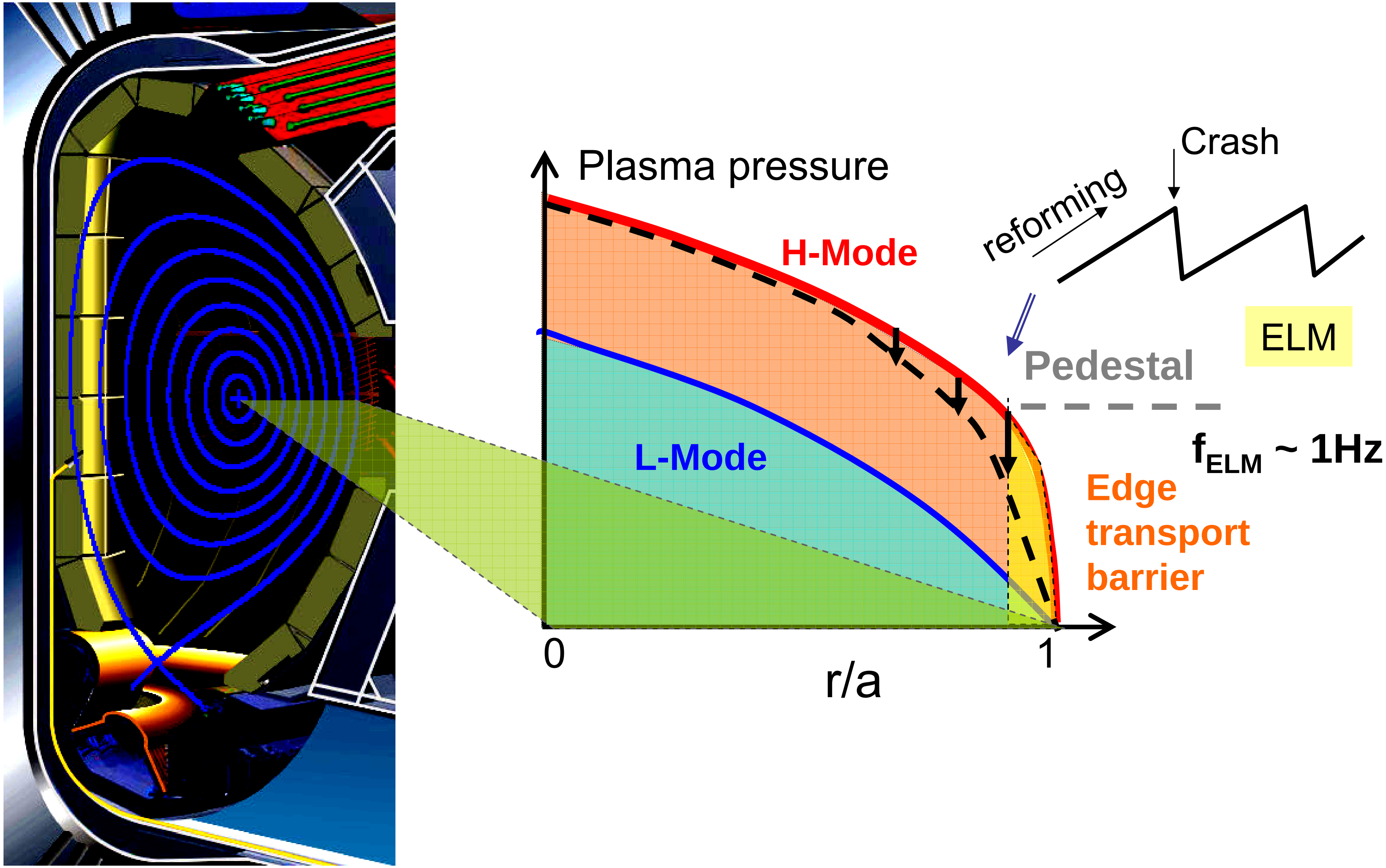
F. Wagner *et al.*Phys. Rev. Lett. 49, 1408 (1982).
ITER Physics Basis, Nucl. Fusion 39, 2137 (1999).

One of the most urgent issues:
How to control ELMs in a fusion reactor?

Outline

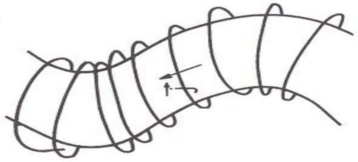
- **Introduction**
  - ☞ What is the Edge Localized Mode (ELM)?
  - ☞ Theory of ELMs
  - ☞ Why is ELM control urgent for ITER?
  - ☞ Methods applied for Type-I ELM control/suppression
- **ELM control/suppression with magnetic perturbations**
  - ☞ Application
  - ☞ Physics mechanism
- **Combination of different ELM control methods**
- **Summary**

What is the Edge Localized Mode (ELM)?



Theory of ELMs (I)

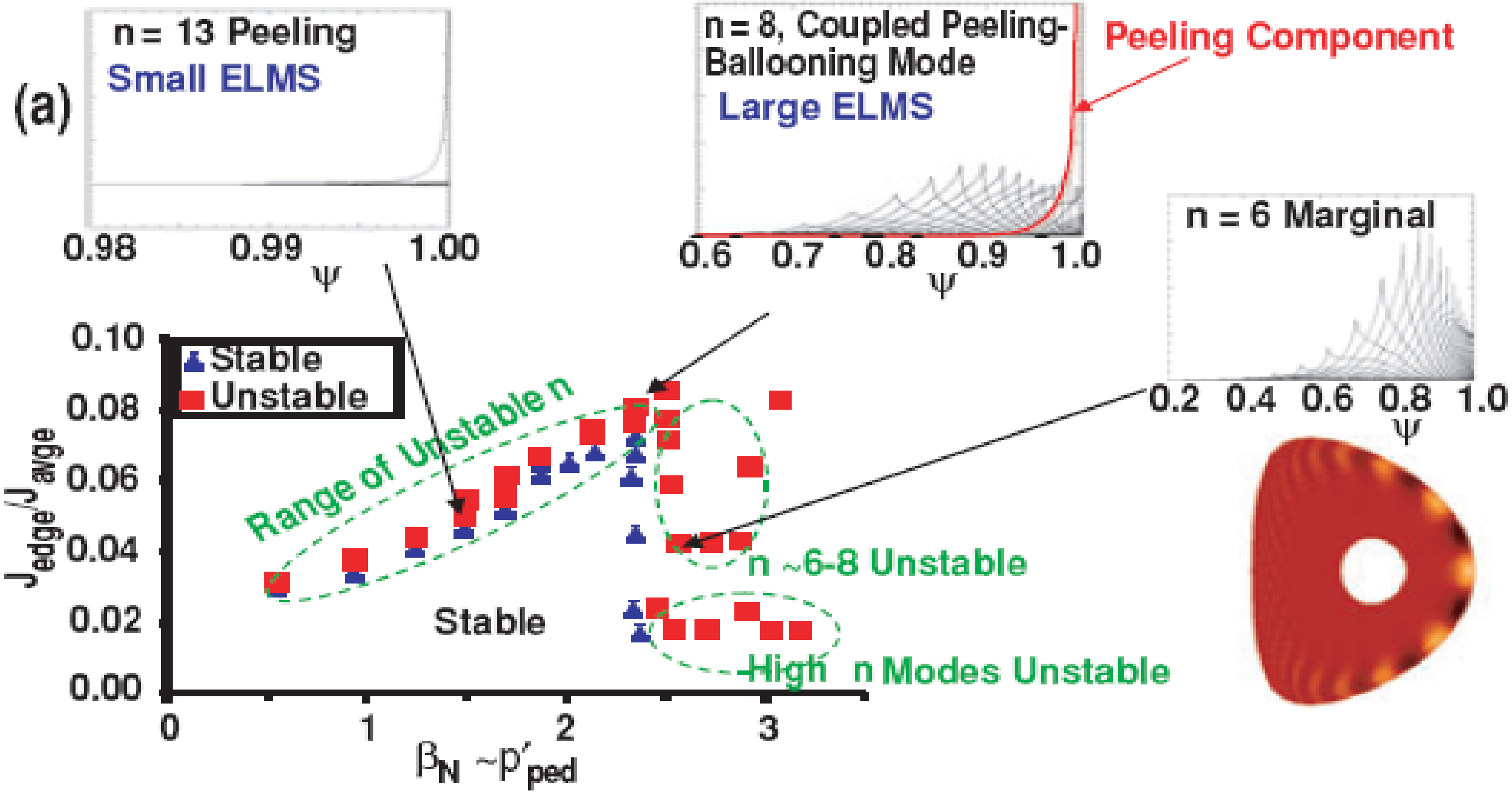
- ELMs are not well understood yet
- Ideal MHD modes driven by the steep current and pressure gradients at the edge transport barrier are regarded as the most likely candidates to explain their origin
- From stability calculations performed on the basis of experimental data three types of ideal MHD instabilities can be expected at the transport barrier:
  - ✓ kink-/peeling-modes
  - ✓ ballooning modes
  - ✓ coupled peeling-ballooning modes



H. Zohm, PPCF 38 (1996).

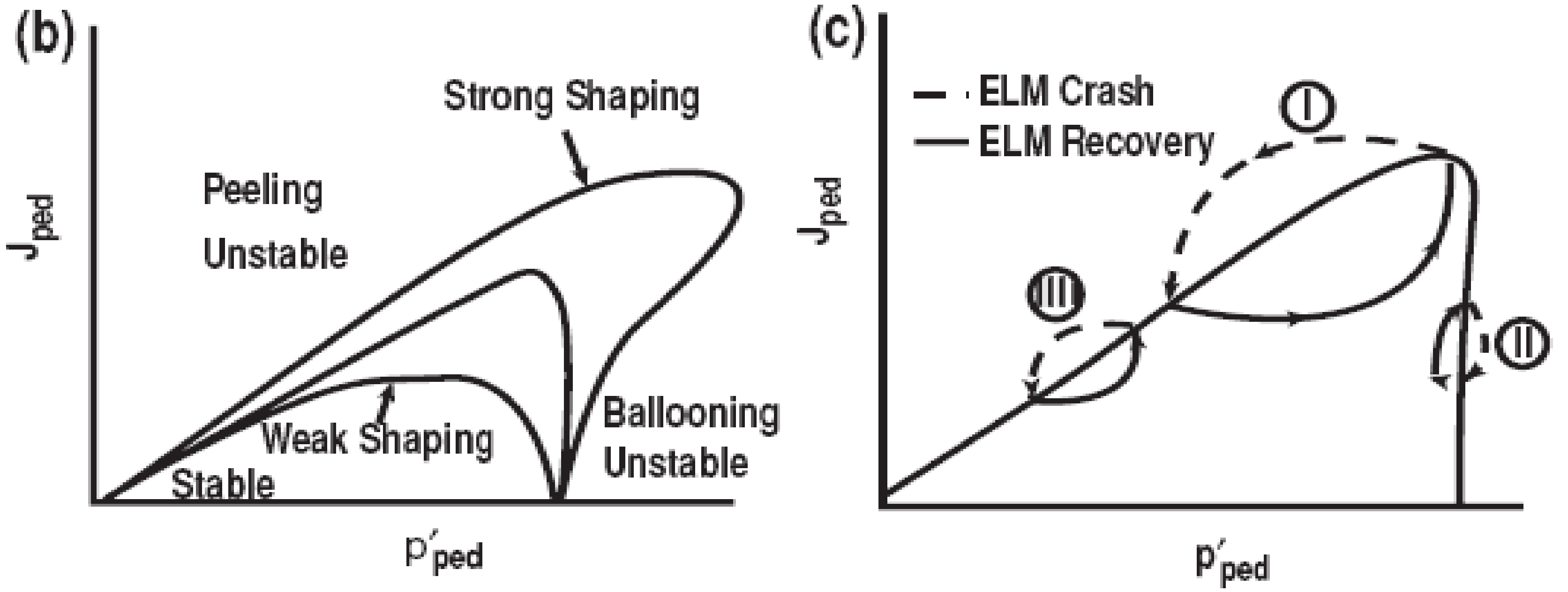
P.B. Snyder *et al*, Nucl. Fusion (2004)

Theory of ELMs (II)



P.B. Snyder *et al,* Nucl. Fusion **44** (2004) 320

Theory of ELMs (III)



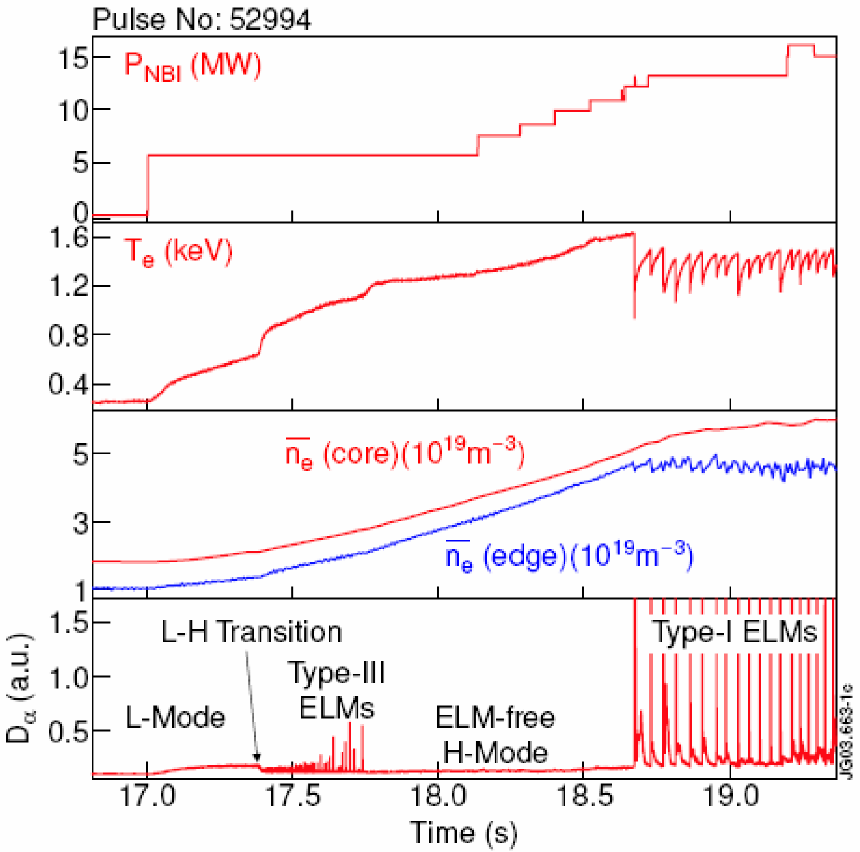
(*b*) A schematic showing the variation of pedestal stability boundaries with discharge shaping.

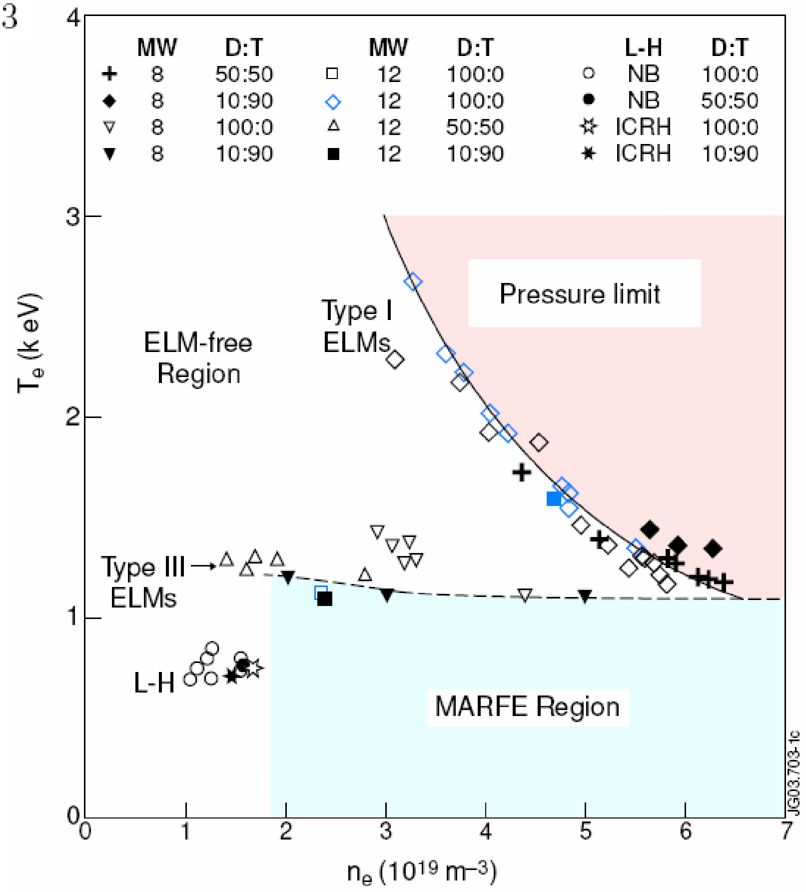
(*c*) Model of three types of ELM cycle.

P.B. Snyder *et al,* Nucl. Fusion **44** (2004) 320

Type-I and III ELM H-mode plasmas in JET

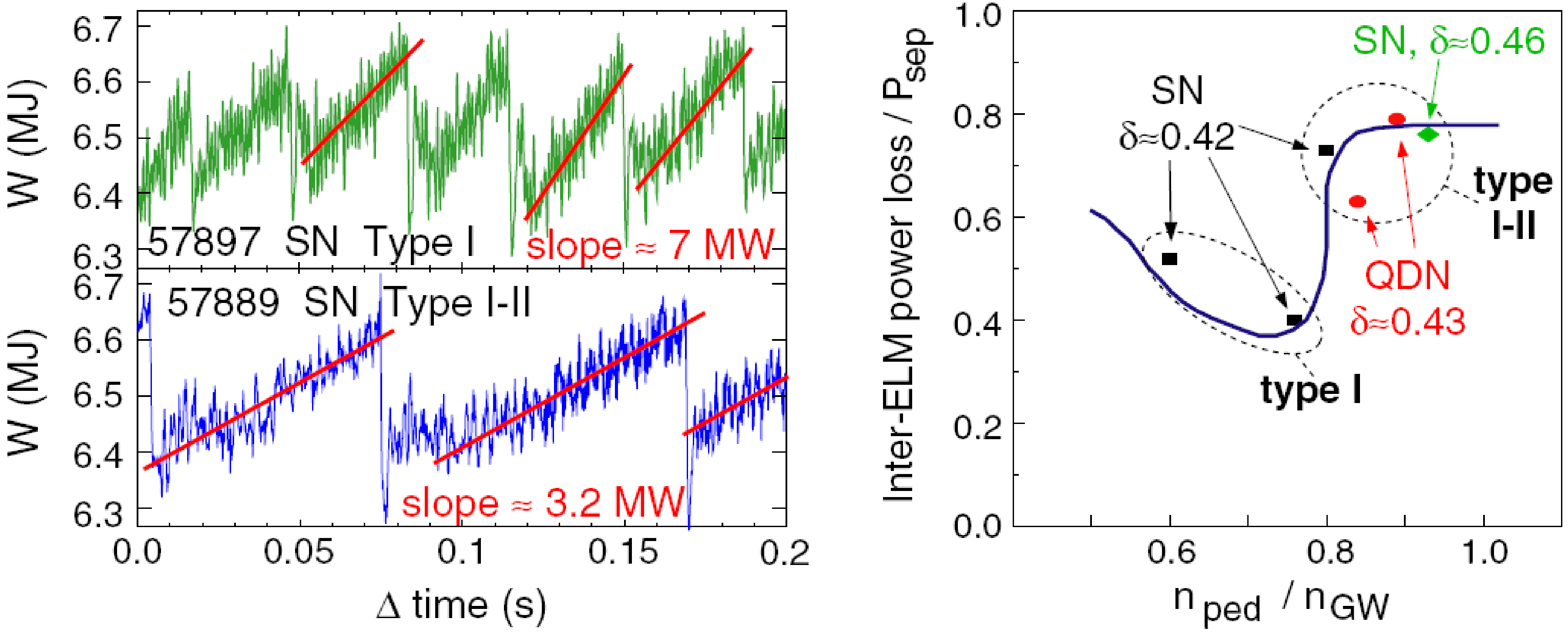
Bhatnagar V P *et al* 1999 *Nucl. Fusion* **39** 353





	Type-I	Type-III
f_{ELM} (Hz), typically	~5-80	~50-500
With increasing P_{SOL}...	f_{ELM} increases	f_{ELM} decreases
n_e-T_e operational space	near edge pressure limit	slightly above L-H power threshold / at high n_e
$\Delta W_{\mathrm{ELM}}/W_{\mathrm{ped}}$	~2-20 %	(< 5 %)

Mixed Type-I and II ELM H-mode plasmas



J. Stober, et al., Nuclear Fusion, 45,1213 (2005)

Mixed Type I and II ELM H-mode has been observed in high δ and high density plasmas in JET

Pedestal Physics and ELM Behavious

Standard ELM-free H-mode plasmas

No ELMs, low edge transport → good energy and particle confinement but also an impurity exhaust problem (not stationary)

Type-III ELMs plasmas

Relaxation oscillations with a high repetition frequency, sufficient particle exhaust and tolerable transient heat loads (rather high overall energy transport, leading to a degradation of the energy confinement of the plasma)

Type-II ELMs plasmas

Relaxation oscillations with a high repetition frequency, sufficient particle exhaust and tolerable transient heat loads. In contrast to type-III ELMs, they also provide good energy confinement. (a narrow operational window, and it is still unclear whether type-II ELMs will be possible to achieve in a burning fusion plasma)

Type-I ELMs H-mode plasmas

More or less strong relaxation oscillations with a low repetition frequency and have sufficiently low edge transport → good compromise between high confinement and sufficient particle exhaust (unacceptably high transient heat loads expected in the divertor of a burning fusion plasma)

Tungsten Erosion

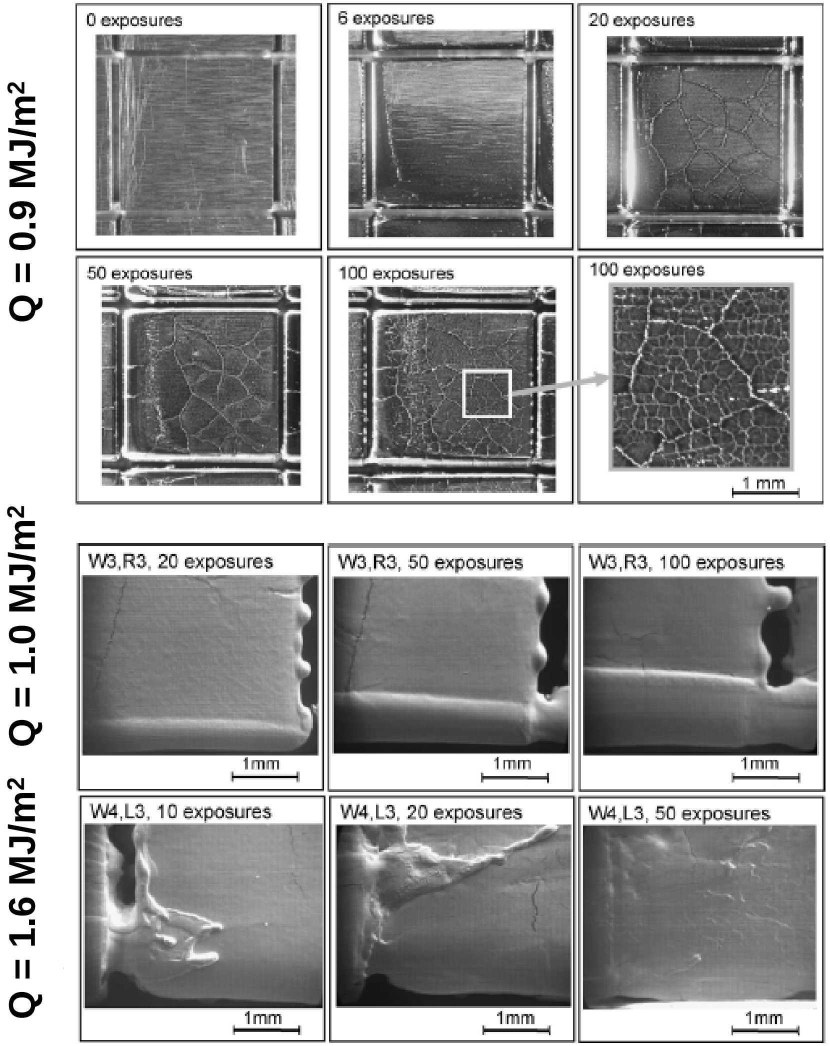
Zhitlukhin JNM 2007

ELM Simulations on QSPA
(0.1-0.6 ms, 30° to surface)

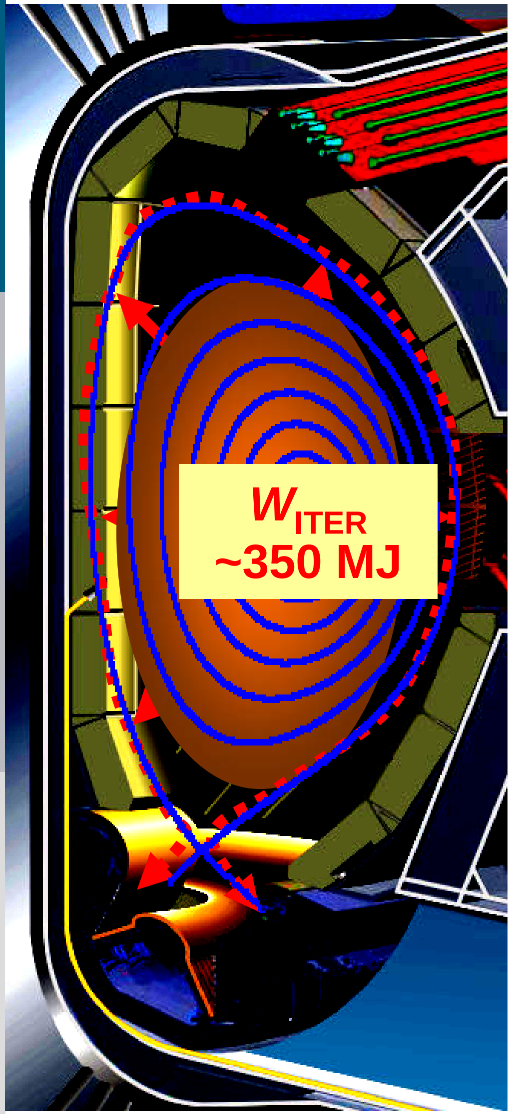
<0.4 MJ/m^2
Negligible erosion

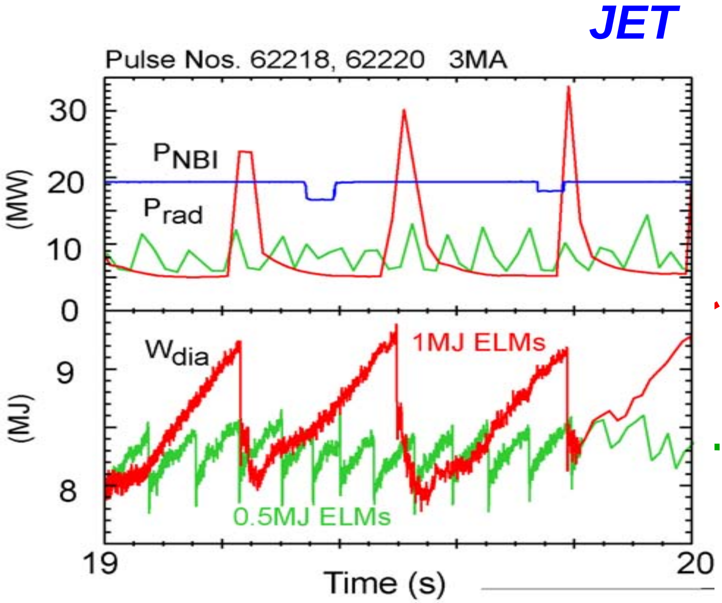
0.4-1.0 MJ/m^2 (JET<1.0MJ/m^2)
Edge melting and surface cracking

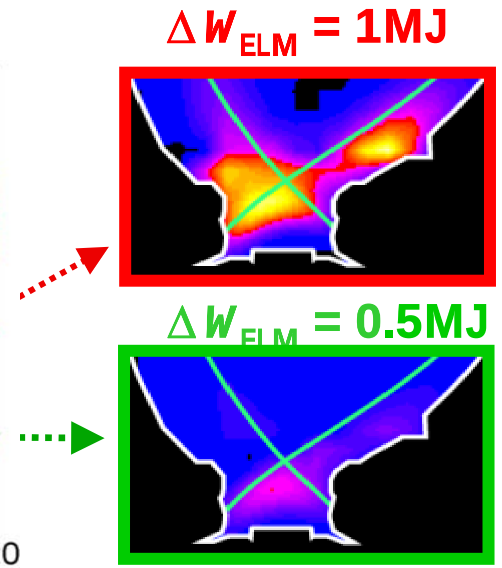
1.0-1.6 MJ/m^2
Surface melting, bridge formation and droplet ejection



Why is ELM control urgent for ITER?







Using best estimates for divertor wetted area and in-out asymmetry, one finds

$$\Delta W_{ELM} = Q_{ELM} \times S_{in} \times (1 + P_{out}/P_{in}) = \mathbf{0.5\ MJ/m^2} \times 1.3\ m^2 \times 1.5 \sim 1\ MJ$$

This requires a decrease in the ‘natural’ ELM size by **a factor of ~ 20**

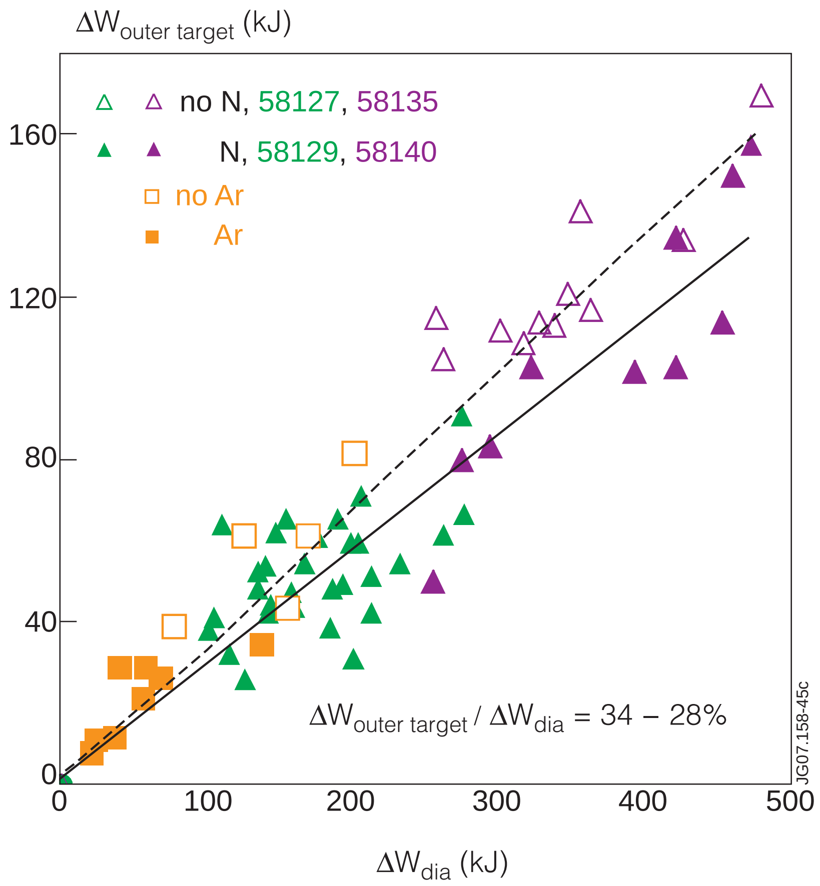
ELM mitigation is required for a steady state operation of ITER!

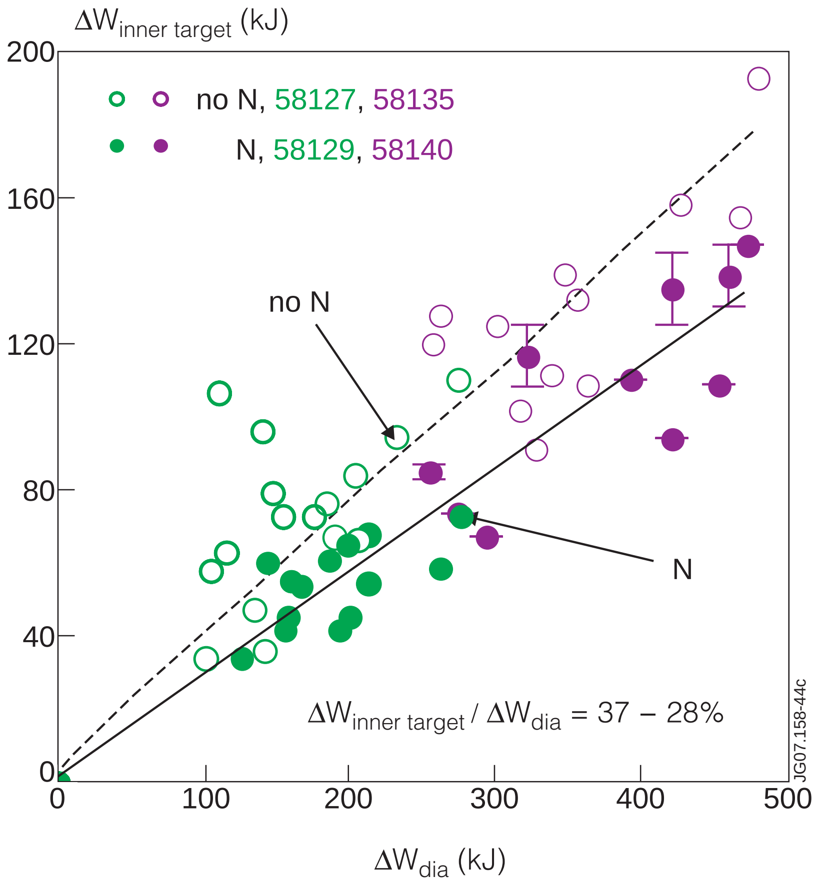
Methods Applied for Type-I ELM Control

Active control of Type-I ELM with acceptable confinement degradation

- Radiating divertors (Impurity gas puffing)
- Magnetic triggering (“vertical kicks”)
- Pellets pacing making
- Edge ergodization / external edge resonant magnetic perturbation (RMP) fields

Mitigation of type-I ELMs with gas puffing

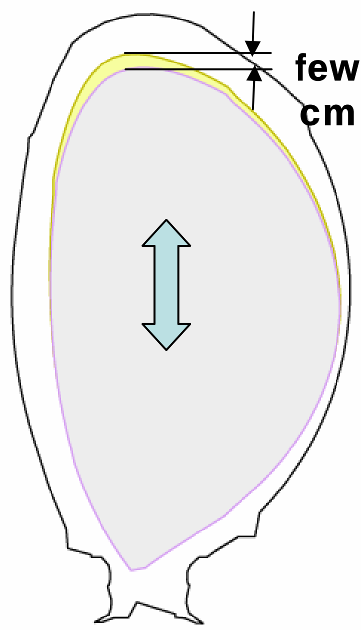




P. MONIER-GARBET et al., *Nucl. Fusion*, **45**, 1404 (2005)

Radiative dissipation of ELM energy is less than 20% (outer target) and less than 25% (inner target)

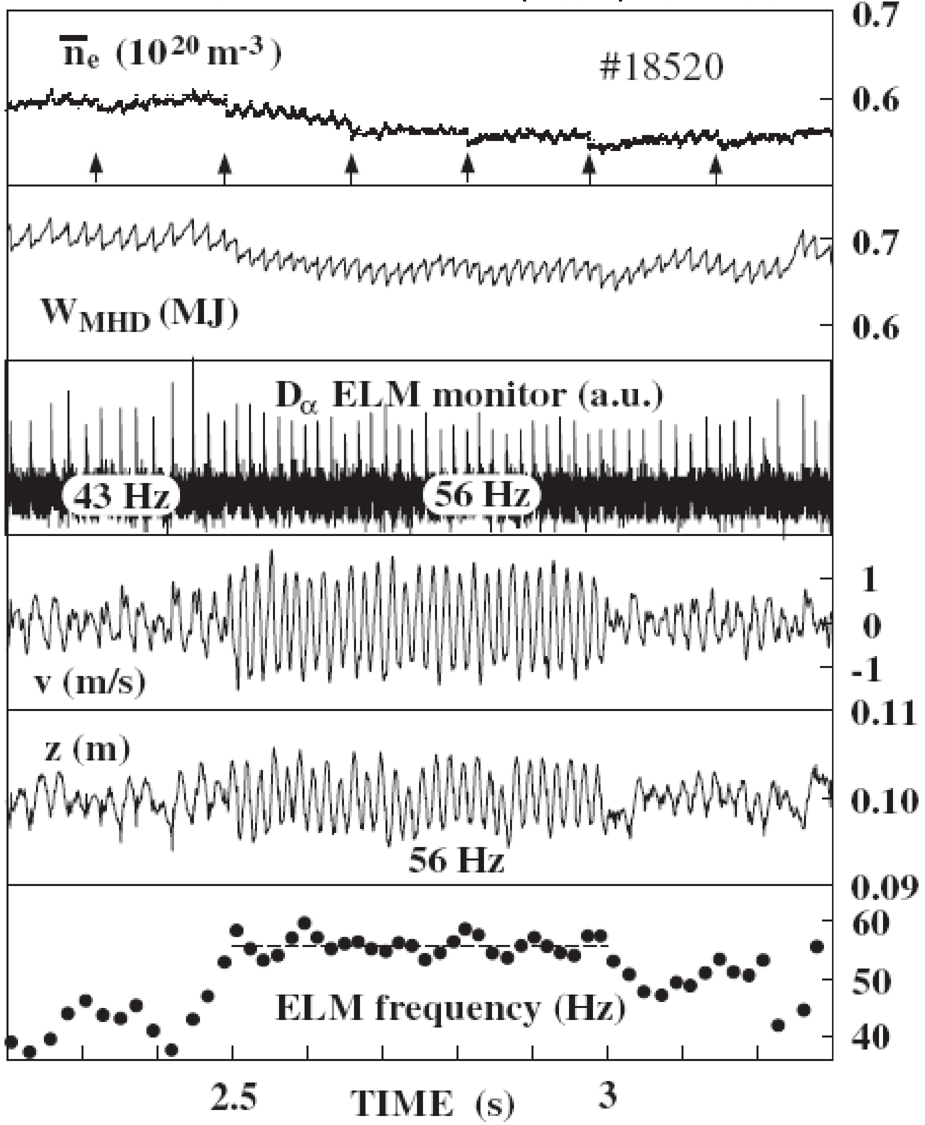
ELM pacing with vertical kicks



The plasma moves up or down and shrink

ASDEX-U

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



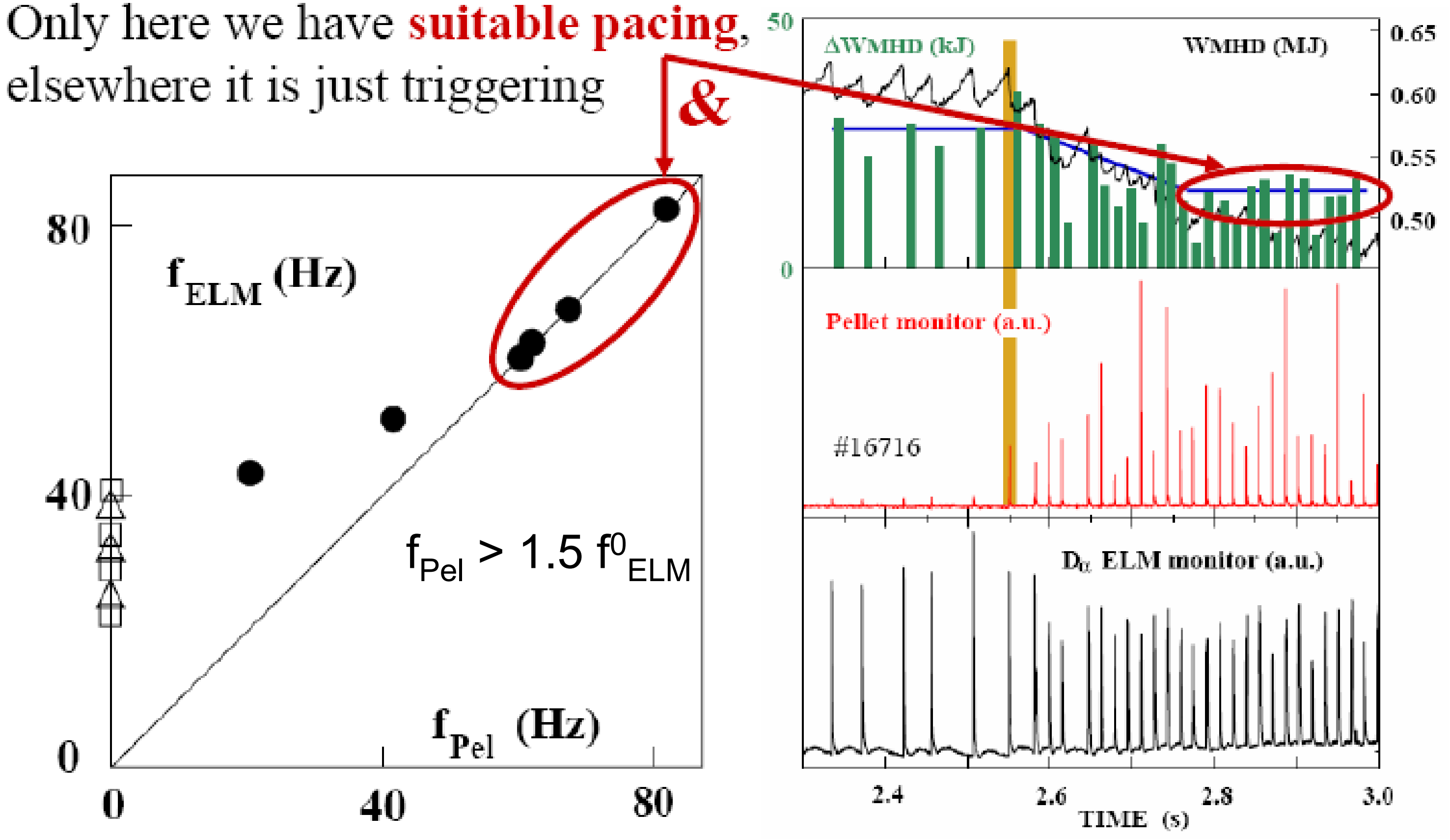
- ✓ Successful locking of the ELM frequency to an imposed vertical plasma oscillation, has also been demonstrated in the ITER-relevant type-I ELM regime in ASDEX Upgrade.
- ✓ Physics of triggering not clear: in TCV ELMs are triggered by moving the plasma UP, in AUG and JET, DOWN

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?
  - Can ELM pacing be demonstrated at N_GW ~ 0.75?

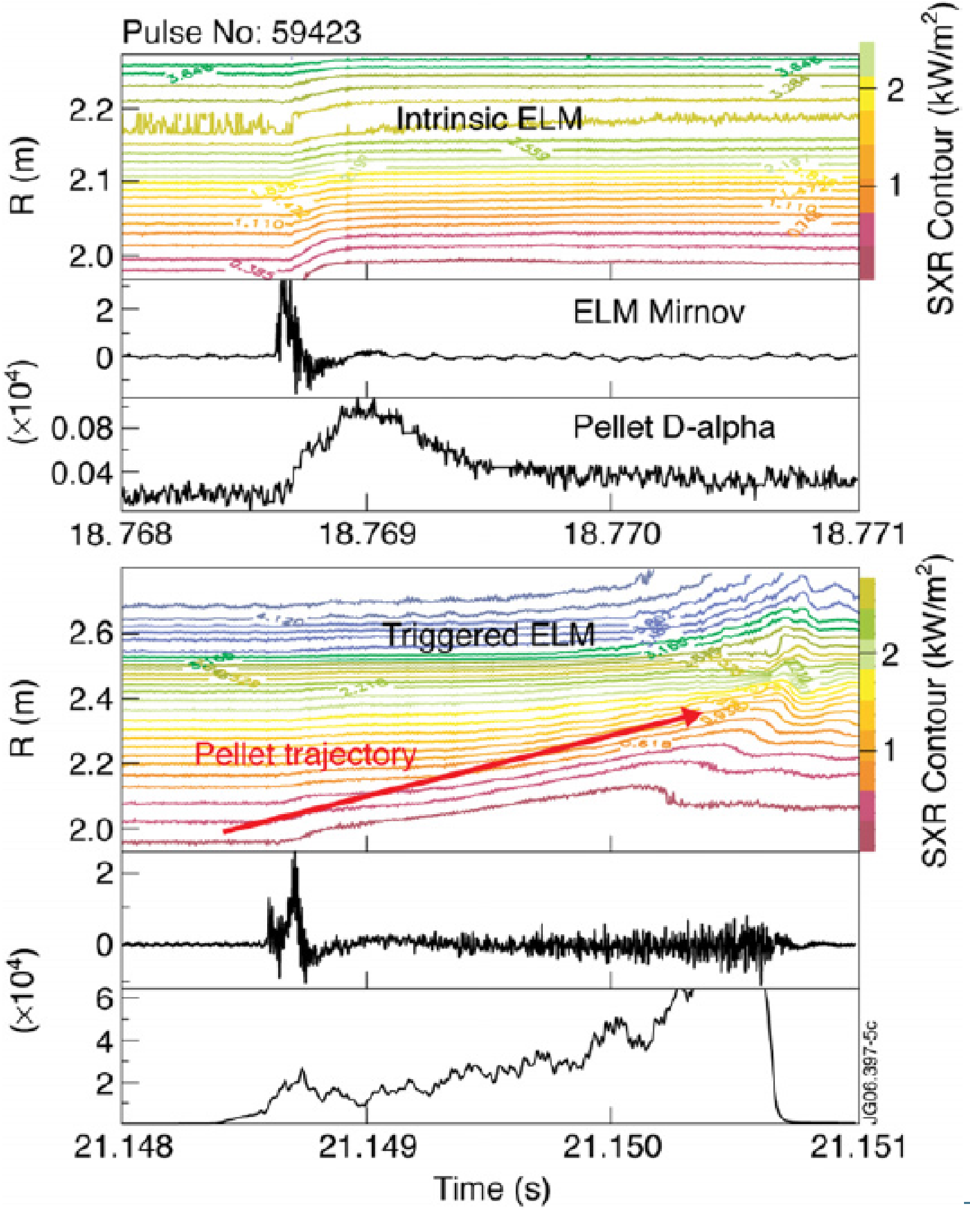
Only here we have **suitable pacing**, elsewhere it is just triggering &



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

ASDEX Upgrade

ELM triggering by local pellet perturbations in type-I ELMy H-mode plasma at JET

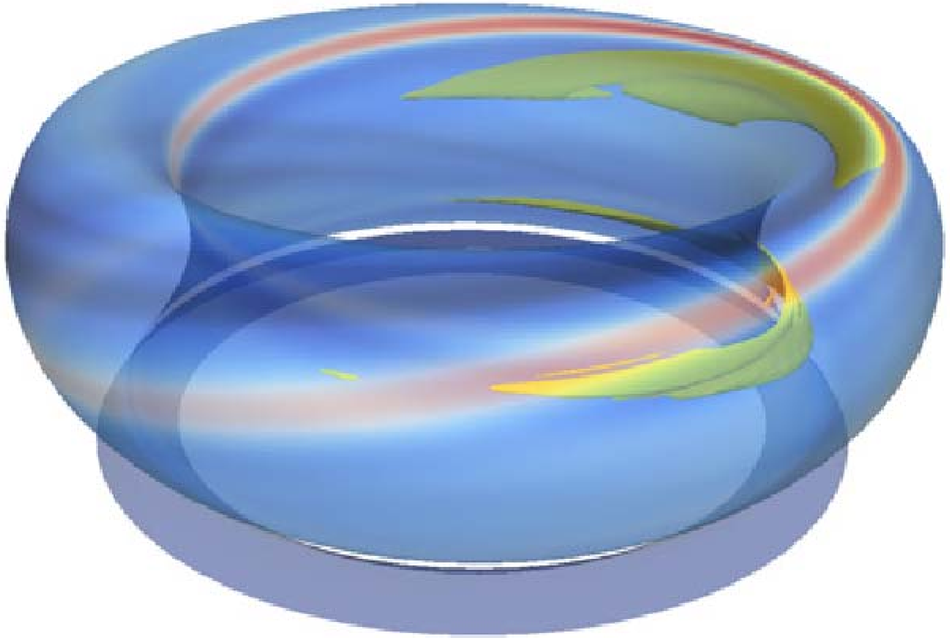


- ✓Pellet injection into JET type-I or ELM-free phases was found to trigger an ELM at any time.
- ✓Pellets with a particle content of only about 4×10^{19} D could be sufficient for ELM pacing in JET but eventually require a reduced radial velocity to compensate for the reduction in the ablation rate with the pellet size.
- ✓Hence, the resulting particle flux can possibly be suppressed to negligible amounts eliminating fuelling constraints which hamper current investigations.

P. LANG et al., *Nucl. Fusion*, **47**, 754 (2007)

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

JOREK



G T A Huysmans, PPCF 51 (2009)

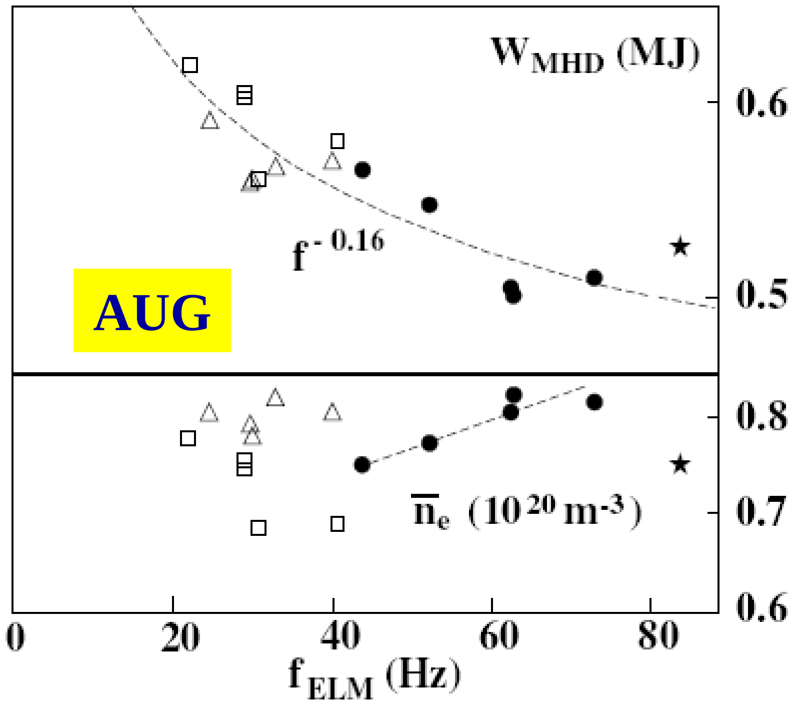
- A strong pressure develops in the high density plasmoid, in this case the maximum pressure is ~5 times the pressure on axis.
- There is a strong initial growth of the low-*n* modes followed by a growth phase of the higher-*n* modes ballooning like modes.
- The coupled toroidal harmonics lead to one 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.

Fuelling burden

When doing pacing, due to the macroscopic pellet size this causes some fuelling,
→ Additional convective losses reducing confinement

Pacing experiments



P. Lang, 16th ITPA PEP meeting 2009

RMP Physics

Field penetration process

Mode excitation

Ergodisation

Rotation screening effect

3D equilibrium

NTV torque

Applications

Mapping Intrinsic field errors

RWM control

NTM control

Locked mode control

ELM control

Runaway electron control

Influence of RMP on sawtooth

Active ELM control with magnetic perturbation fields in tokamaks

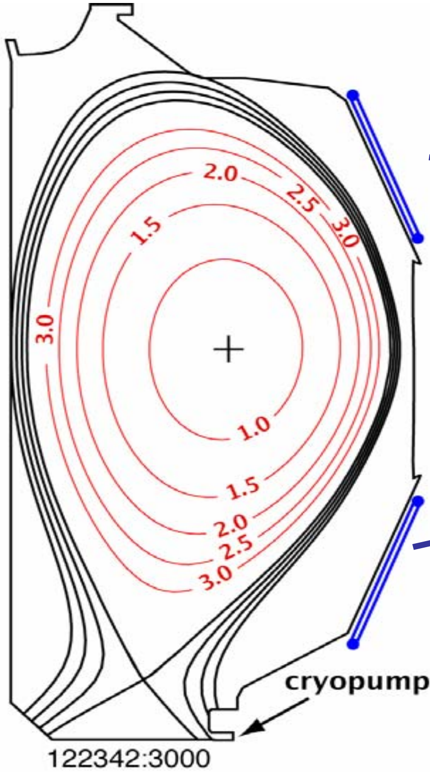
Internal Coils

JFT-2M (n>4) →	Triggering of small ELMs in ELM-free H-mode plasmas	*M Mori et al, 14th IAEA Vol.2 576 (1992).*
COMPASS-D (n=1; m=4-5) →	Increasing the frequency of Type-III ELMs	*S J Fielding et al, ECA 25A 1825 (2001)*
DIII-D (n=3) →	Complete suppression of type-I ELMs in • collisional and • collisionless H-mode plasmas in Single null configuration	*T Evans, PRL 92 235003 (2004)* *Nature physics Vol. 2 419 (2006)*
MAST ($n = 3$) →	Increasing the frequency of Type-I ELMs; no ELM suppression	*E. Nardon et al., PPCF 2009* *A Krik et al., NF 2010*

External Coils

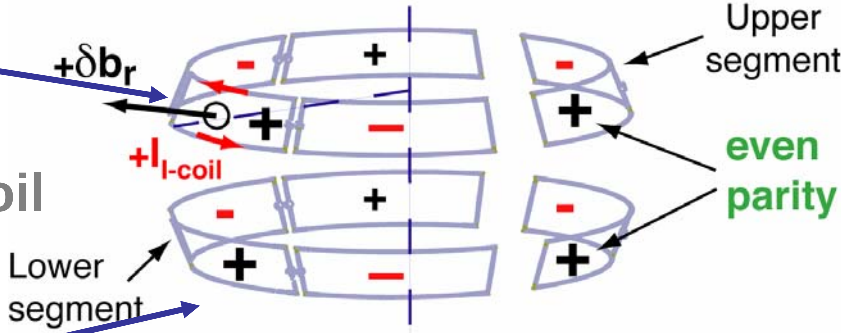
JET (n=1; n=2) →	Increasing the frequency of Type-I ELMs in a wide windows of q_{95}, High δ, High β, ITER-like υ^* H-mode plasmas	*Y Liang et al., PRL 98 265004 (2007)* *PPCF 49 B581 (2007)* *NF 50 025013 (2010)*
NSTX ($n = 3$) →	Triggering ELM in ELM free H-mode plasmas	*J.M. Canik et al., NF 2010*

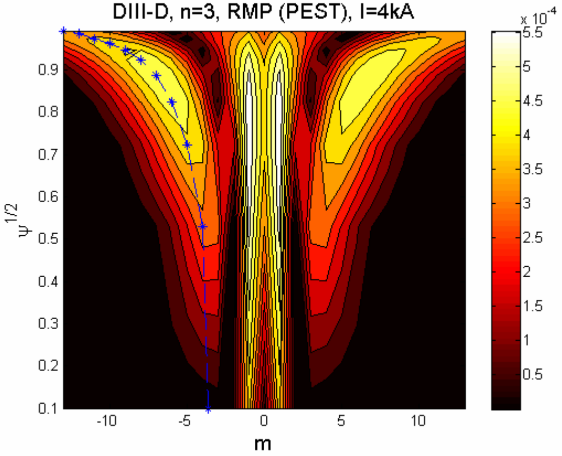
Experiments of Active Control of ELMs with a RMP on DIII-D Tokamak

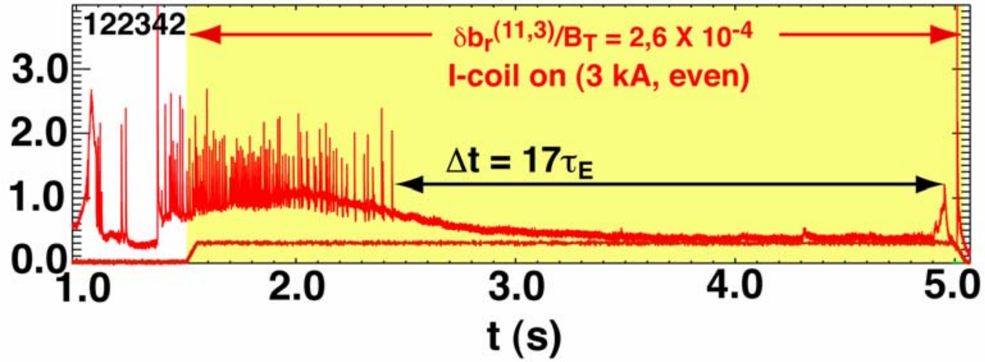


Internal coil (I-coil)

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





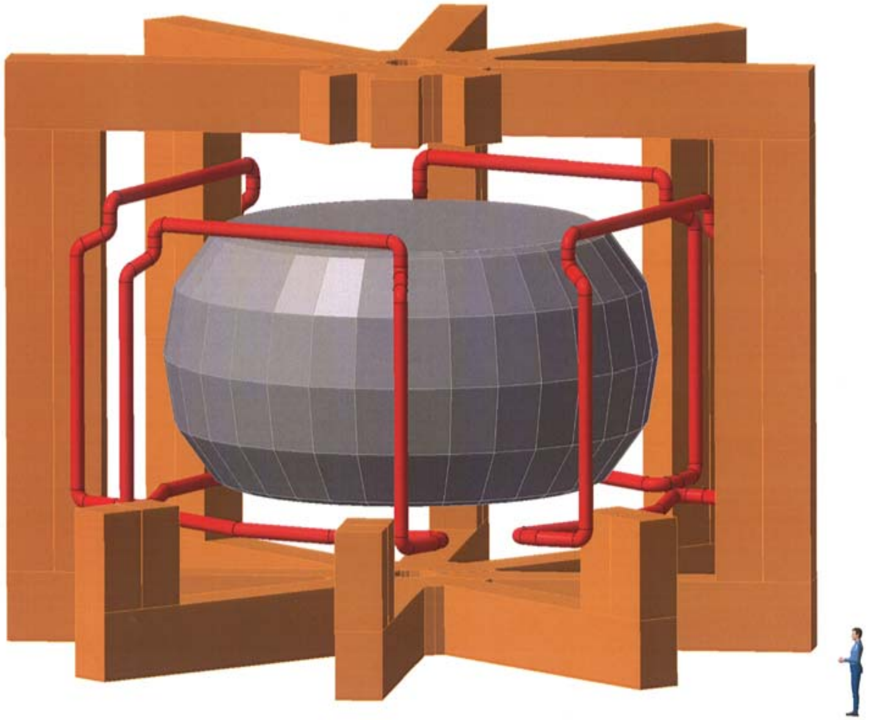


T. E. Evans,et al., PRL, 92, 235003 (2004)

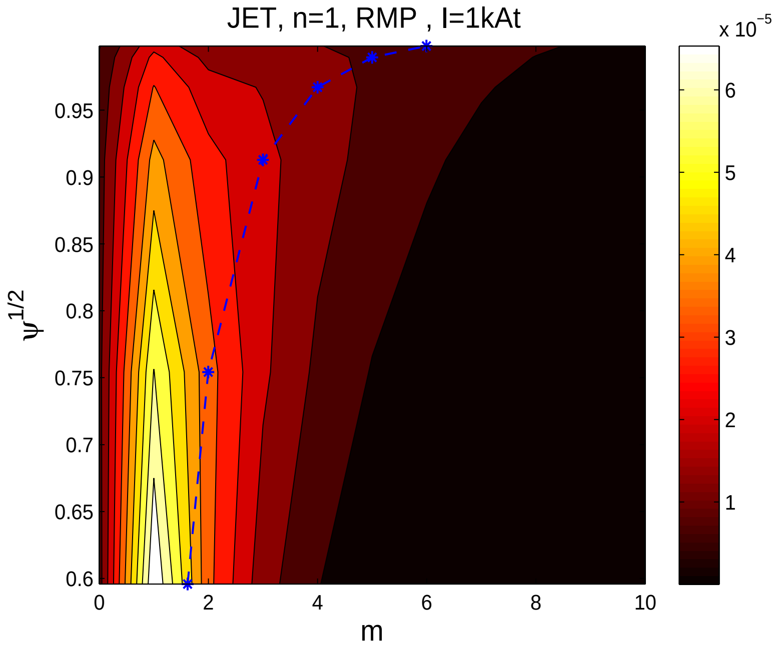
T. E. Evans,et al., Nature physics, Vol. 2, p419, June 2006

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

Error field correct coils (EFCC) on JET



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

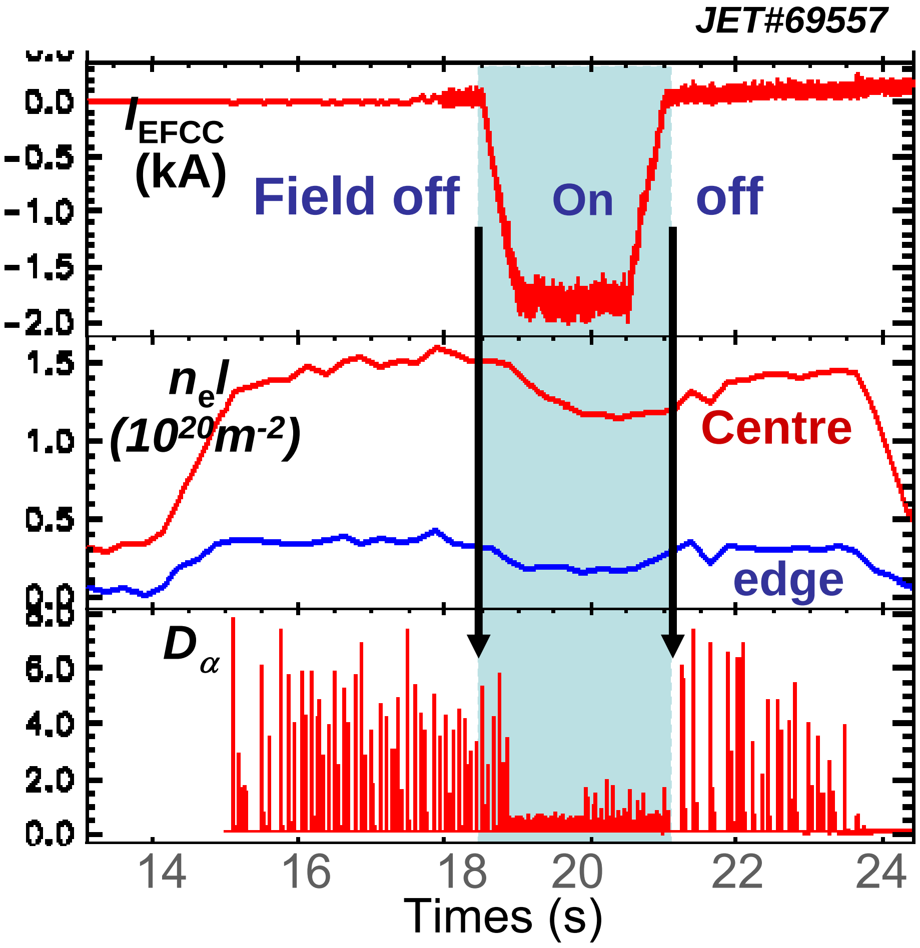


- Depending on the relative phasing of the currents in individual coils, either *n*=1 or *n*=2 fields can be generated
- $I_{\mathrm{Coil}} \leq$ 3 kA x 16 turns (*n* = 1 *and* 2)
- *R* ~ 6 m; Size ~ 6 m * 6 m
- B_r at wall ~ 0.25 mT/kAt

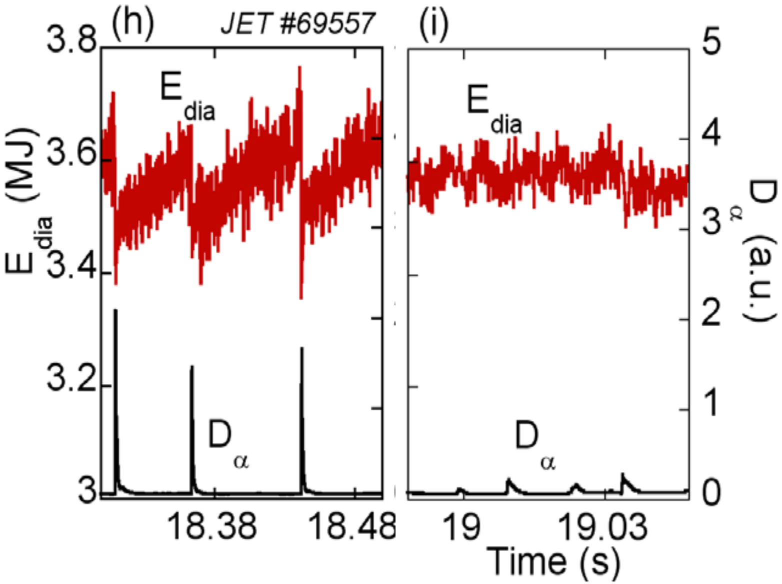
Y.Liang et al., PPCF 2007

ELM control with a low n external magnetic perturbation field

I_p = 1.5 MA; B_t = 1.78 T; q_{95} ~ 4.0; δ_U ~ 0.45



Y.Liang et al., PPCF 2007



- f_{ELM} increases by factor 4 to 5
- $\Delta W/W$ reduces from 6% to below the noise level of measurement (2%)
- The electron density in the centre and at the edge decreased (pump-out effect)
- No or moderate reduction in thermal energy confinement

Type-I ELM control/suppression with RMP

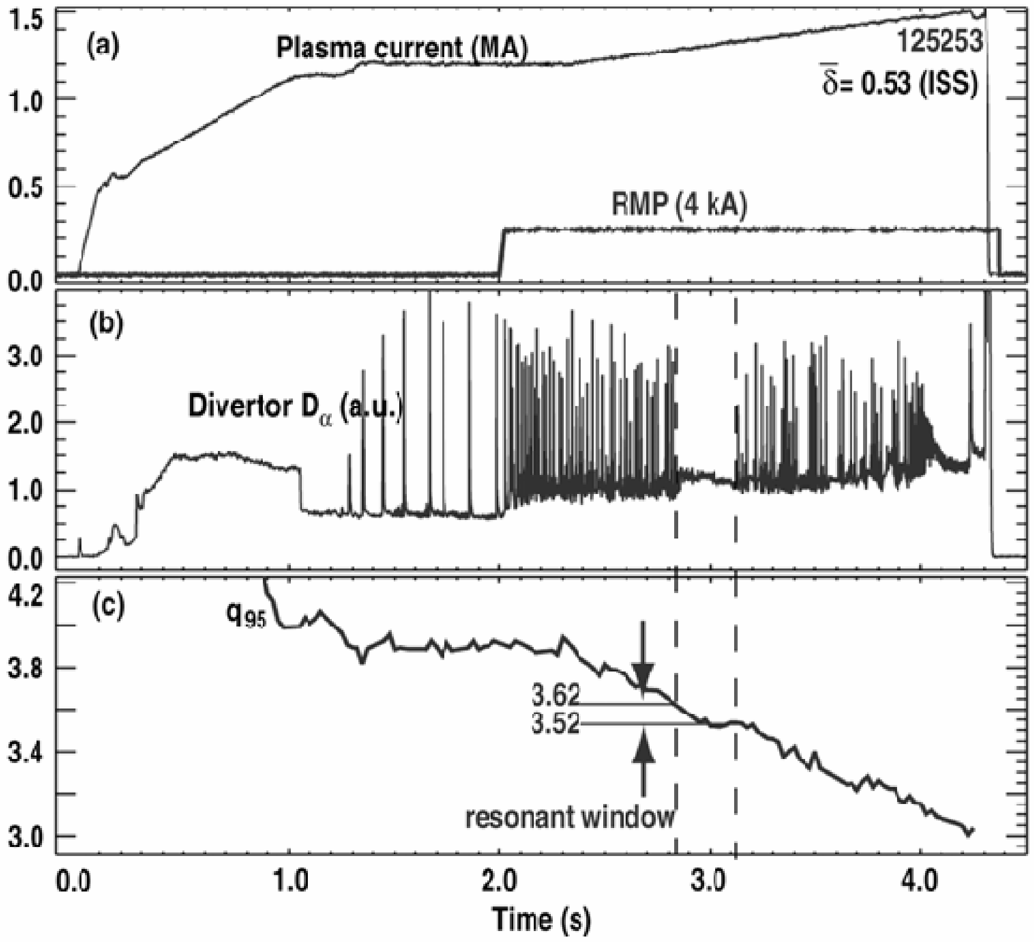
Application

- ELM
  f_{ELM}; ΔW_{ELM}; Q_p
- Confinement
  T_e; n_e; p_e; ∇p_e W_p; H_{98}
- Operation window
  Locked mode; q_{95}
- Rotation braking
- Density Pump-out effect
- Application for ITER
  ITER-like scenarios:
  Base line; Advanced; Hybrid

Physics mechanism

- Edge Ergodisation:
  Strike-point Splitting
  Edge Er
- Plasma responses:
  Screening
  3D-equlibrium
- ELM stability
  Peeling-Balooning
- Dynamics of
  Edge profiles
- Multi-resonance effect
- Open questions:

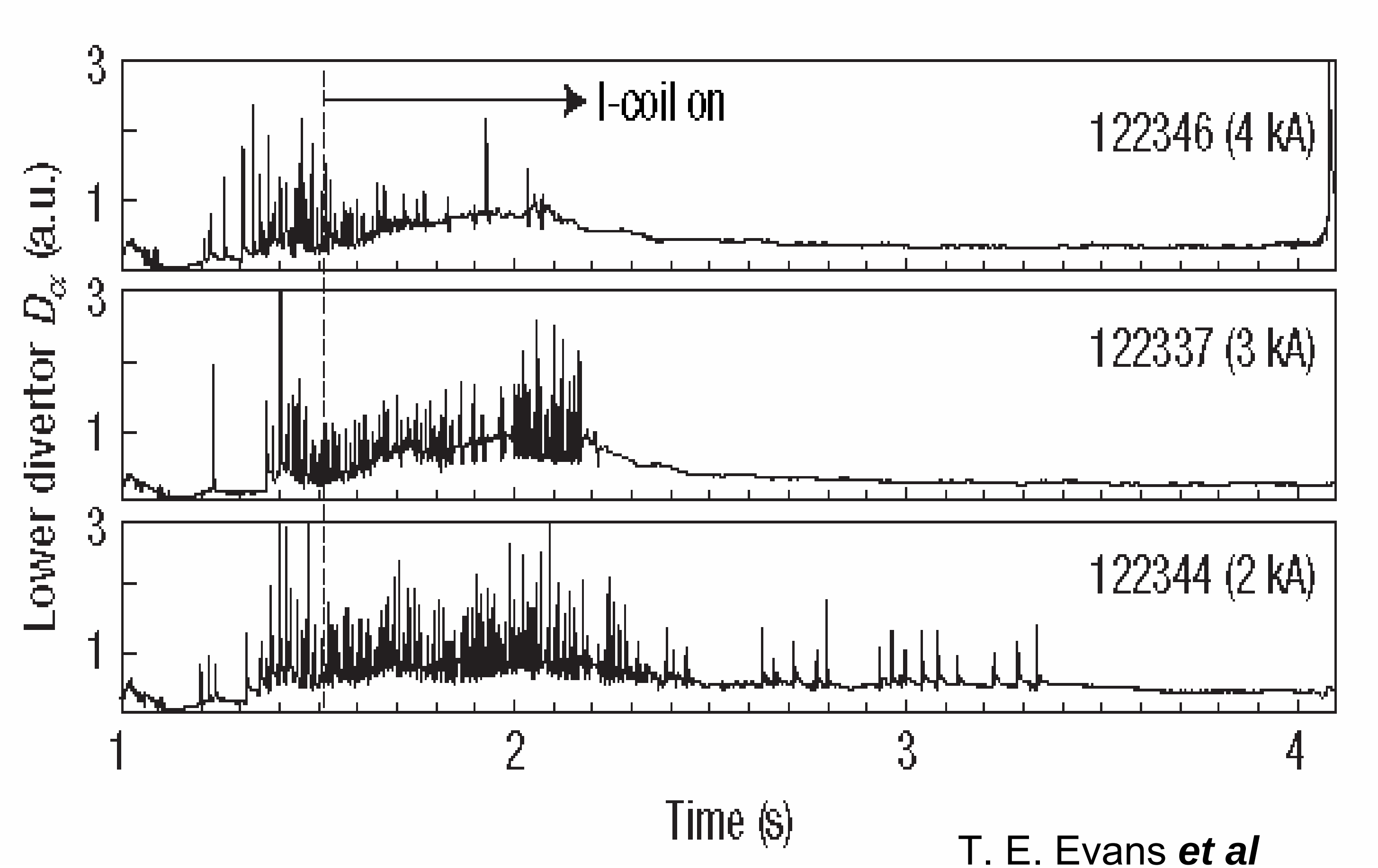
ELM suppression window on DIII-D



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

- ✓ 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.

Threshold of ELM suppression

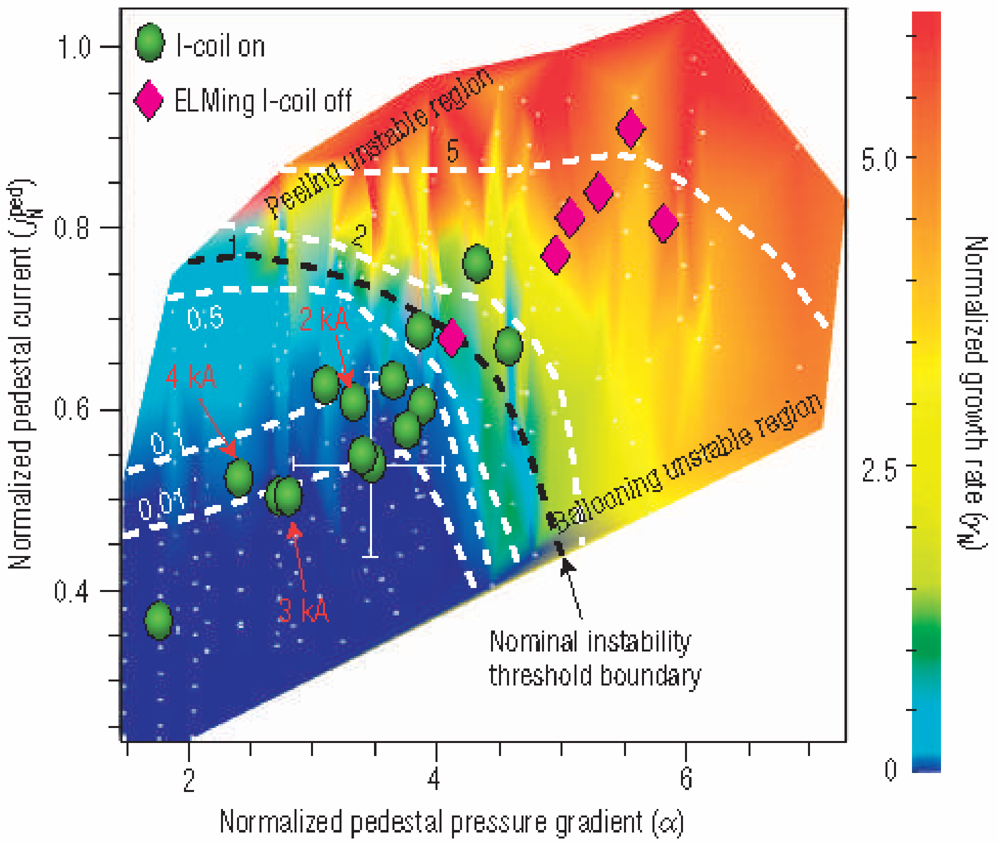


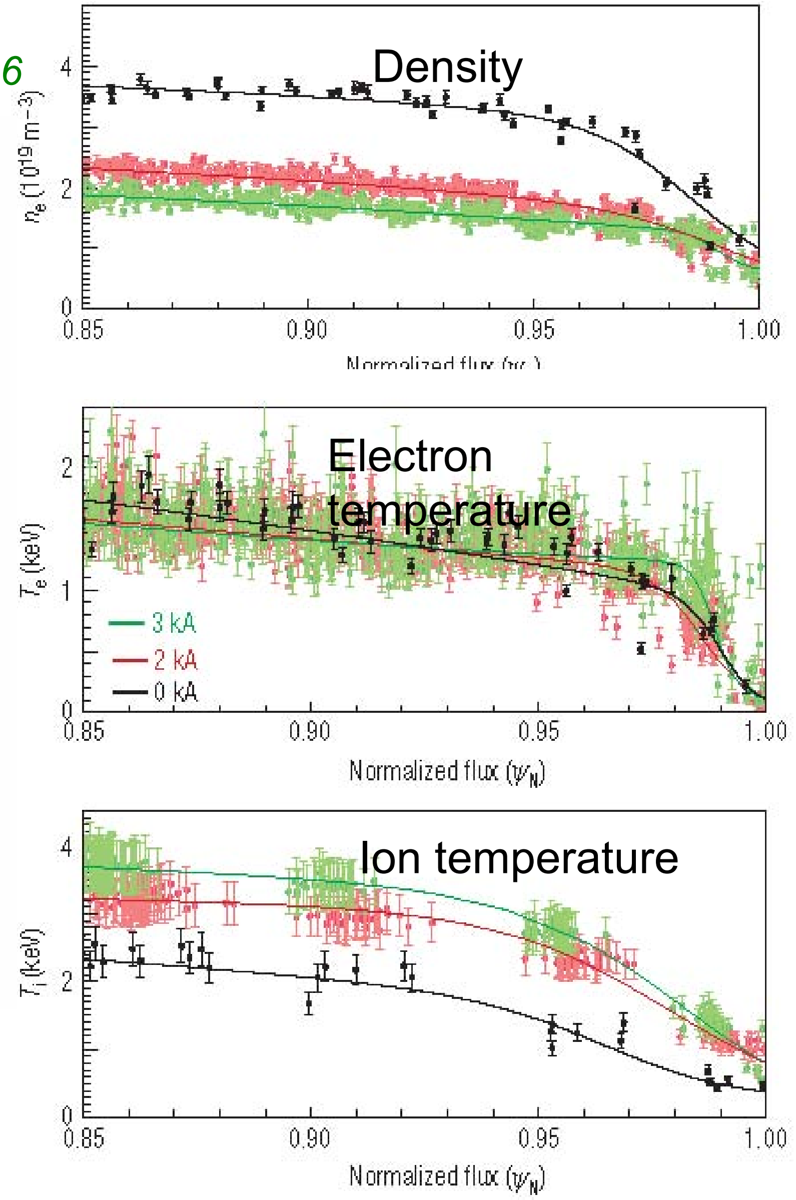
T. E. Evans ***et al***
Nature Physics 2 (2006) 419

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

Dominant mechanism of ELM suppression

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

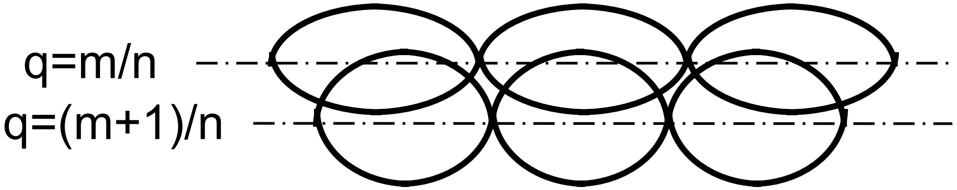


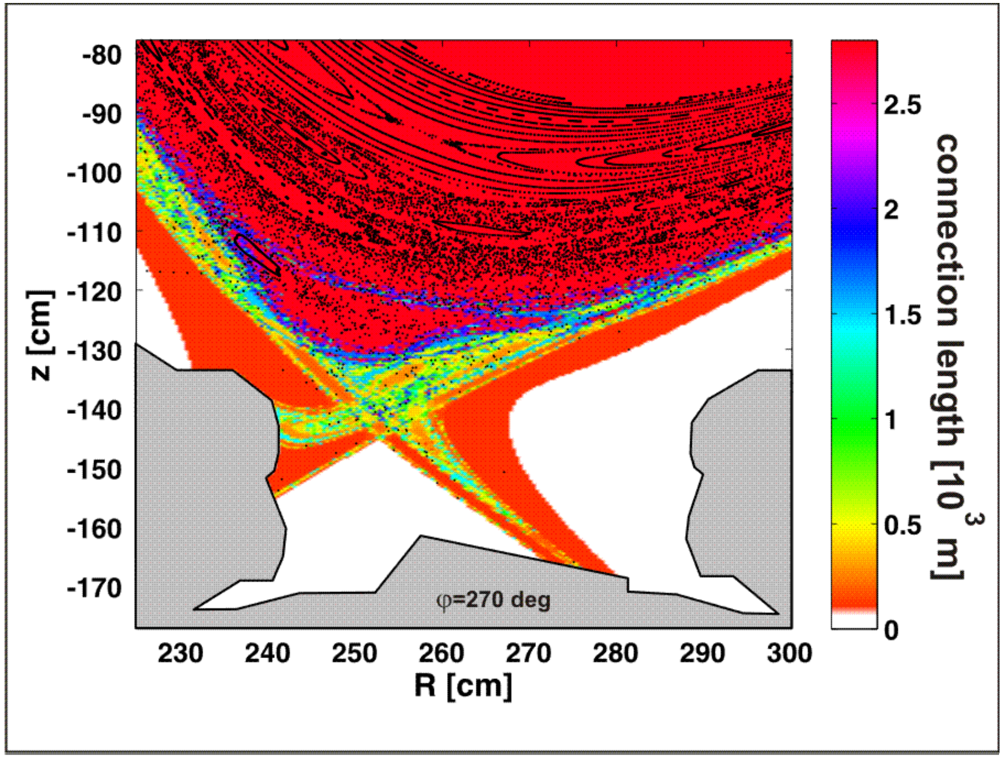


Reduction of edge pressure below instability threshold

Edge ergodisation

Equilibrium Magnetic Field at Plasma Edge





Chirikov parameter

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

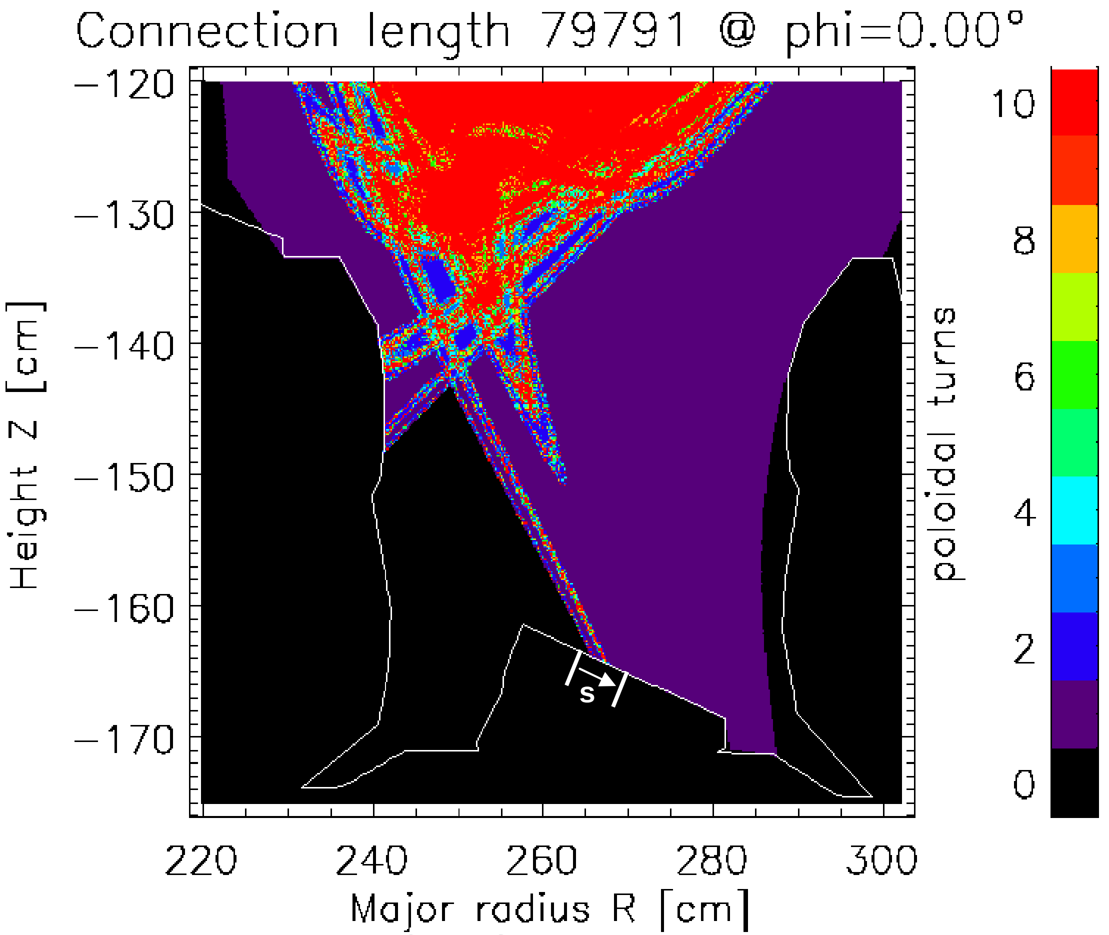
larger than 1

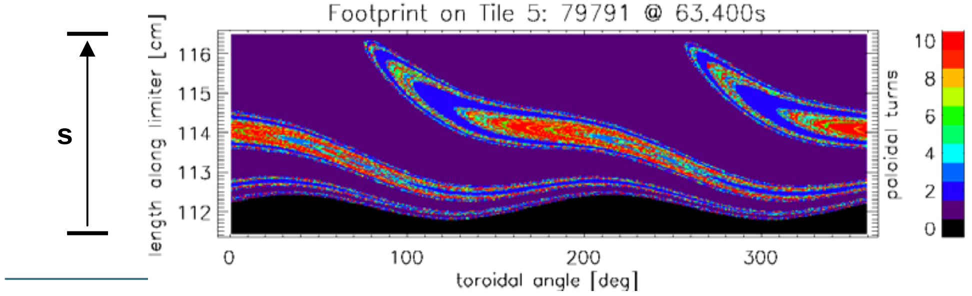
❑ Splitting of strike point

❑ Spin-up plasma rotation to co-current direction

Edge Ergodisation with a magnetic perturbation

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

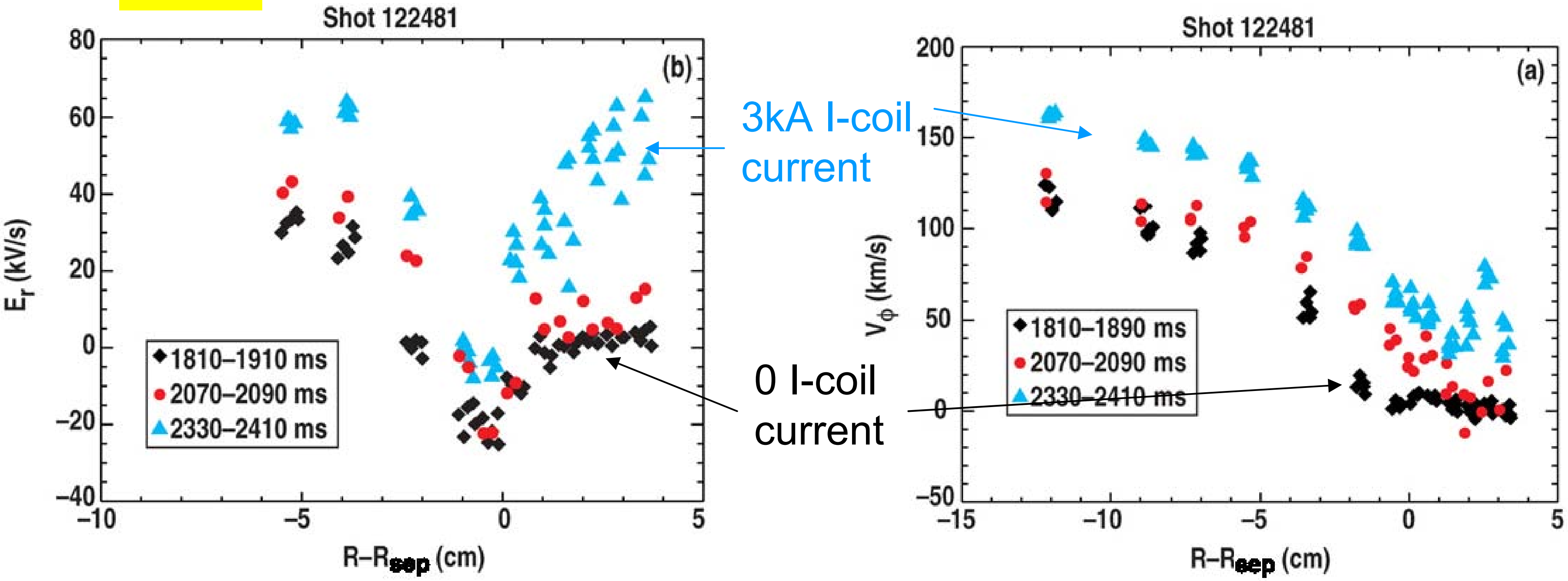
O. Schmitz, PPCF (2008)

I. Joseph JNM, 2007

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

Influence of magnetic perturbation on the Edge Electric field and rotation

DIII-D



3kA I-coil current

0 I-coil current

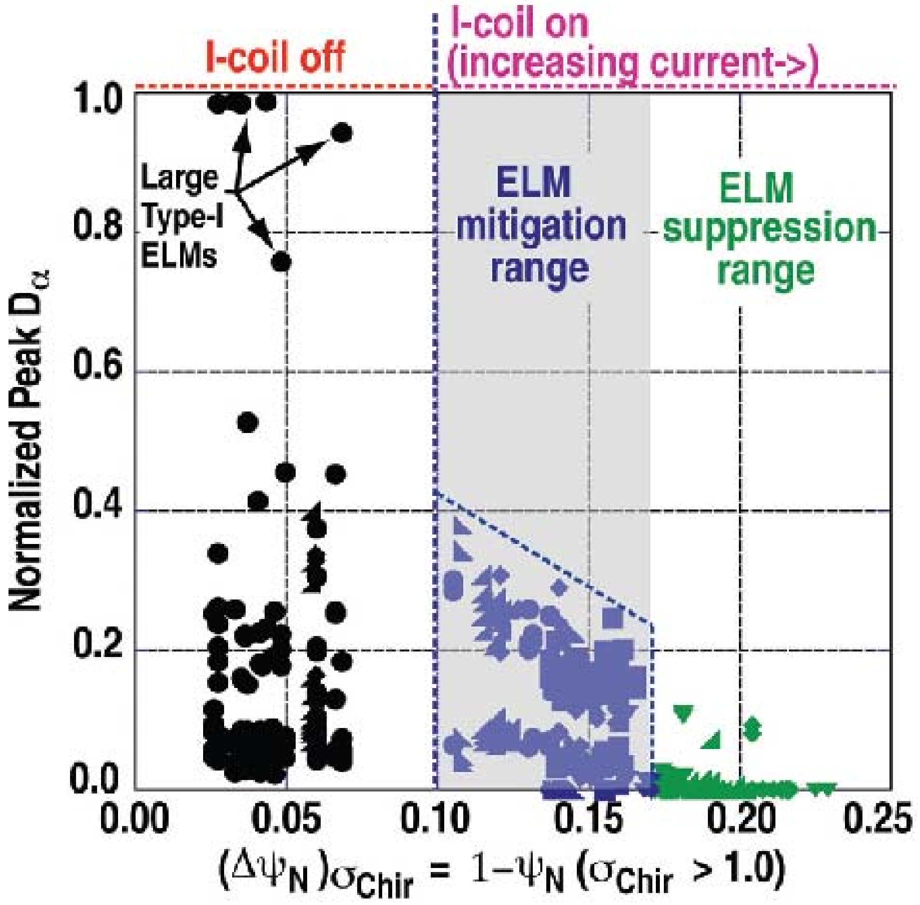
K. Burrell, PPCF 47, B37, 2005

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

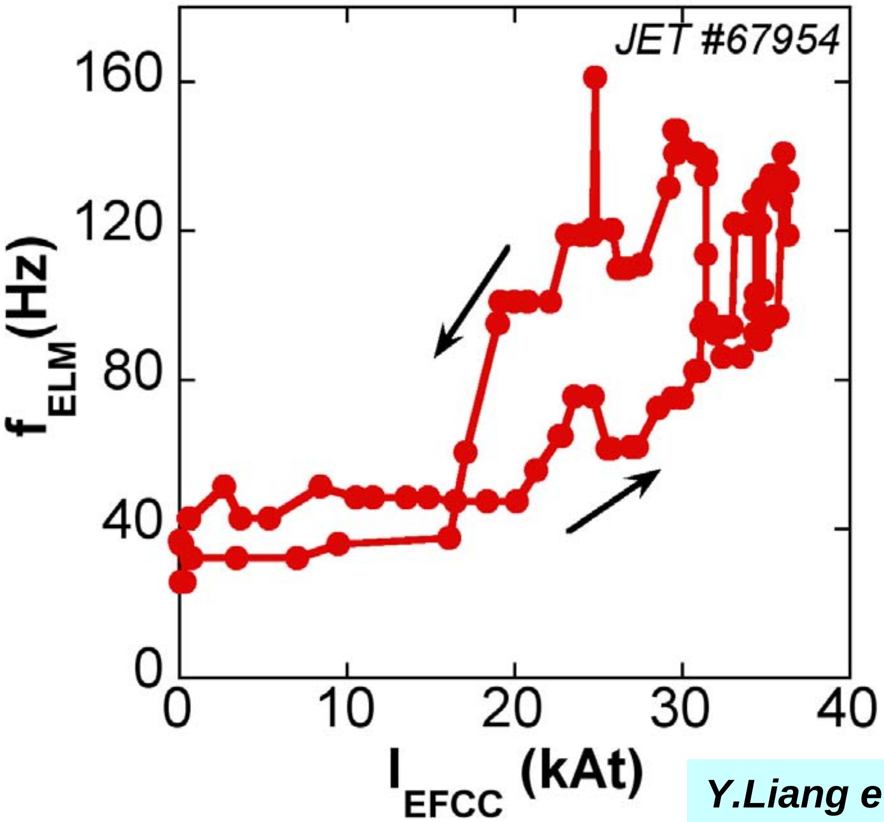


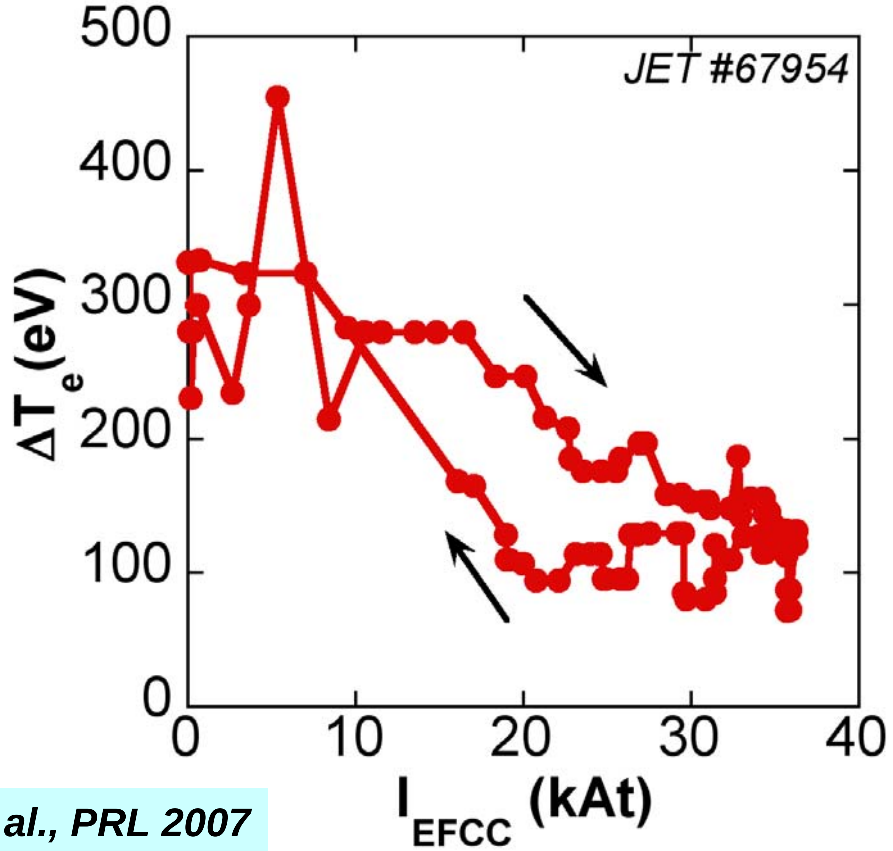
M.J. Schaffer, et al.,
IEEE (2009); NF (2008)

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

Active control of type-I ELM by n = 1 field

$I_p = 1.6$ MA; $B_t = 1.84$ T; $q_{95} \sim 4.0$;

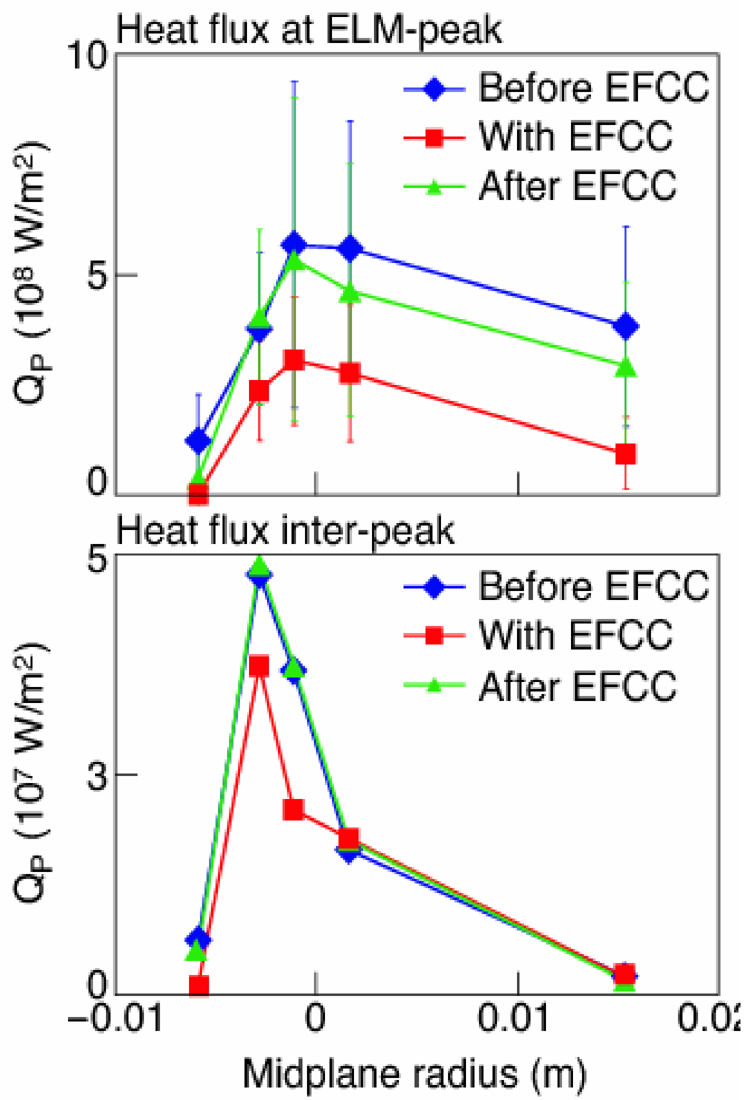




Y.Liang et al., PRL 2007

ELM frequency and temperature drop during ELM follow perturbation field amplitude (above threshold)

Heat and particle fluxes onto the divertor



JET #69555

I_p = 1.8 MA, B_t = 2.16 T,

q_{95} = 4.4, δ = 0.45;

P_{NBI} = 9.5 MW, $n_e l$ = 1.3 ($10^{20} m^{-2}$),

I_{EFCC} = 32 kAt

✓Reduction of ELM peak heat

✓No much effect on the inter-ELM heat flux

Outer Strike Line (Measured by embedded Langmuir probes)

S. Jachmich, et al., EPS 2007

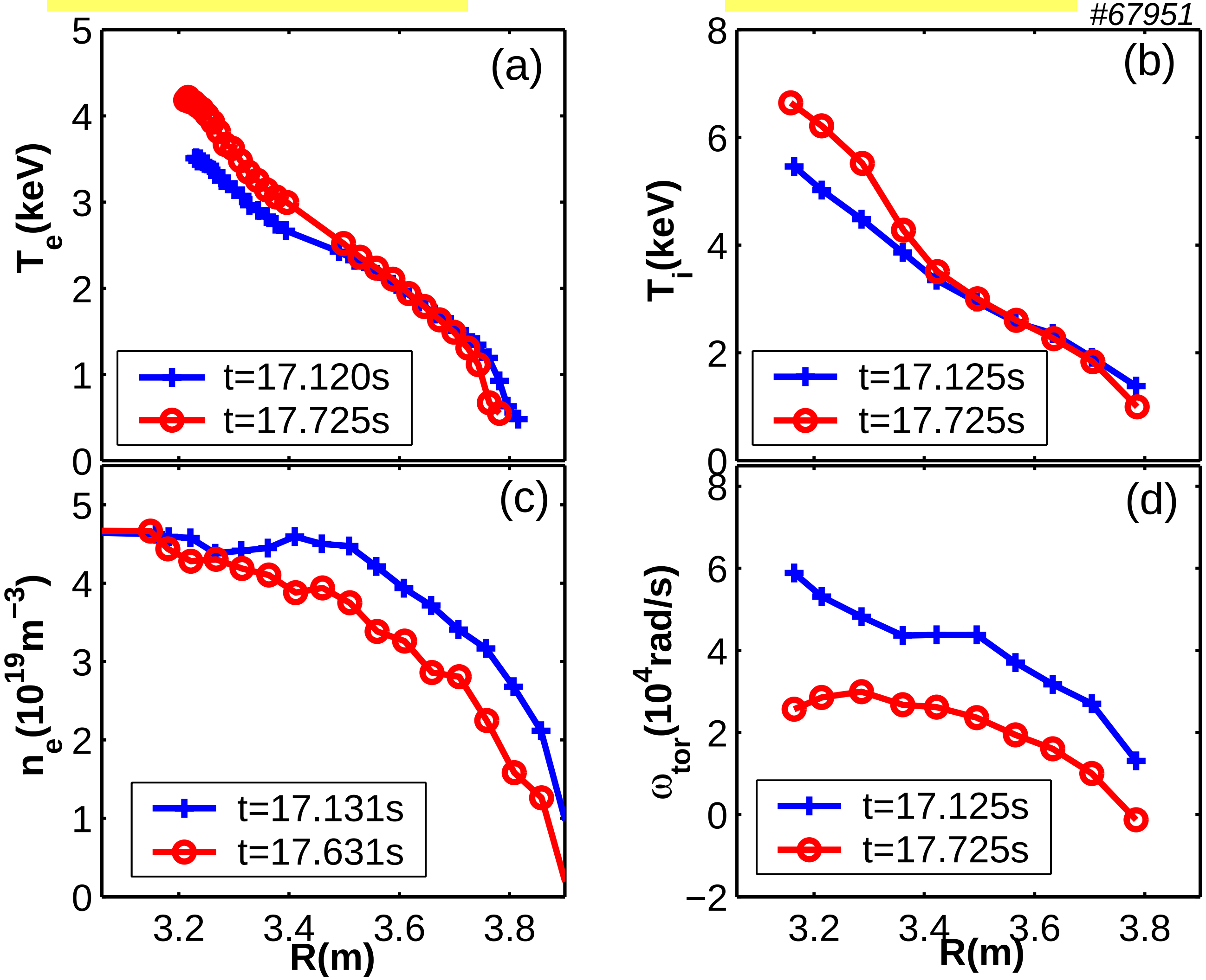
Influence of $n = 1$ field on profiles

EFCC $n = 1$; 135 degree; $I_p = 1.6$ MA; $B_t = 1.84$ T; $q_{95} \sim 4.0$; $\delta \sim 0.3$

Without $n = 1$ field

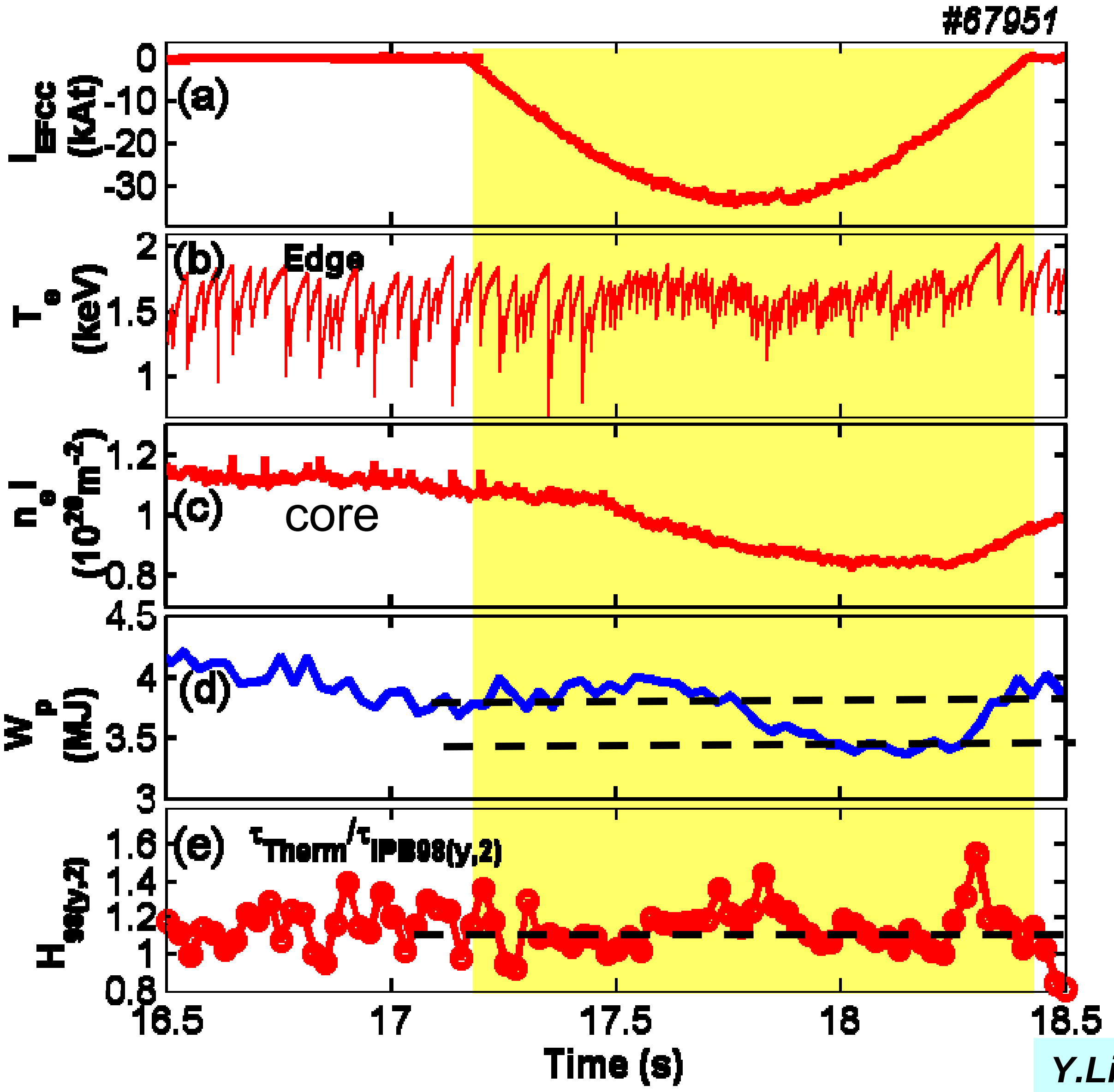
With $n = 1$ field

Y.Liang et al., PRL 2007



- ✓ Electron and ion temperatures are increased during ELM mitigation phase
- ✓ Electron density decreases in the centre and at the edge due to pump-out effect
- ✓Plasma braking observed during application of $n = 1$ field

Influence of n=1 field on confinement



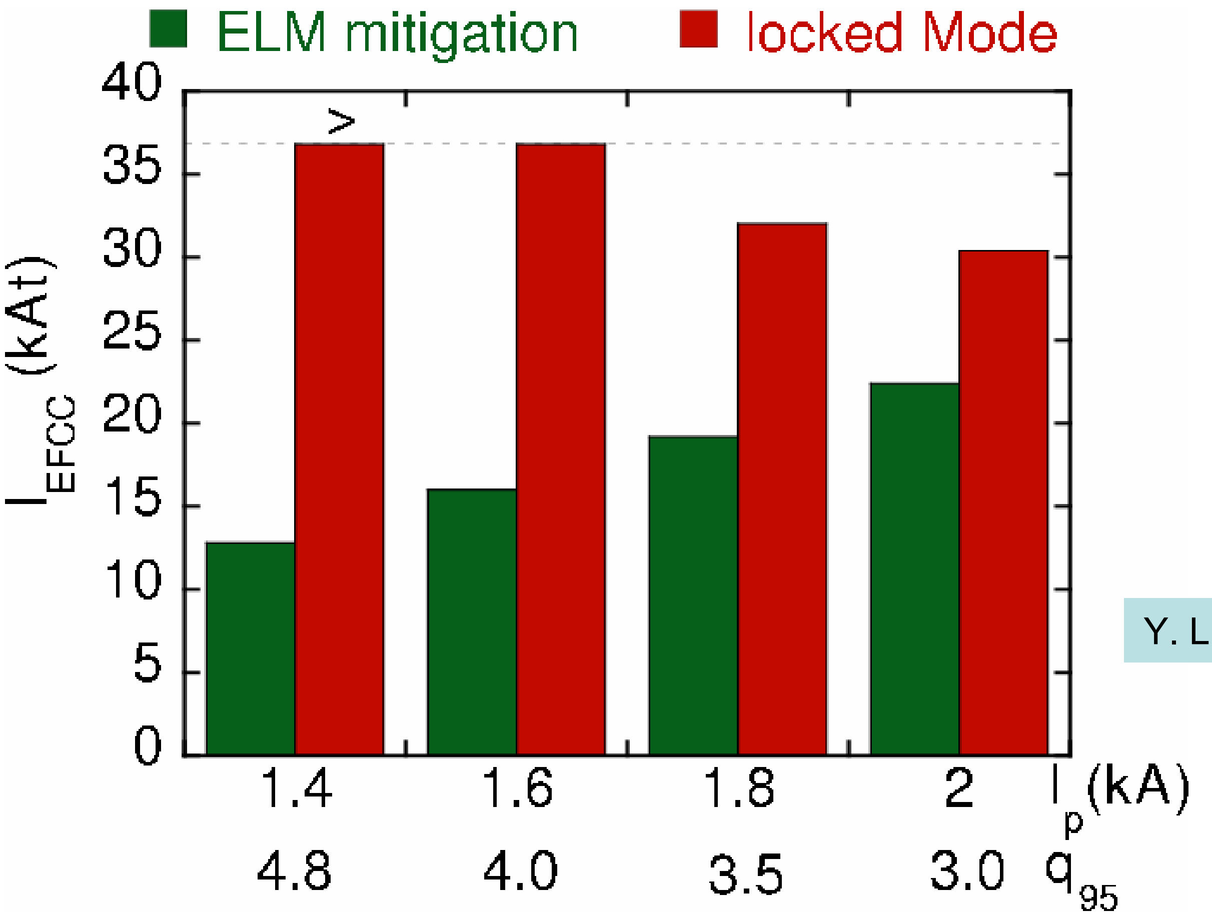
-23%

-10%

constant

Y.Liang et al., PRL 2007

Operational window of ELM control on JET

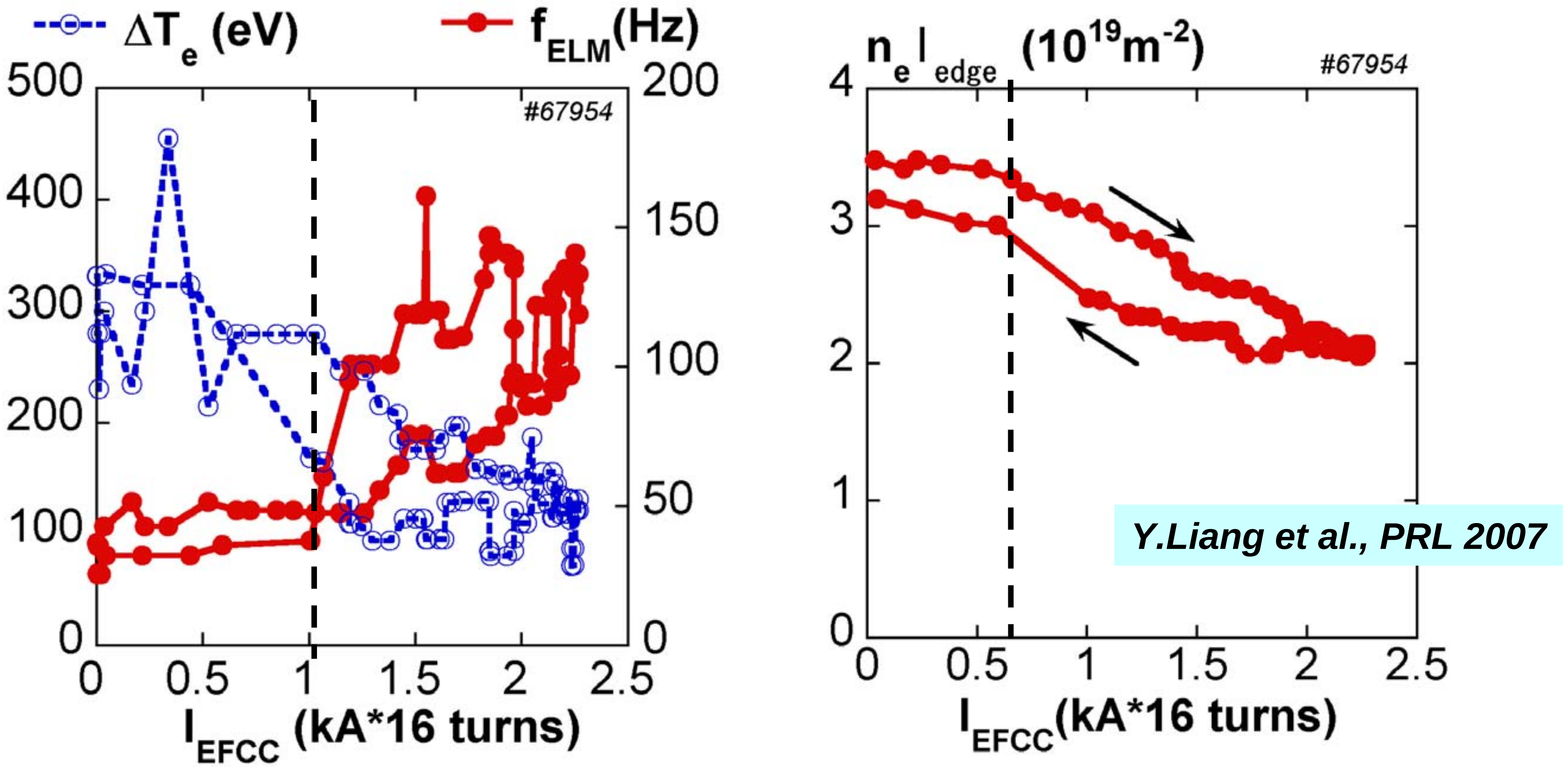


Y. Liang, PPCF (2007)

The minimum perturbation field amplitude for ELM mitigation increased but remained always below the *n*=1 locked mode threshold.

Density Pump-out effect

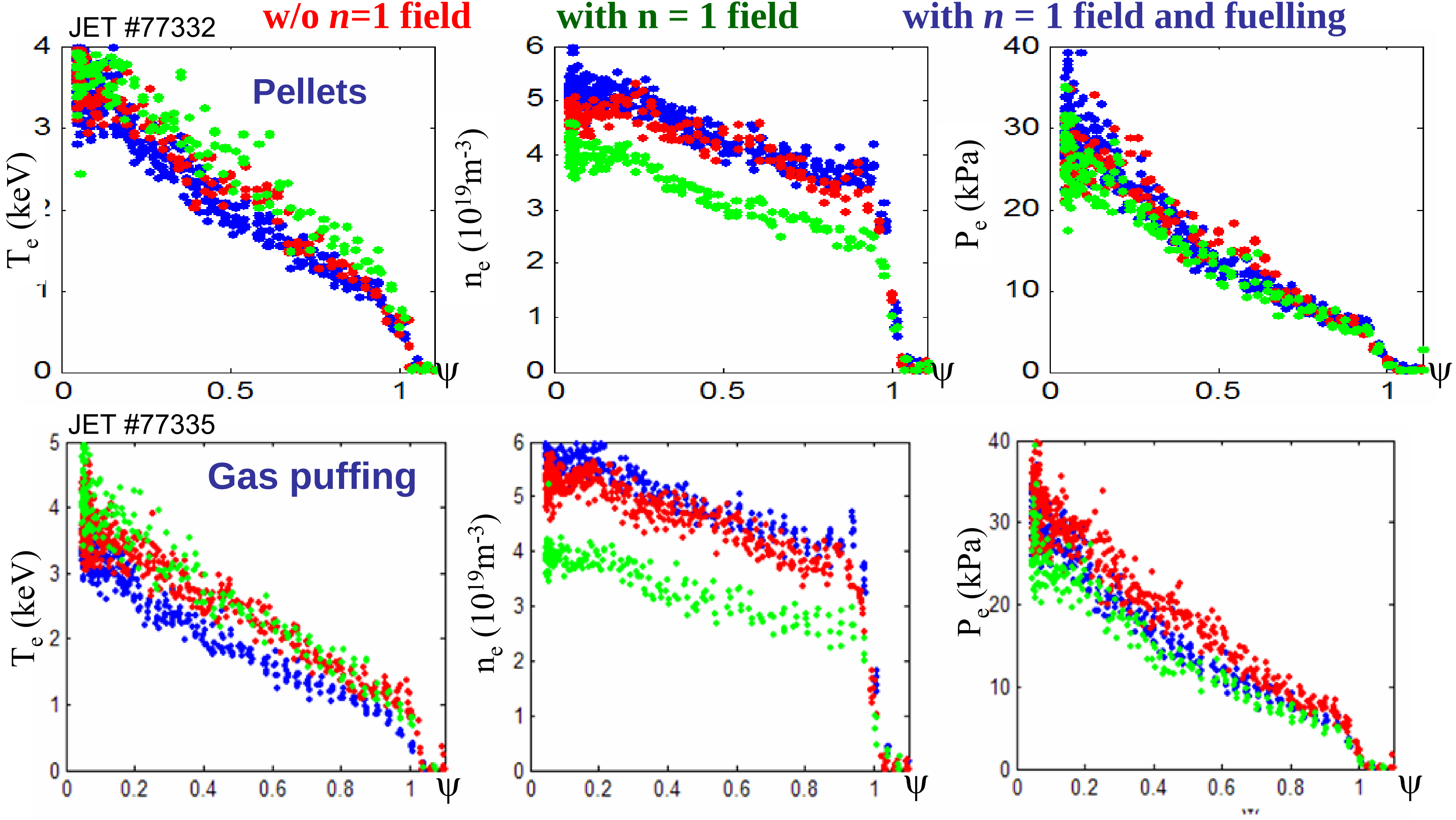
JET



Y.Liang et al., PRL 2007

- ✓ Drop of density at the plasma core and edge when the RMP field was applied.
- ✓ There is a threshold of density pump-out, However, it is different to the threshold of ELM control.
- ✓ Depends on the target plasmas
    - ❑ No clear density pump-out in L-mode, and type-III H mode plasmas
    - ❑ Less density pump-out in discharges with a less pump efficiency.
- ✓ No change of particle confinement in plasma core; (JET, TEXTOR).

Comparison of different methods for density pump-out compensation

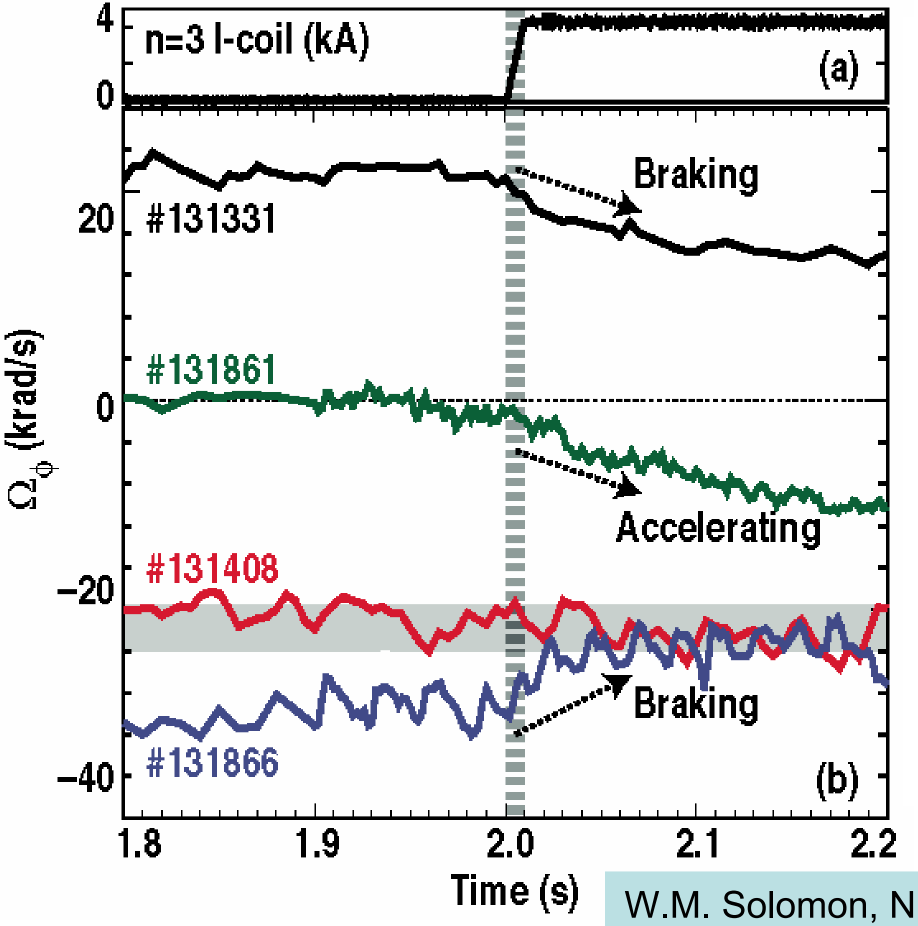


- ➢ Density pump-out effect can be compensated by either gas fuelling or pellet injection
- ➢ However, no recovery of energy confinement has been observed

Y. Liang, 19th ITC (2009)

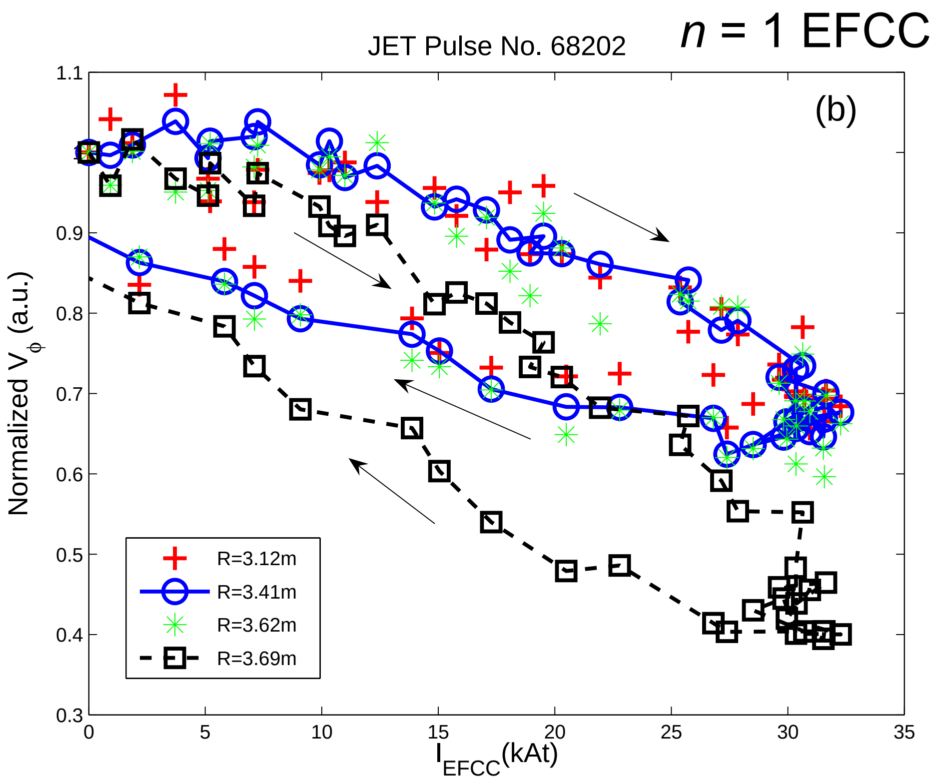
Influence of magnetic perturbation on the plasma rotation

DIII-D



W.M. Solomon, NF 49 (2009)

JET



Y. Liang, NF (2010)

- ➢ DIII-D results show not only to slow the plasma rotation, but also to accelerate the plasma, depending on the initial rotation.
- ➢ Similar plasma braking effect observed with *n* = 1 and *n* = 2 external fields on JET

Comparison between observed torque and NTV torque

Non-resonant magnetic braking Theory:

Neoclassical Toroidal Viscosity (NTV) theory

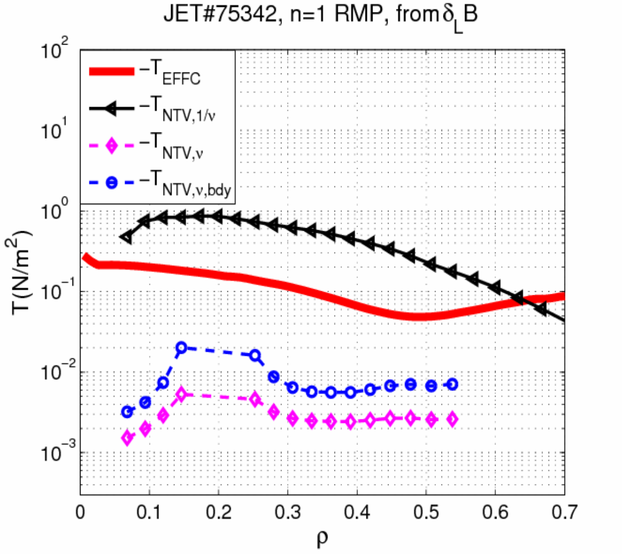
K. C. Shaing, POP **10**, 1443(2003)

$\tilde{B}_{n\neq 0}$ → Toroidal symmetry broken → Non-ambipolar diffusion of trapped particles → NTV torque

Non-resonant magnetic braking observation:

NSTX W. Zhu et al., PRL **96**, 225002 (2006)

DIII-D A. M. Garofalo et al., PRL **101**, 195005 (2008)



- The JET target plasma is mainly in the ν regime.
- The NTV torque (T_{NTV}) profile in the 1/ν regime agrees well with the measured torque profile induced by EFCC field on JET.
- However, the NTV torque in the ν regime from the boundary layer contribution is still about one order smaller than the observed torque.

Y. Sun, et al., submitted to PPCF, 2010

Operational domain

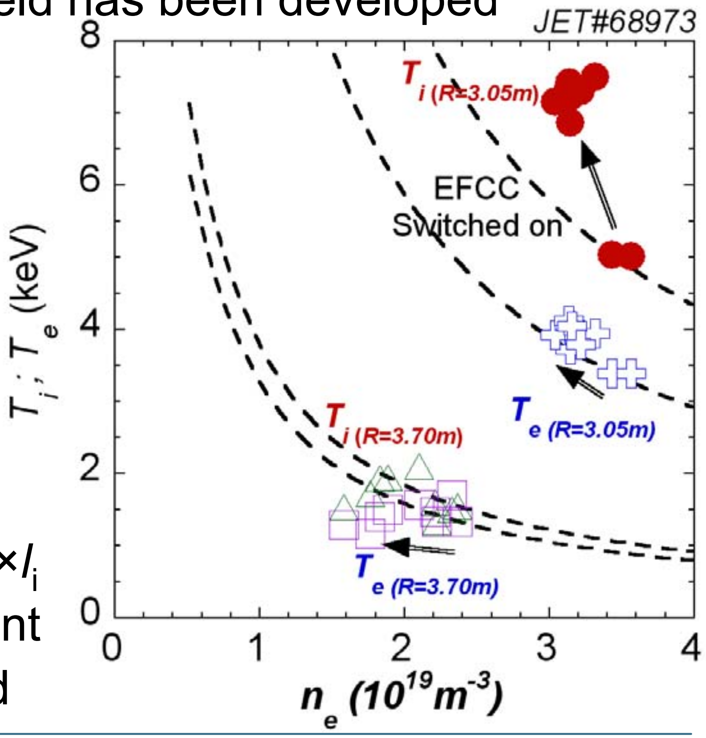
ELM suppression:

✓ RMP ELM suppression has been achieved in plasmas with ITER similar shapes and collisionalities on DIII-D

✓ Edge safety factor dependence of ELM suppression may limit the application for all ITER scenarios.

ELM Control:

Operational domain of ELM mitigation with a low *n* field has been developed towards ITER-relevant regimes on JET



Plasma current

- ✓ I_p ~ 2.0 MA (Further development needed)

Low collisionality

- ✓ Electron collisionality δ^*_e~ 0.09 at pedestal

High triangularity plasma

- ✓ δ^U ~ 0.45 and δ^L ~ 0.4

High β plasmas

- ✓ β_N ~ 3.0 ≈ approximate no-wall beta limit $4\times l_i$
- ✓ No reduction in Thermal energy confinement
- ✓ No locked mode excited by EFCC *n*=1 field

Comparison the results between DIII-D and JET

DIII-D
(*n*=3; i-coils)

JET
(*n*=1, 2 EFCCs)

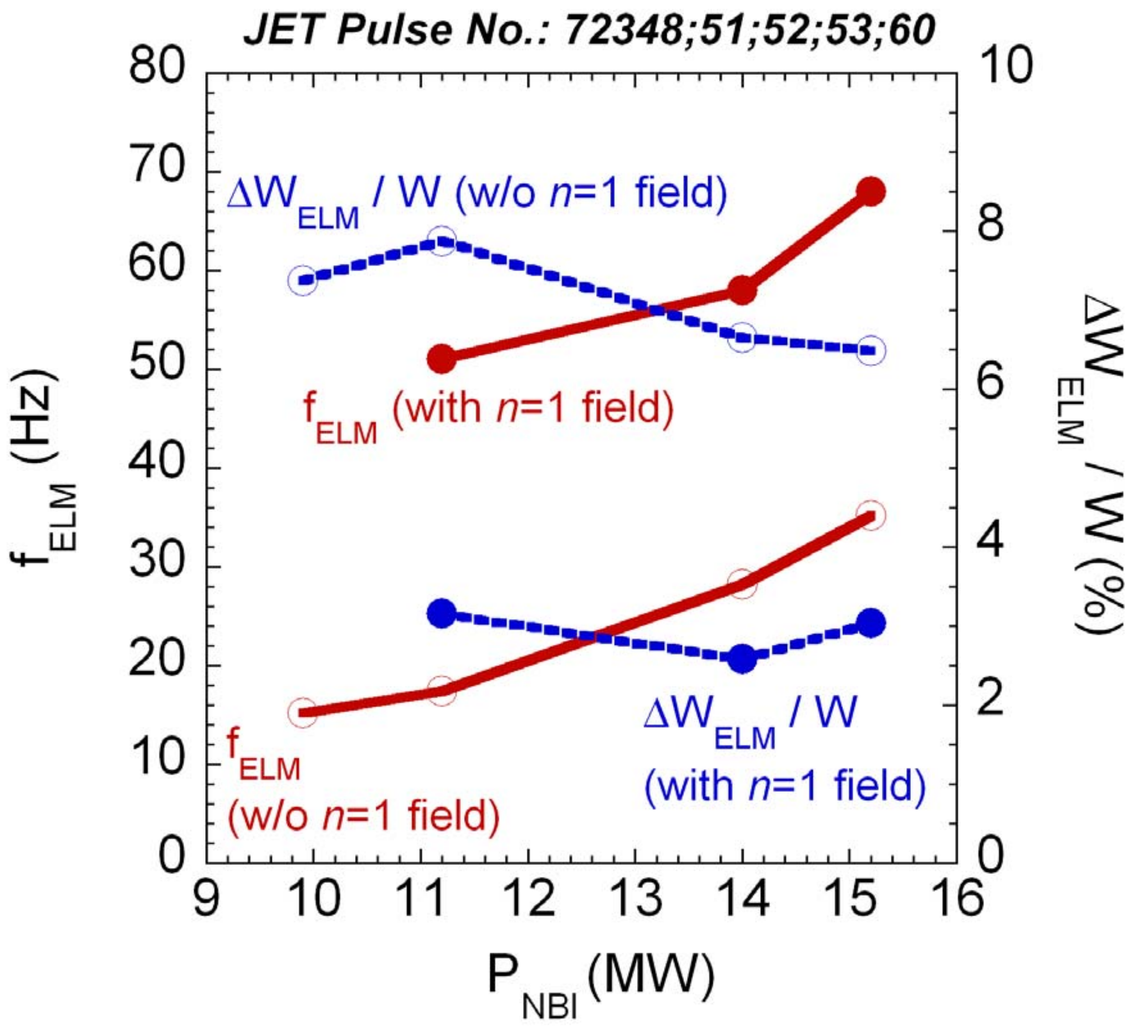
What are the same observations?

- ✓ Density pump-out
- ✓ Drop pedestal pressure and pressure gradient
- ✓ Plasma rotation braking

What are the different observations?

DIII-D	JET
✓ ELM suppression	✓ ELM control (frequency/size)
✓ A single narrow q_{95} window	✓ A wide q_{95} window

Heating power dependence



I_p = 2MA; B_t = 1.85T

q_{95} = 3.1; low δ

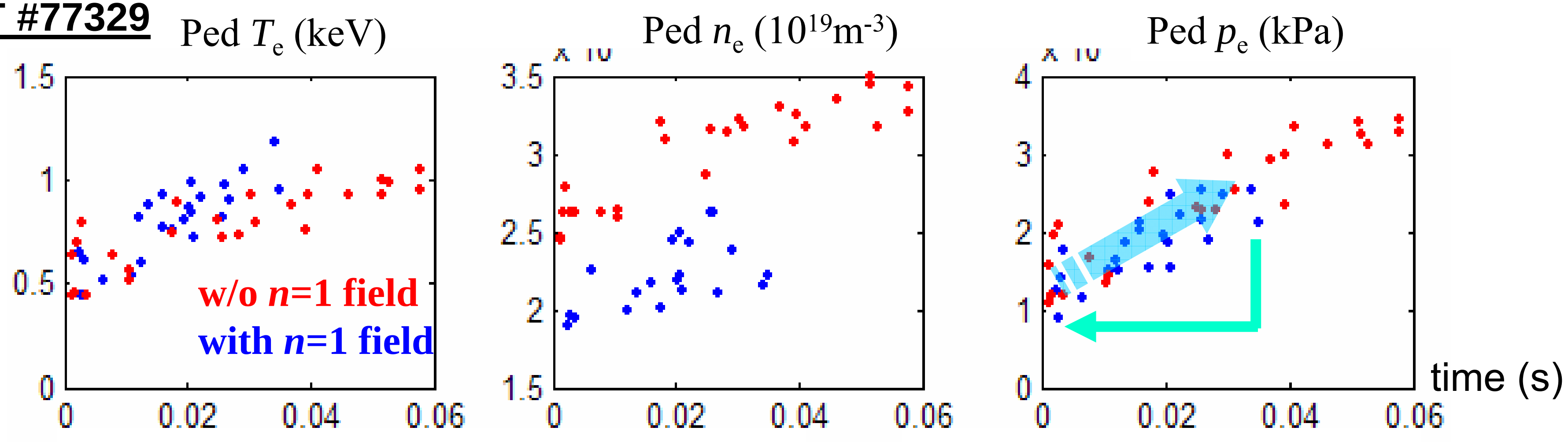
$$\mathbf{P_{NBI}} \nearrow \Longrightarrow \mathbf{f_{ELM}} \nearrow$$

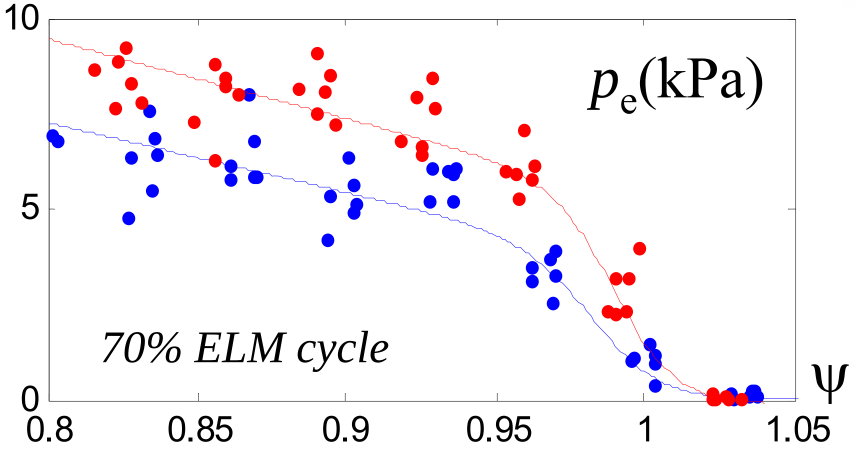
The power dependence of the ELM frequency is similar to normal type-I ELMs. However, the mitigated ELMs with n = 1 field have a higher frequency and smaller in size.

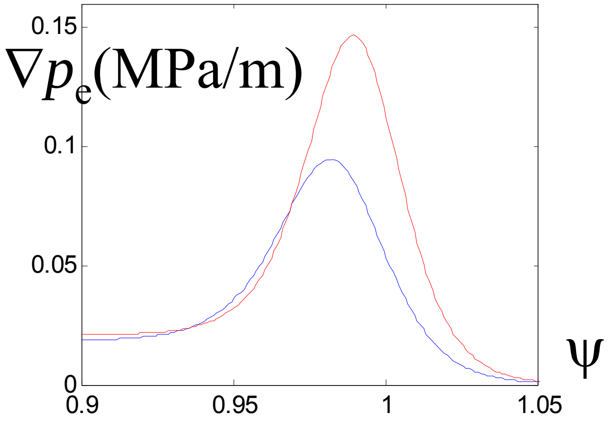
Y. Liang et al., NF, 2010

Dynamic of edge profiles with n = 1 field

JET #77329





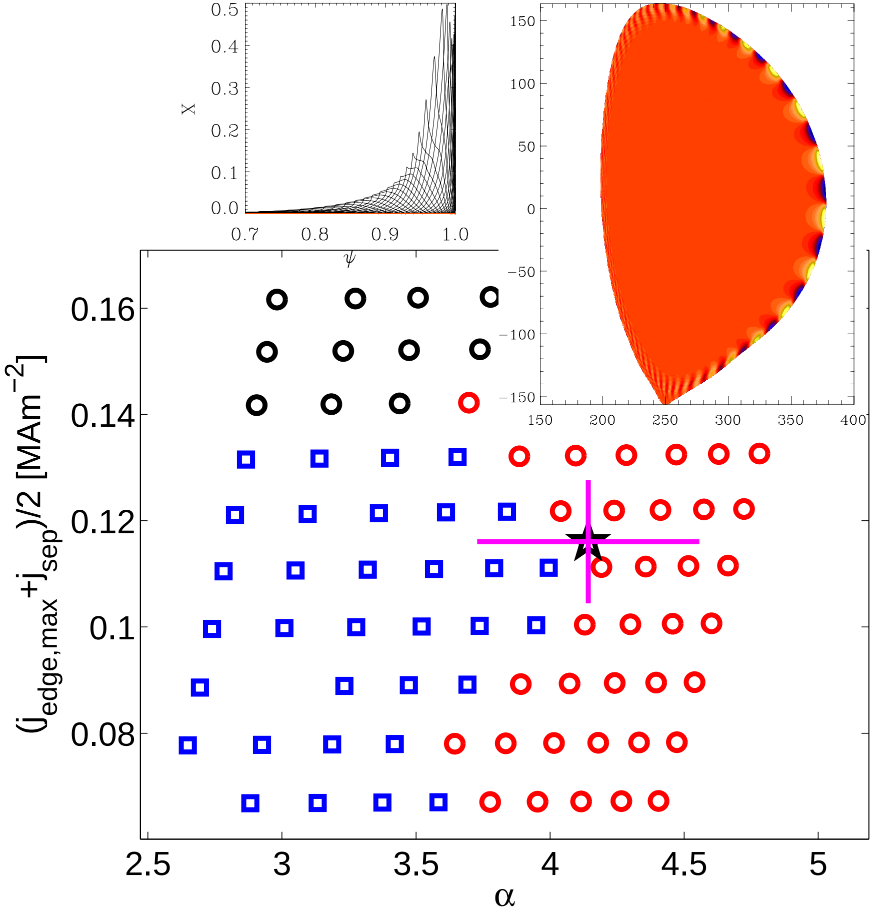


Y. Liang et al., 19th ITC 2009

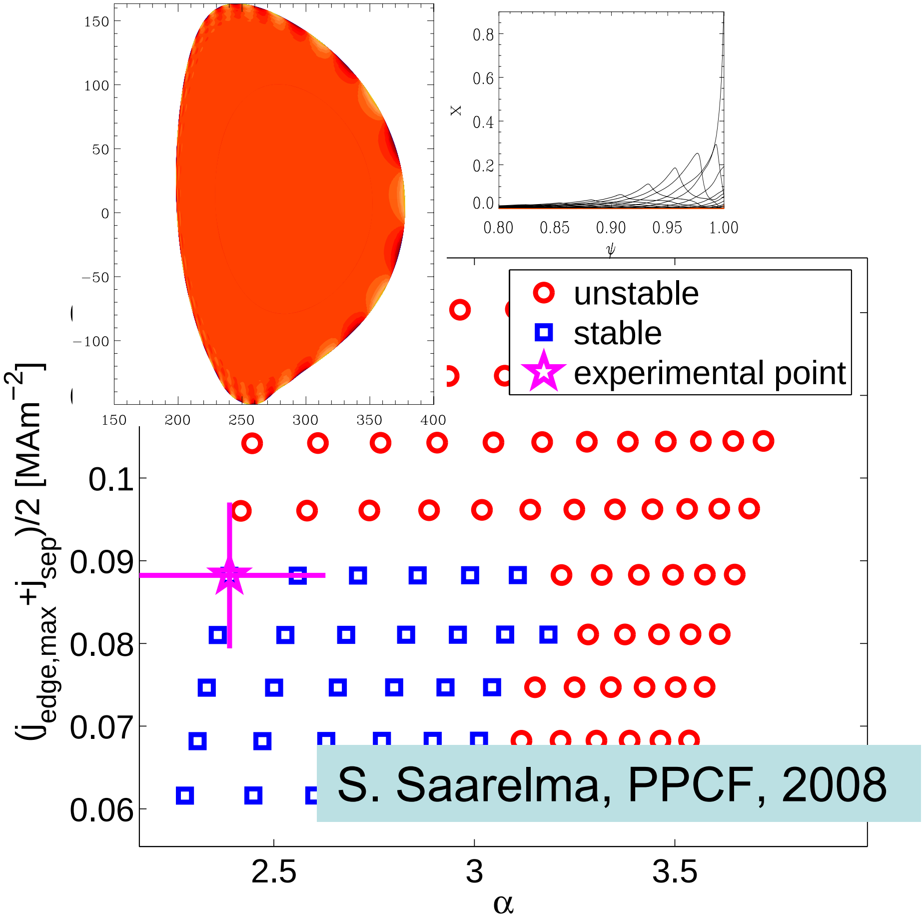
- ➢ Pedestal pressure with n = 1 field applied recovers at same rate, but the ELM crash occurs earlier at lower $p_{e,ped}$.
- ➢ Pedestal n_e is reduced by ~20% while the edge T_e is increased. ∇p_e is ~20% smaller.

Stability analysis of mitigated ELMs with n=1 fields

Type I ELM phase



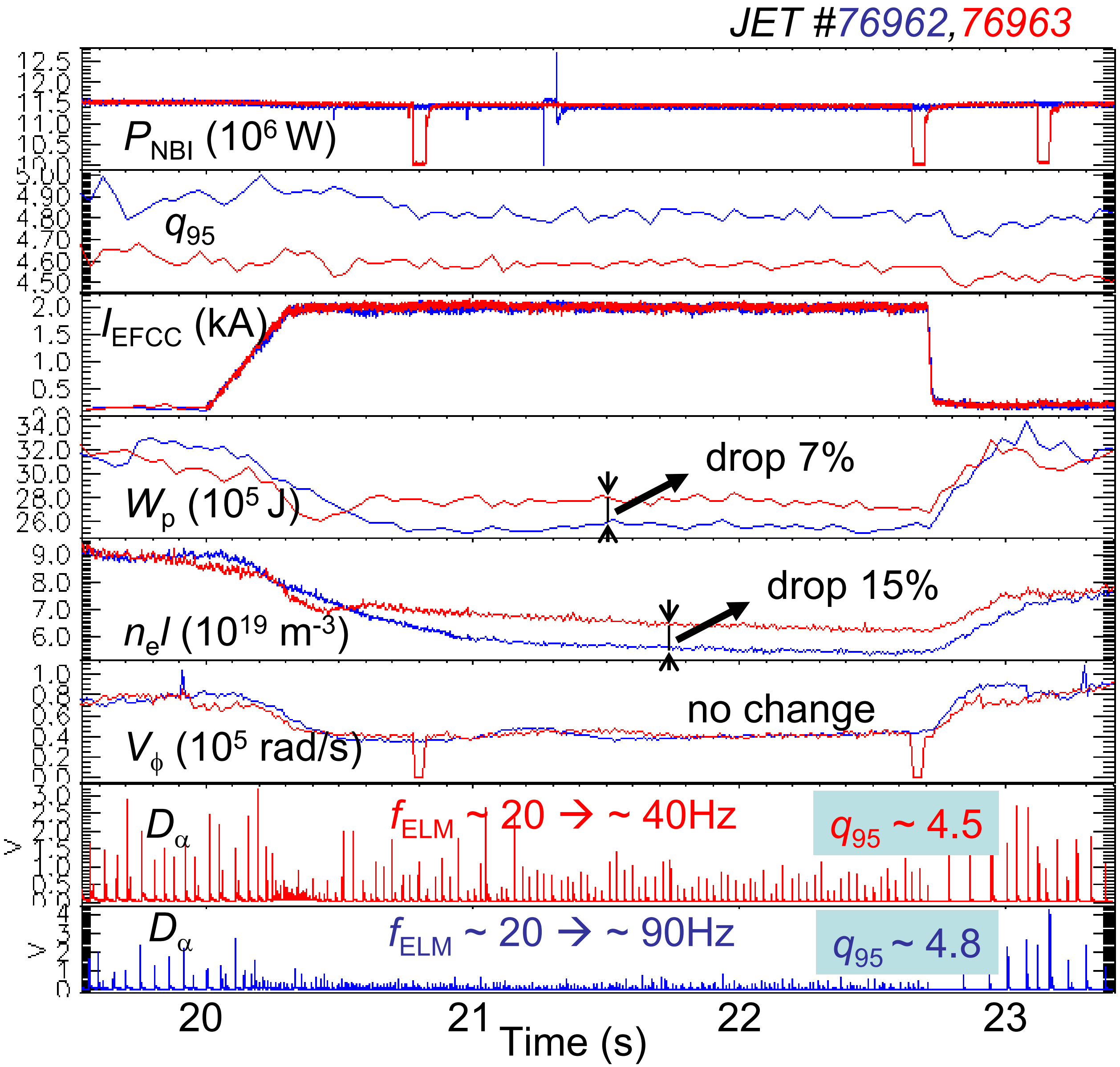
Mitigated phase



S. Saarelma, PPCF, 2008

With *n* = 1 perturbation field the operational point moves from intermediate-*n* peeling-ballooning (wide mode) boundary to low-n peeling (narrow mode) boundary.

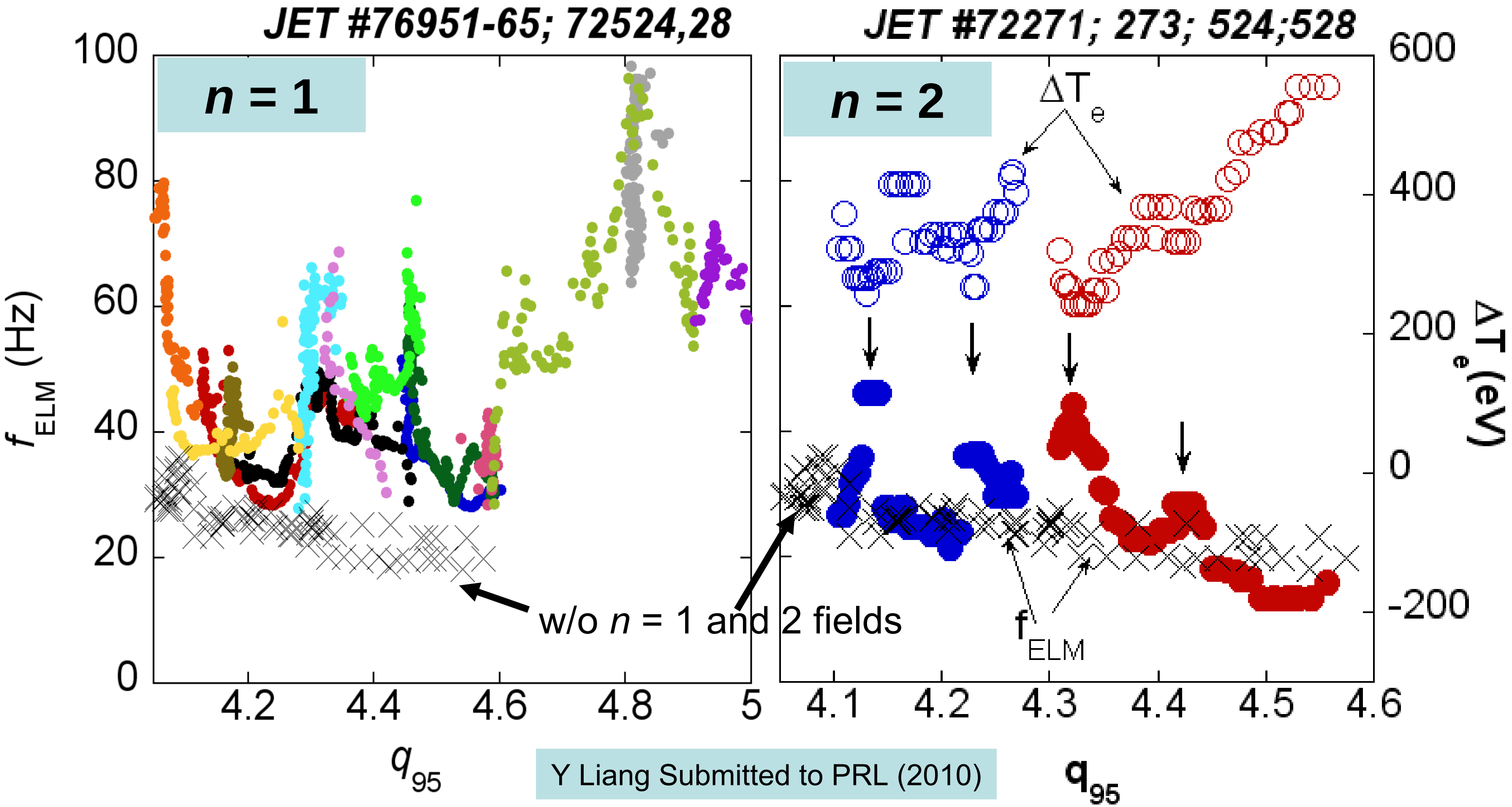
Resonance effect in ELM frequency vs q_{95}



- ➢ ELM control with $n = 1$ field is very sensitive to the edge safety factor.
- ➢Small change of q_{95} from 4.5 to 4.8 results in an increase of f_{ELM} by a factor of 2-3 and a drop of n_el by 15% while almost no difference is observed without $n = 1$ field.
- ➢ Plasma rotation braking from the $n = 1$ field does not depend on q_{95}.

Y Liang Submitted to PRL (2010)

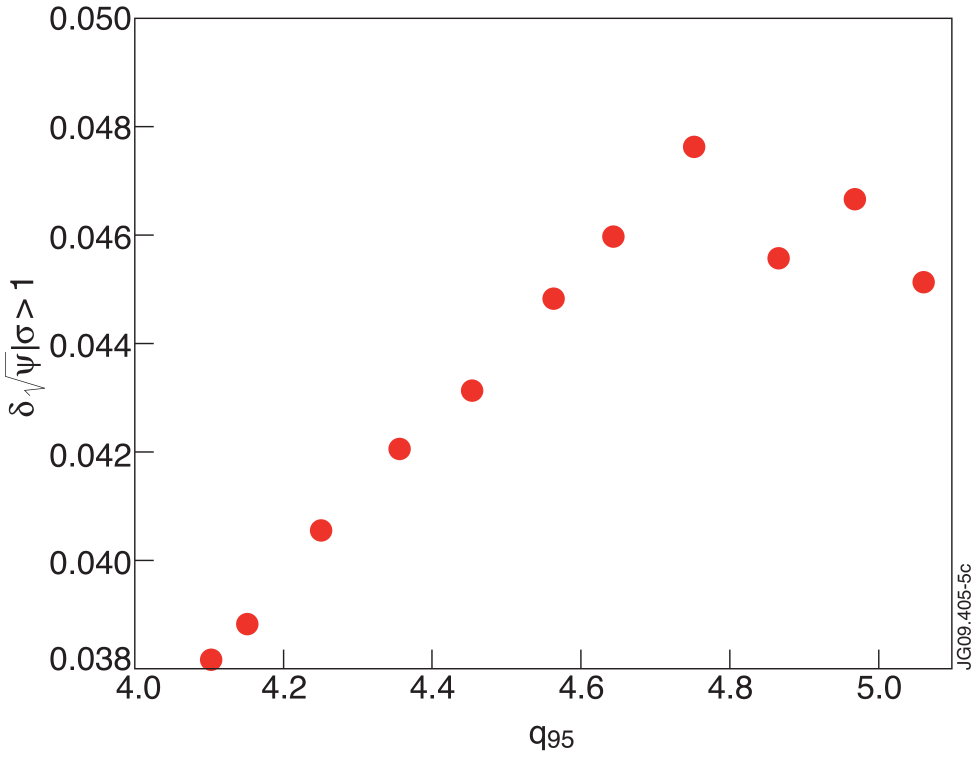
Multi-resonance effect with n = 1 and 2 fields



Y Liang Submitted to PRL (2010)

- Multiple resonances in f_{ELM} vs q_{95} have been observed with n = 1 and 2 fields
- Possible explanation in terms of ideal peeling mode model by Gimblett et al [*C G Gimblett et al., PRL, **96**, 035006-1-4(2006)*] currently being investigated

Width of the edge ergodisation zone vs q_{95}



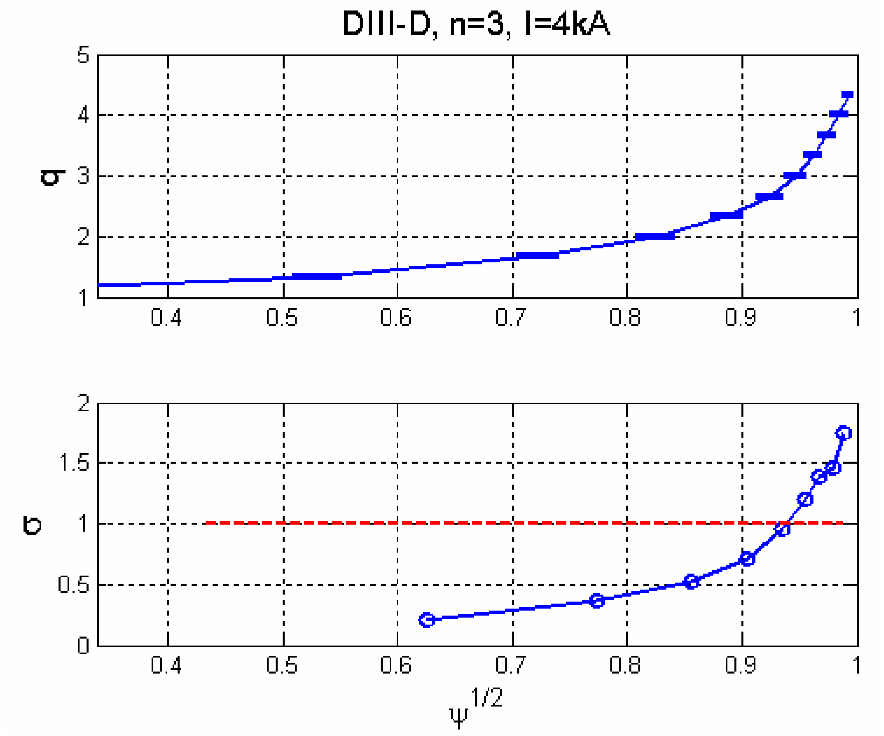
Y Liang Submitted to PRL (2010)

The mechanism of edge ergodisation, can not explain the multi-resonance effect observed with the low *n* fields on JET.

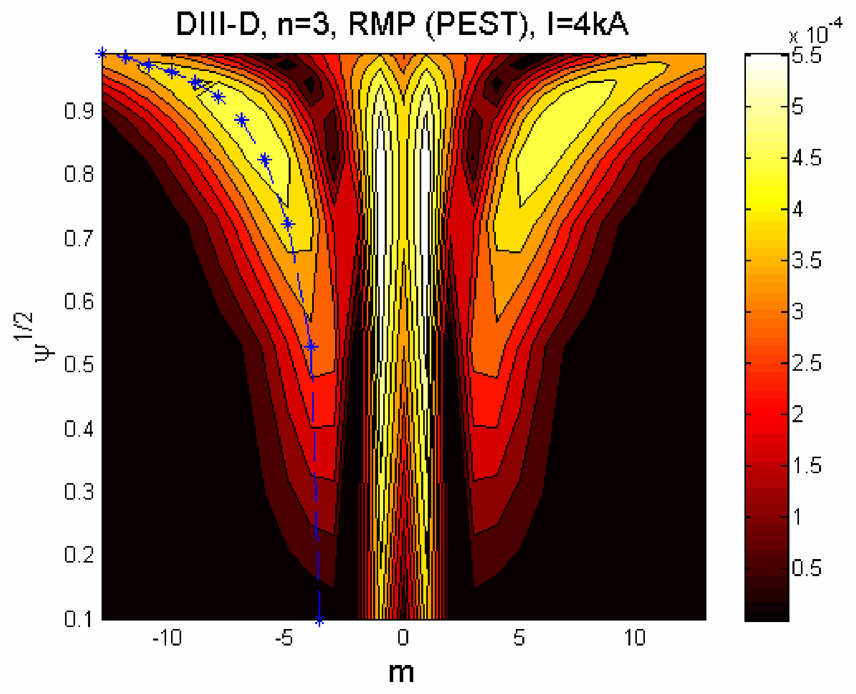
What is the physics mechanism of ELM suppression with magnetic perturbations?

DIII-D *n*=3 Even parity

A.) Chirikov parameter, σ



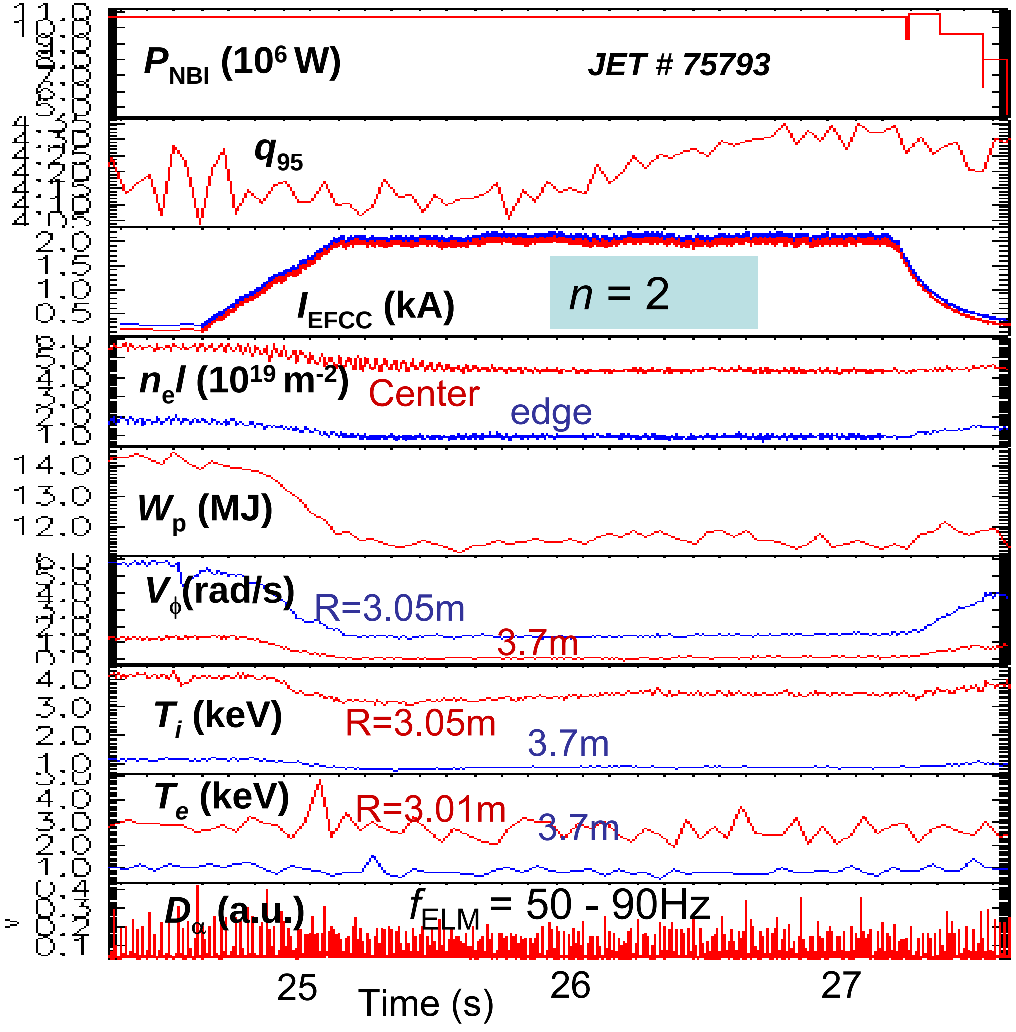
B.) Spectrum



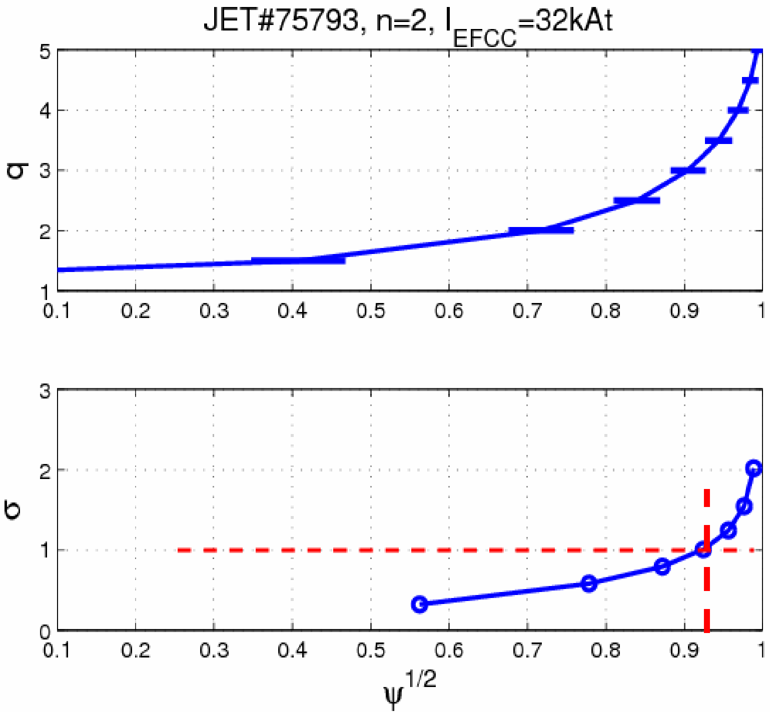
C. Others?

Optimisation of stochastic edge region

I_p= 0.84 MA; B_t= 1.0 - 1.06T



Y Liang, et al., ITPA PEP 2009

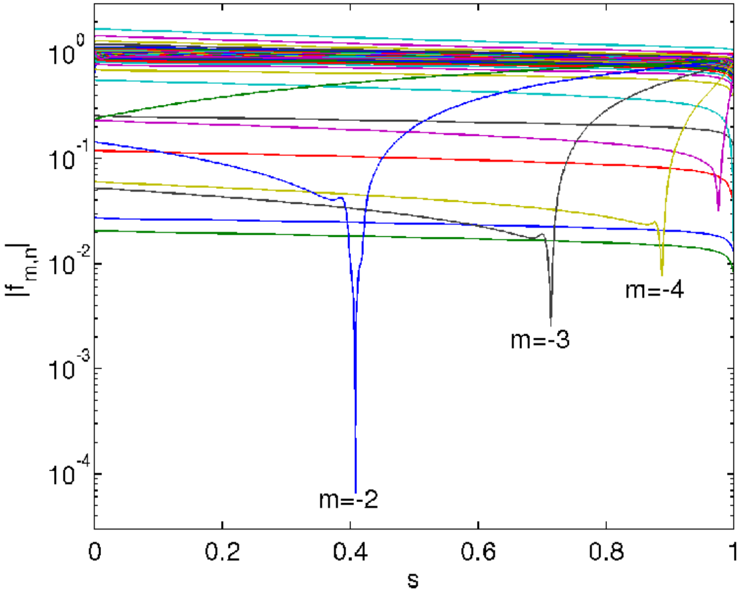


➢ No complete ELM suppression was obtained by application of n = 1 or n = 2 fields with a Chirikov parameter larger than 1 for a $\Psi_{pol}^{1/2} > 0.925$

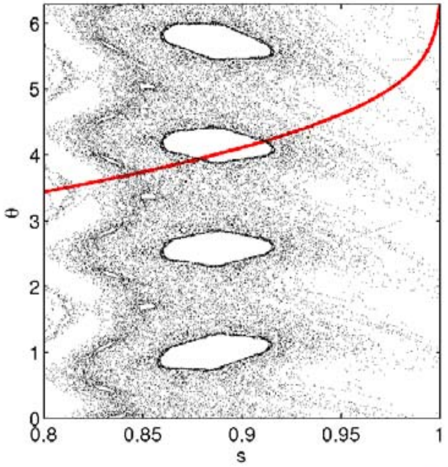
Effect of plasma shielding of the RMP

M. Heyn, JET science meeting, 2010

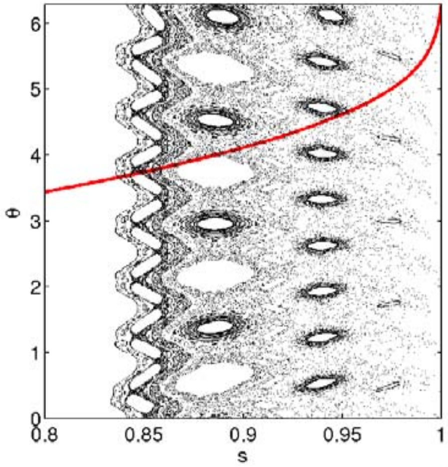
$$f_{mn} = B_{r,mn}^{(\mathrm{plas})} / B_{r,mn}^{(\mathrm{vac})}$$



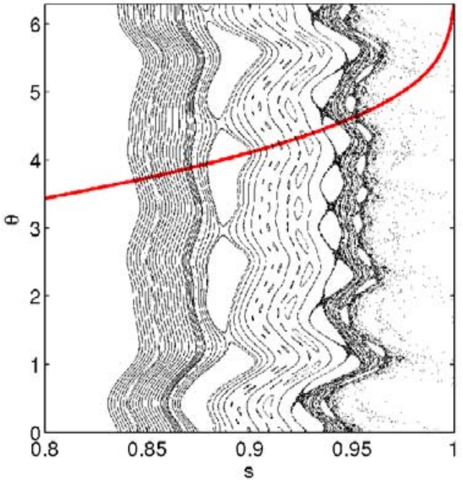
- ✓ The resonant perturbation is shielded due to plasma rotation and the magnetic field topology in the plasma core is not affected by RMP's.



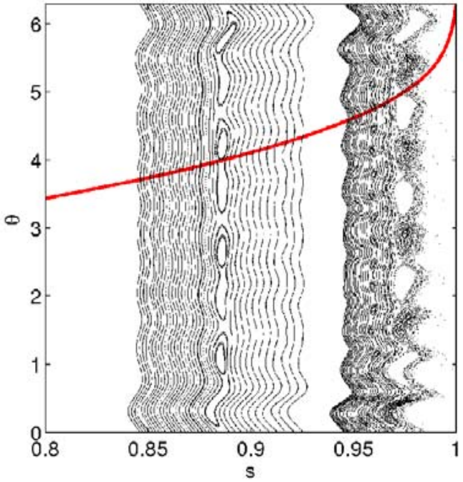
vacuum, $n = 1$



vacuum, $n = 2$



plasma, $n = 1$



plasma, $n = 2$

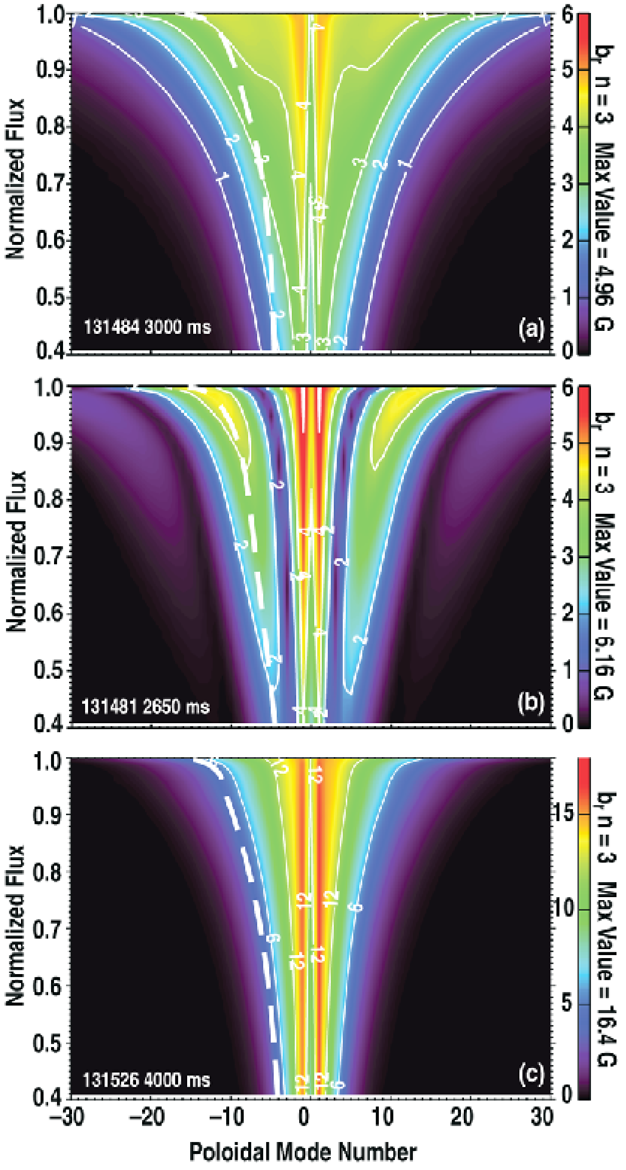
What is the role of the magnetic perturbation spectrum?

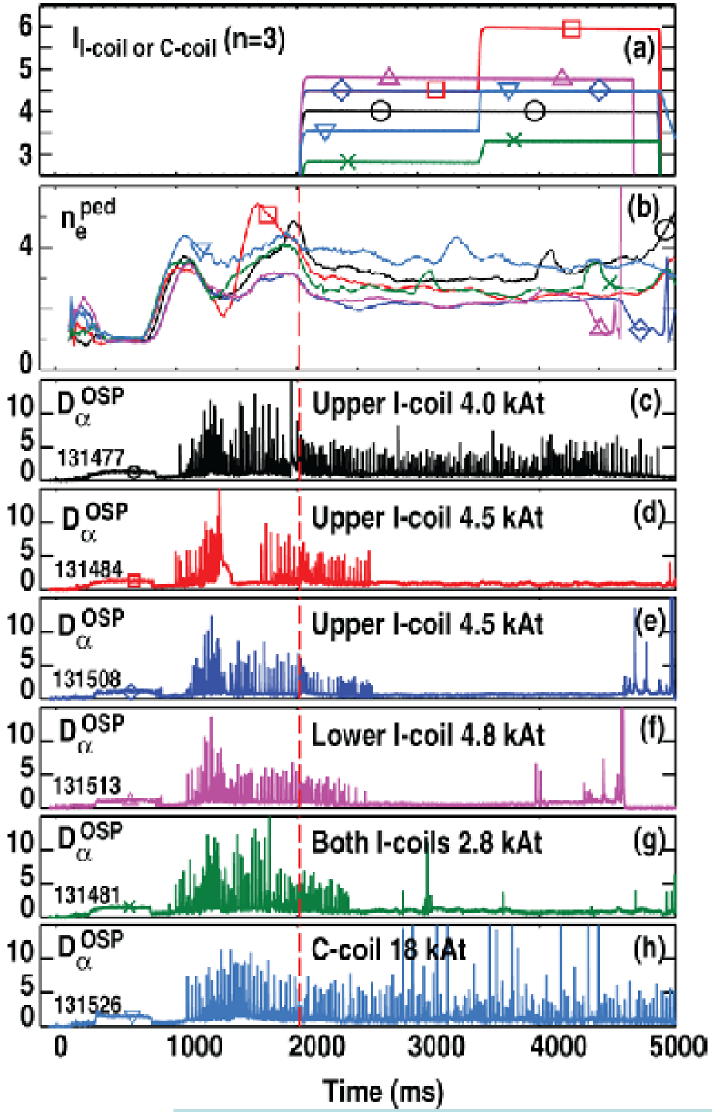
DIII-D

Upper in-vessel coils only

Both Upper and lower In-vessel coils

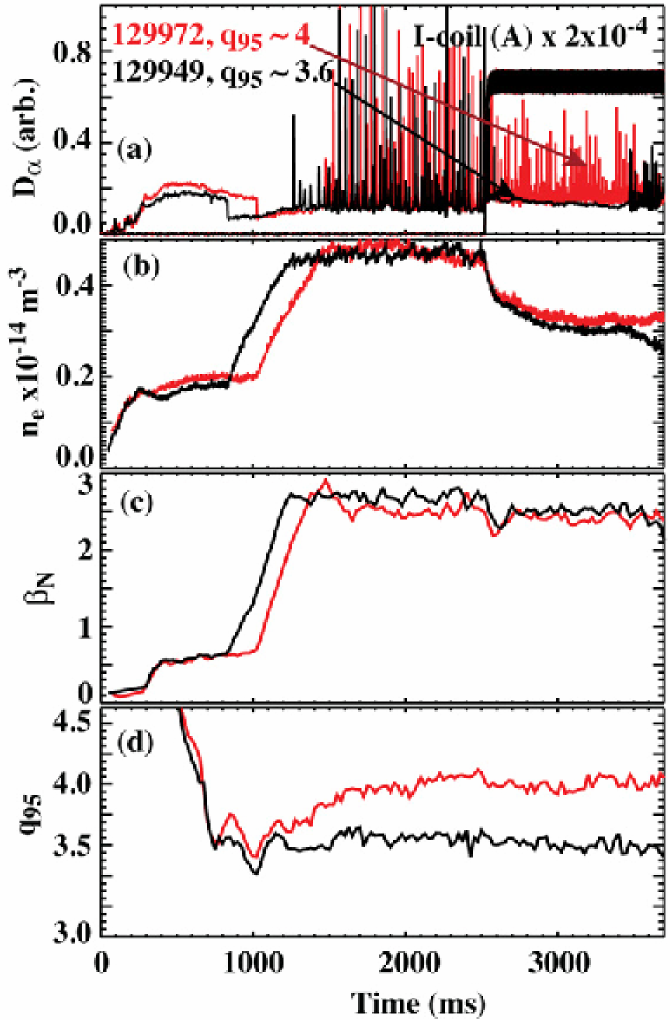
External C coils





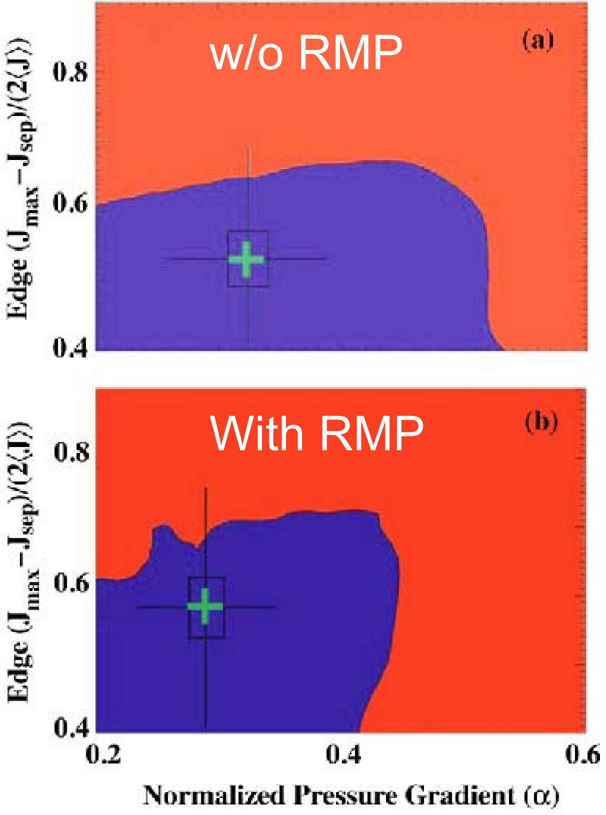
M.E. Fenstermacher, NF (2008)

Open questions:



DIII-D Hybrid

DIII-D 129972 q_{95} ~4

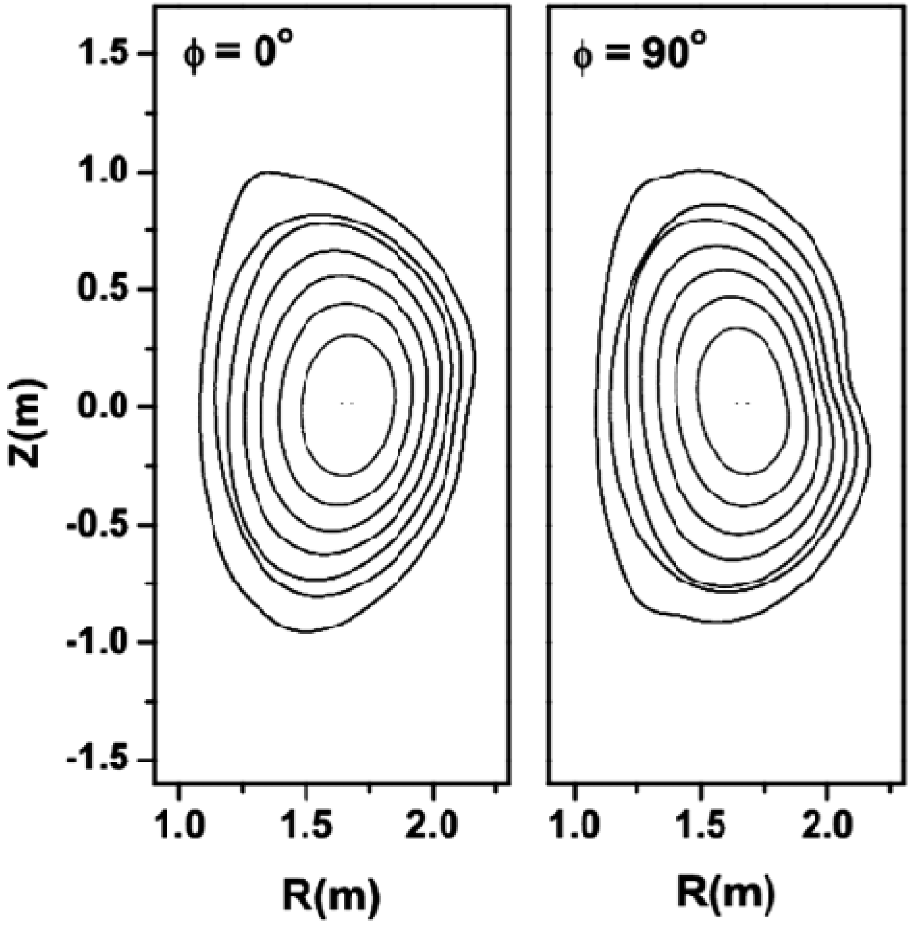


B. Hudson, et al., NF, 50 (2010) 045006

On DIII-D, Small ELMs can appear when the edge safety factor is outside the resonance window or when the H-mode pedestal is perturbed, which are not related to P–B stability.

3D effect of perturbation fields on the plasma equilibrium

With n = 1 field



3D equilibrium code IPEC

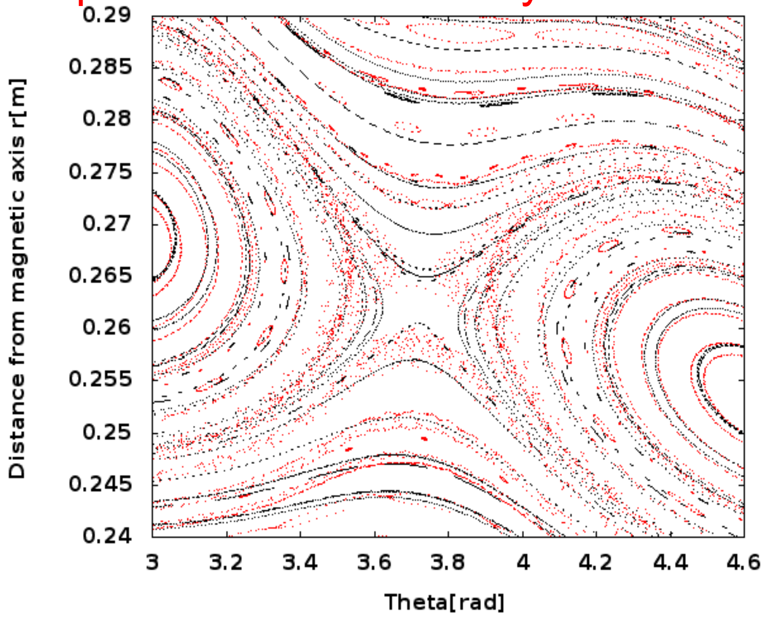
- ➢ Magnetic flux surfaces of the target plasma can be perturbed by each dominant error field.
- ➢ It suggests 3D effect need to be included in the stability analysis.

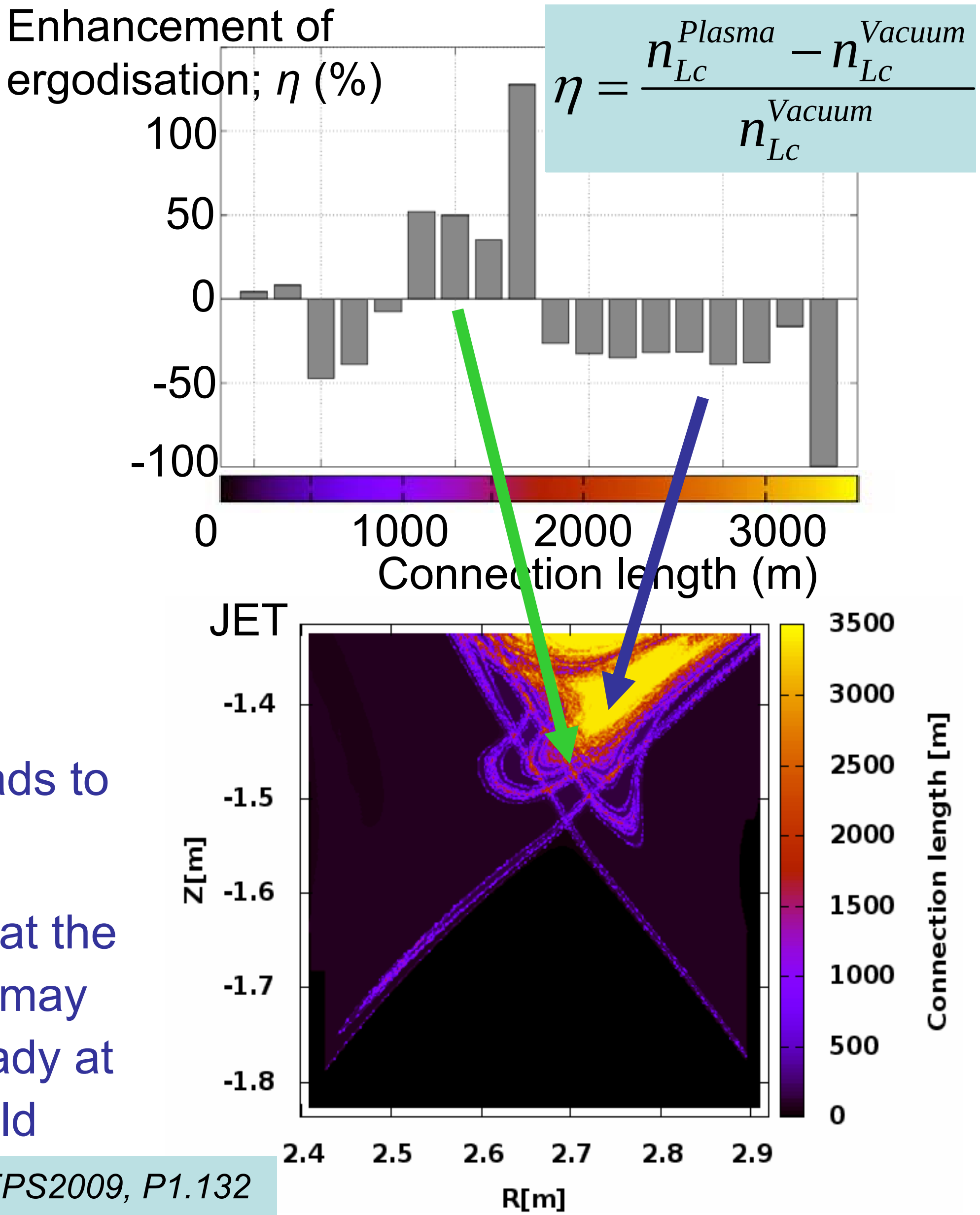
Jong-kyu Park, PRL 2007

Influence of magnetic perturbation on X-point

Vacuum

3-D Equilibrium calculation by HINT2 Code





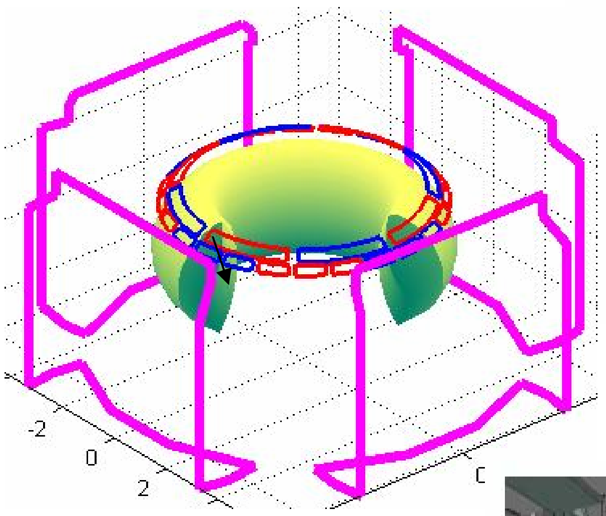
$$\eta = \frac{n_{Lc}^{Plasma} - n_{Lc}^{Vacuum}}{n_{Lc}^{Vacuum}}$$

- ➢ 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 perturbation field

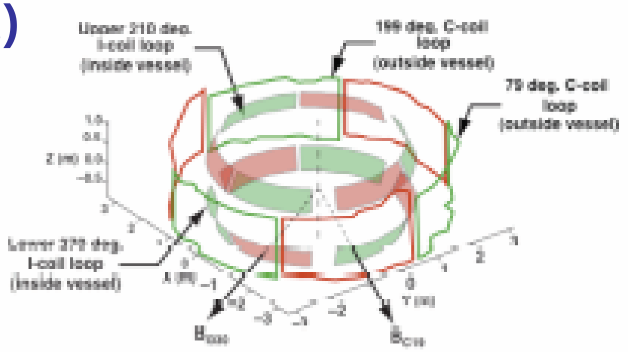
C. Wiegmann, et al, EPS2009, P1.132

RMP experiments

JET EFCC
& In-vessel coils (planned)

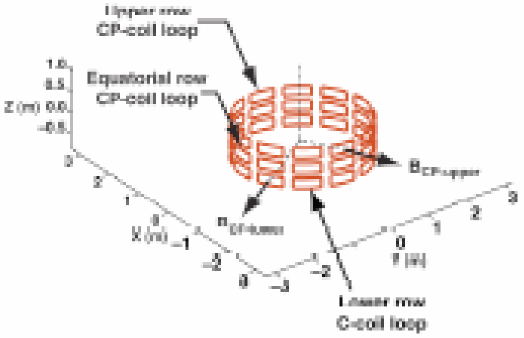


DIII-D existing

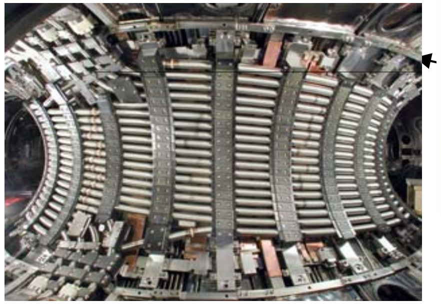


+

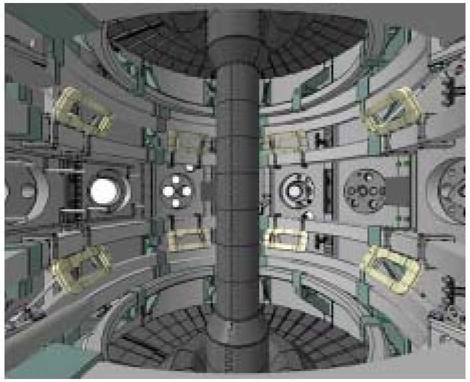
DIII-D planned



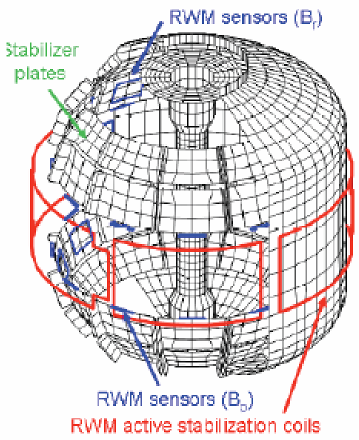
TEXTOR



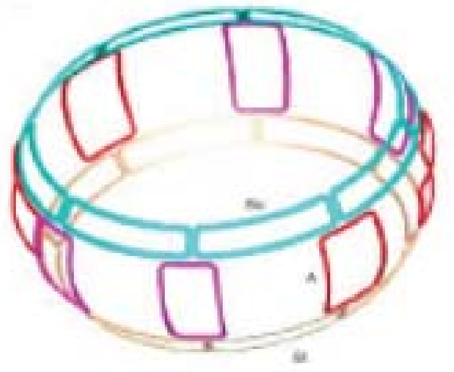
MAST



NSTX



ASDEX-U



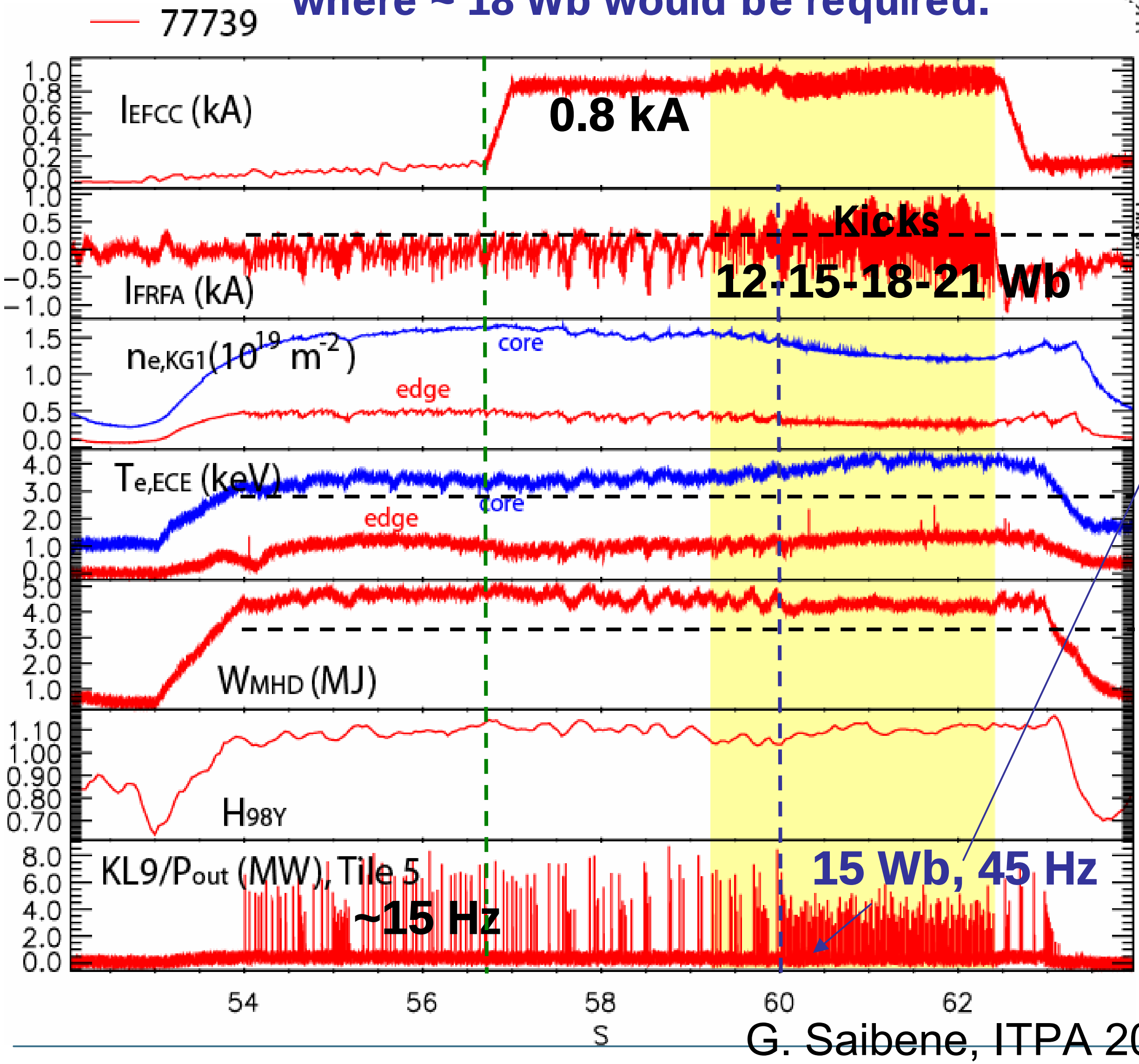
…… providing input to modelling for ITER.

Combination of different ELM control methods

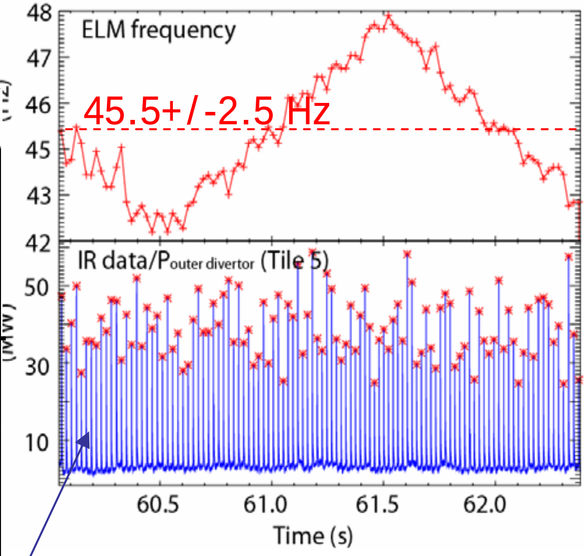
- RMP + vertical kicks
- RMP + pellet injection
- RMP + impurity gas puffing

n=1 perturbation fields & kicks sub-threshold

- **Target plasma reproduces conditions where ~ 18 Wb would be required.**



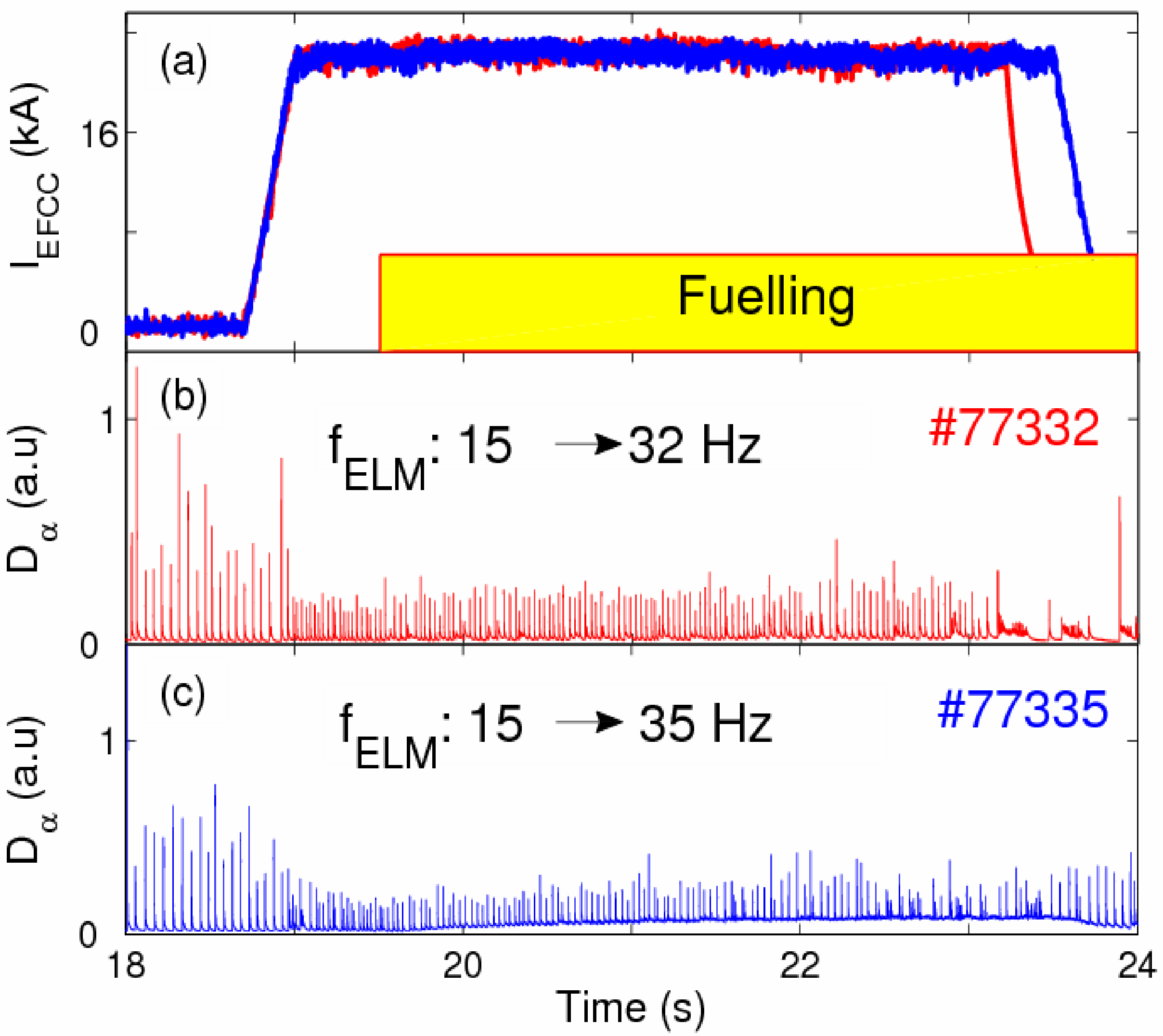
G. Saibene, ITPA 2009



- **n_e pump-out correlated with the increase in f_{ELM}**
- **10% reduction in W_{MHD}**
- **f_{ELM} = f_{kicks} is obtained with smaller kick size**

Potentially very useful for JET (ILW) and ITER

ELM control with n = 1 field + pellet injection



C_SFE_LT

I_p = 2.0 MA; B_t = 1.85 T;

f_{GWL}~ 0.6

Pellets:

#77332 Pellets: 3.5 mm, 10 Hz

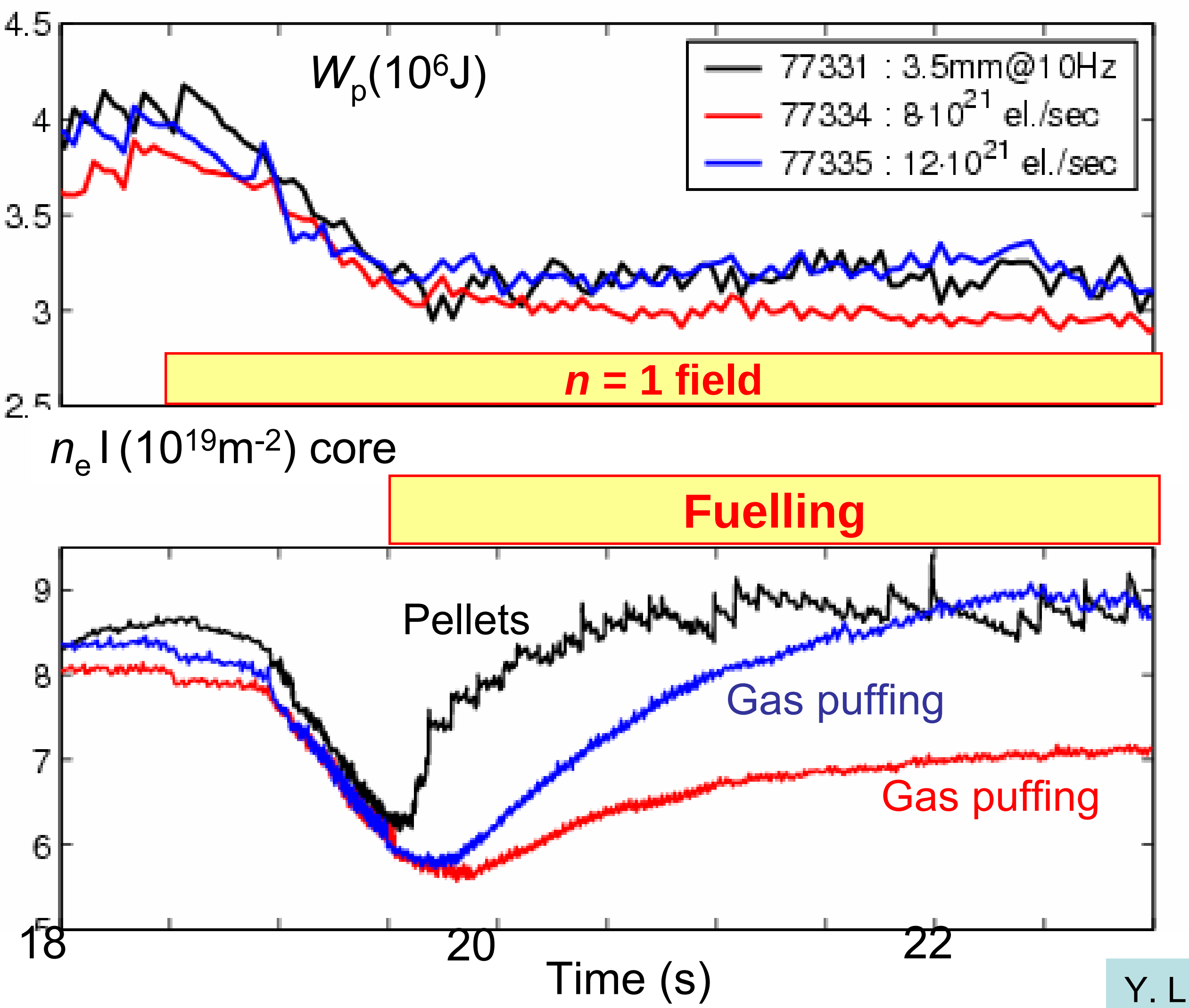
Gas puffing:

#77335 puffing rate: $12E10^{21}$el/s

Y. Liang et al., 19th ITC 2009

- ELM control with recovery of density has been achieved

ELM control with *n* = 1 field + pellet injection

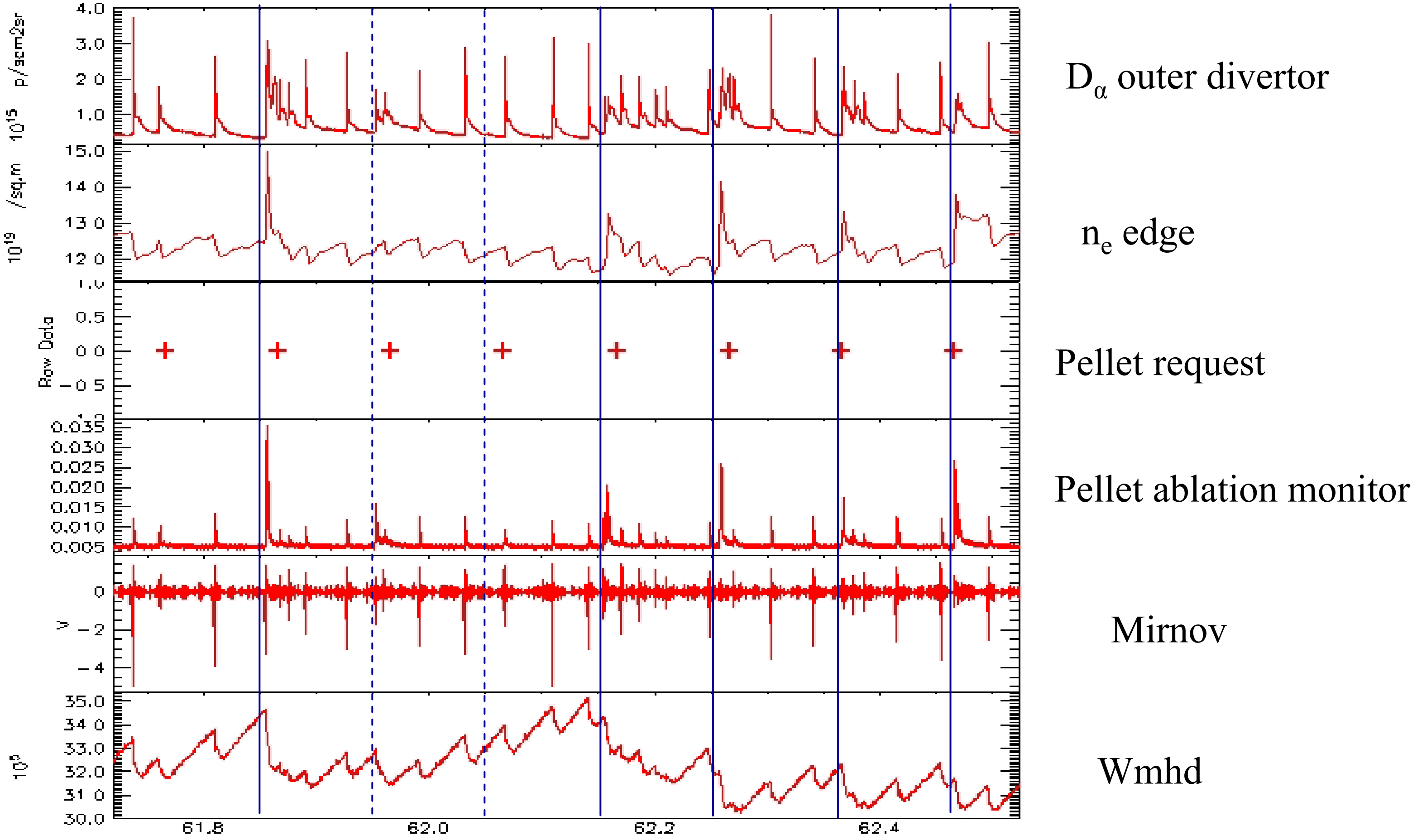


Y. Liang, 19th ITC (2009)

- However, no recovery of energy confinement has been observed

ELM control with n = 1 field + pellet injection

JET



Arriving pellet trigger ELMs (and do fuel, here it was welcome)

P. Lang, 16th ITPA PEP meeting 2009

Summary (I)

Active control of ELMs by resonant magnetic perturbation fields offers an attractive method for next-generation tokamaks, e.g. ITER.

- ✓ D-III D has shown that type-I ELMs are completely suppressed when $n = 3$ magnetic perturbations are applied.
- ✓ Increasing of ELM frequency or ELM triggering has been observed on JET, MAST and NSTX, but not DIII-D with mid-plane C-coils.
- ✓ Up to date, no complete ELM suppression was obtained on JET, MAST even with a Chirikov parameter larger than 1 at $\Psi_{pol}^{1/2} > 0.925$ which is one of the important criterions for the design of ITER ELM suppression coil.
- ✓ Density pump-out effect with application of RMP from midplane coils has been observed on JET, MAST and NSTX, but not DIII-D with mid-plane C-coils. It can be compensated by either gas fuelling or pellets injection. However, no recovery of energy confinement has been observed.
- ✓ Plasma response (screening and 3D equilibrium) helps for understanding the mechanism of ELM suppression/control with magnetic perturbations

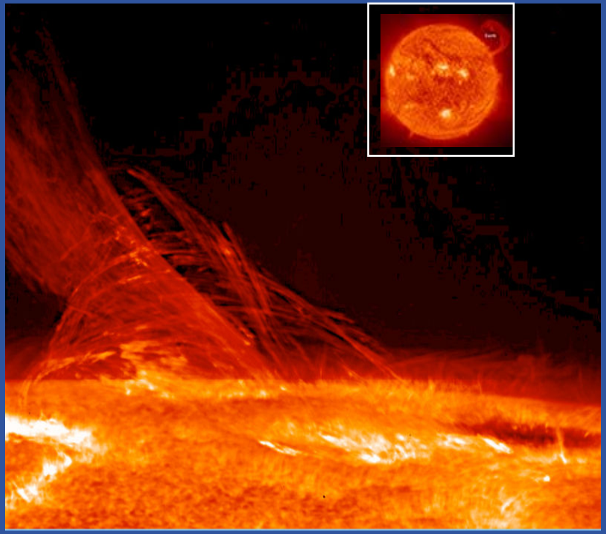
Summary (II)

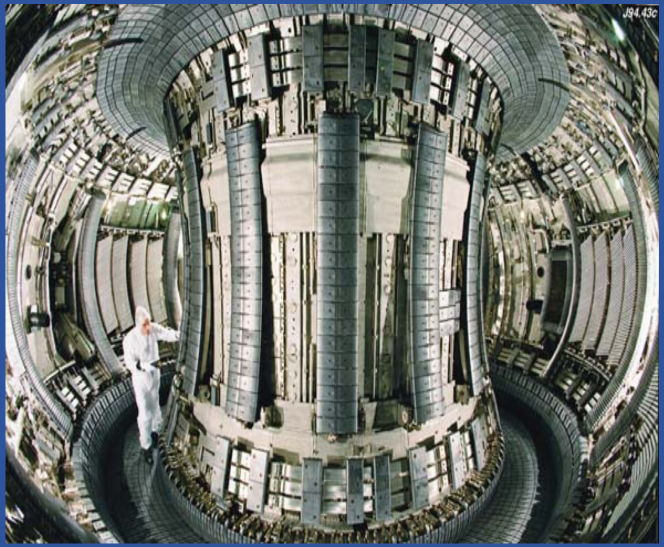
- ✓ ***Radiating divertors (type-III ELM)***, successful ELM control and full H-mode confinement have still to be demonstrated.
- ✓ ***Magnetic triggering*** (“vertical kicks”) need in-vessel coils. Promising technique for ILW on JET, in which case the ELM size need only be reduced by ~ 2-3 times
- ✓ ***Pellet pacing*** can typically achieve a factor of two reduction in the energy per ELM – this is not enough. Also, for ITER the reliability of a pellet system, for a safety application, has to be questioned.
- ✓ ***External magnetic perturbation*** Very promising results up to now and further development needed in the future. Joint experiments (DIII-D, MAST, TEXTOR, AUG, …) will help to understand physics
- ✓ ITER may need combination of different ELM control methods

Thanks for your attention!

Fusion …

… on Earth





We are on the way ……