Discussion: MHD stability of ETB. ELMs control.

1. ETB: turbulent transport is suppressed=>Transport through ETB=ELMs.=> Present theoretical understanding of ELMs:

-Status of ideal linear MHD.

-ELM size,convective and conductive losses. Explanation?

-Transport and non-linear MHD.

What can be used already and what should be done to progress both in understanding and “theory motivated” Integrated Modelling of ELMs?

2. ELMs control:

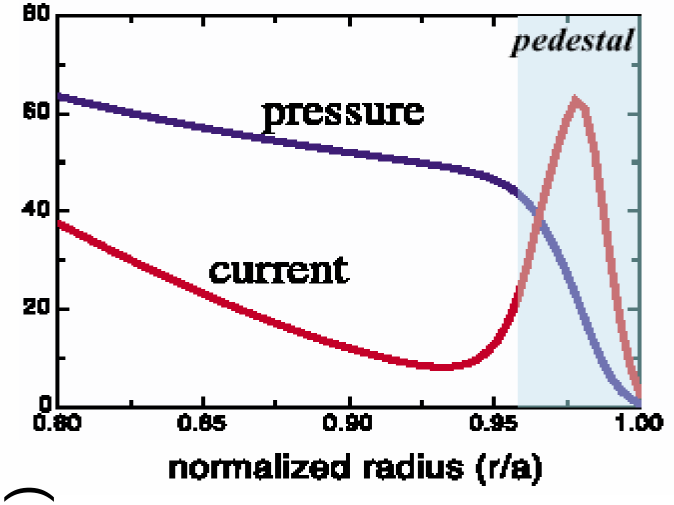
-Stochastic boundaries.

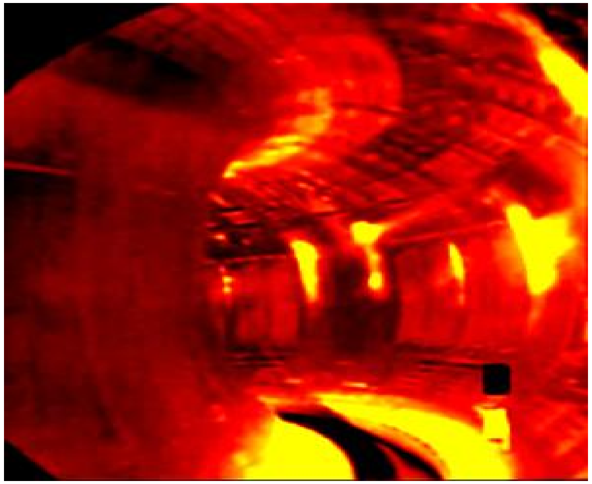
-Ripple losses to control ELMs.

-Pellet injection (AUG).

Understanding? =>Integrated Modelling? Tests on JET? Implementation on ITER?

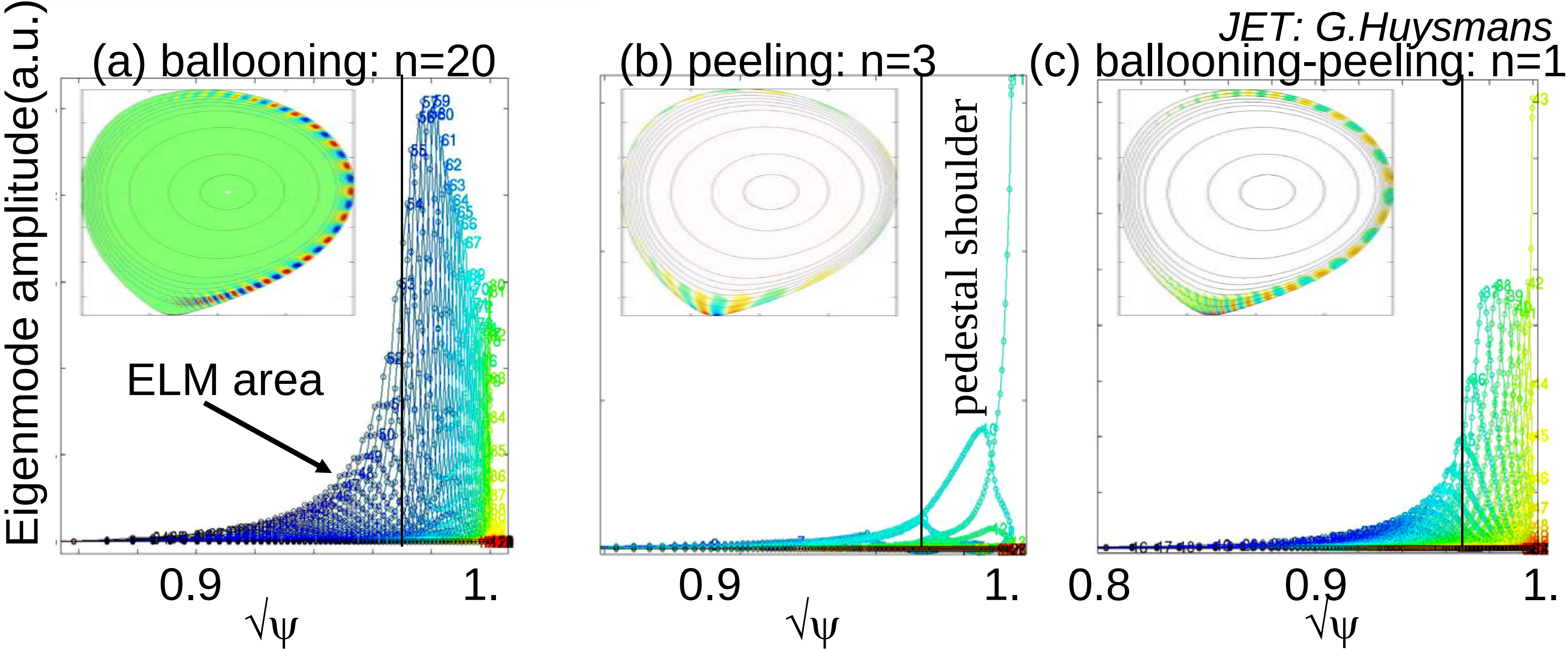
Starting point: linear ideal MHD. *(MISHKA, GATO, ELITE)*





Experimental facts: LFS (=ballooning?) instability

JET: G.Huysmans '01


(a) ballooning: n=20

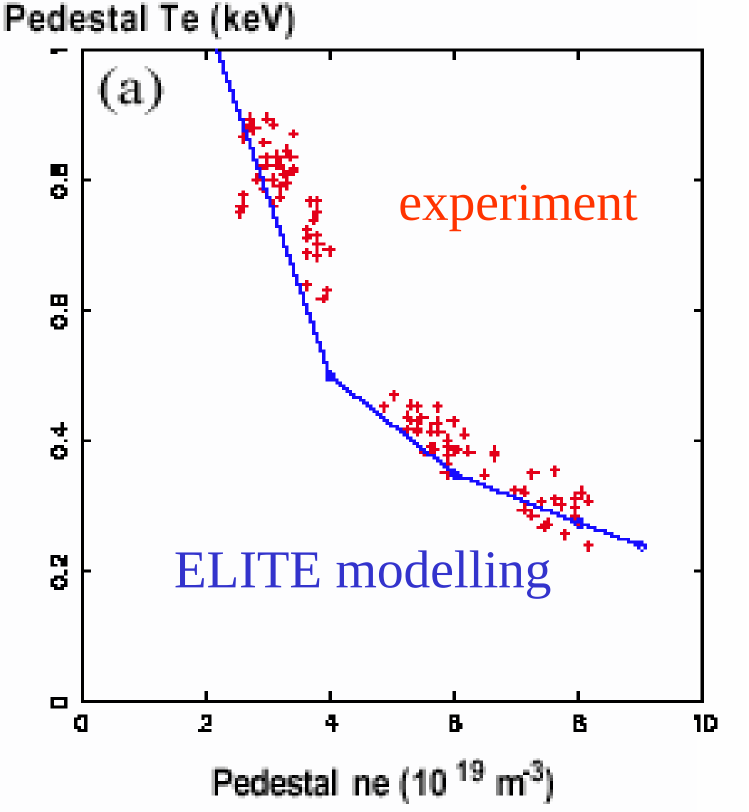
(b) peeling: n=3

(c) ballooning-peeling: n=12

Predictive capability of linear ideal MHD.

Max pedestal pressure is limited by ideal MHD.

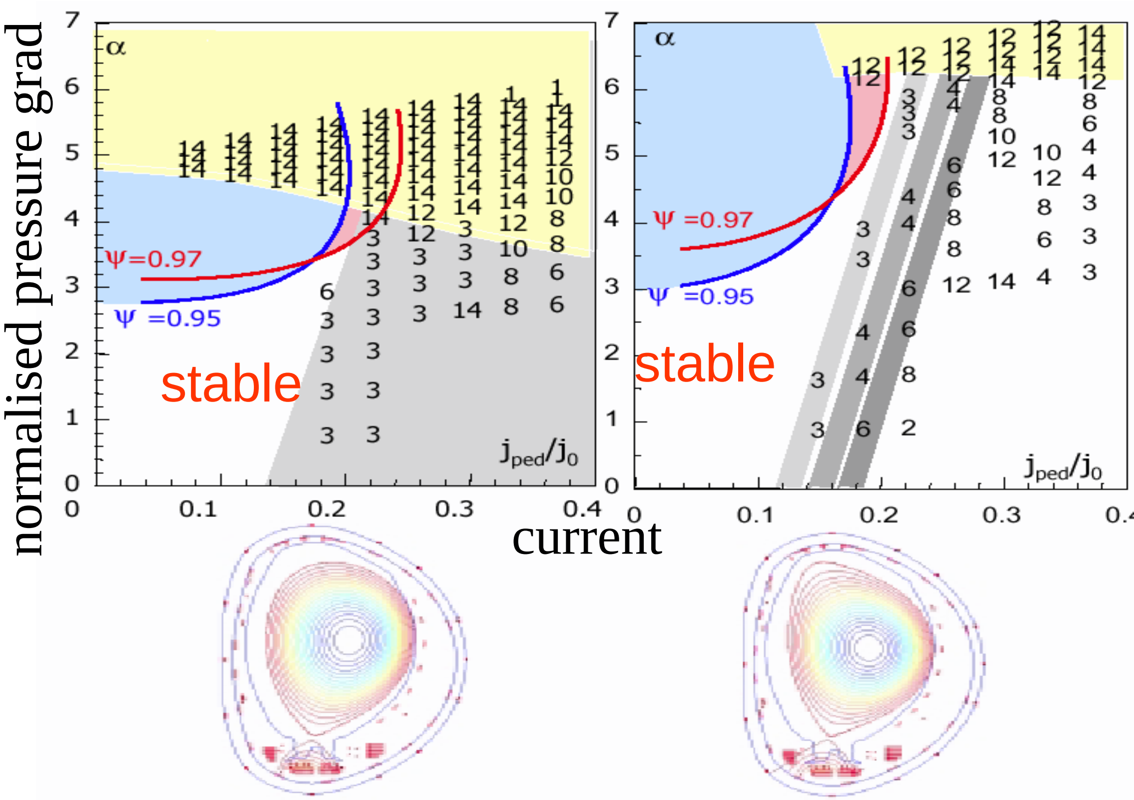
DIII-D(ELITE): Snyder '02



Role of triangularity δ.

Max P_{ped} increases with high triangularity (δ) => increase of edge magnetic shear => higher confinement.

Low δ *JET(MISHKA):Huysmans '01* High δ



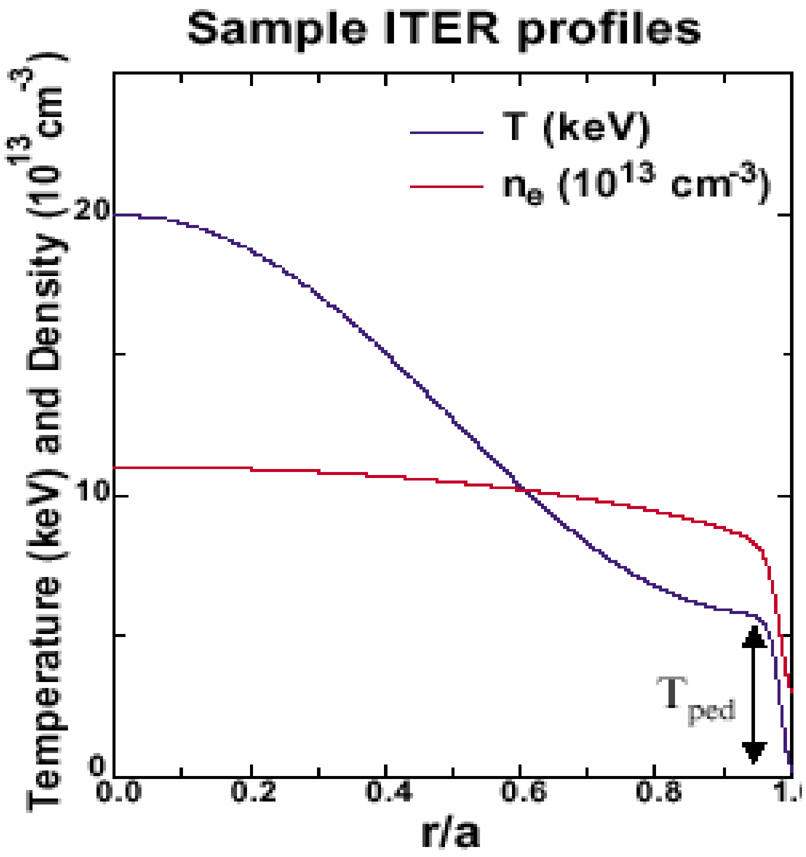
(a) Low triangularity: JET # 50460 (δ_u=0.11, δ_l=0.36) (b) High triangularity:JET # 52308 (δ_u=0.53, δ_l=0.43)

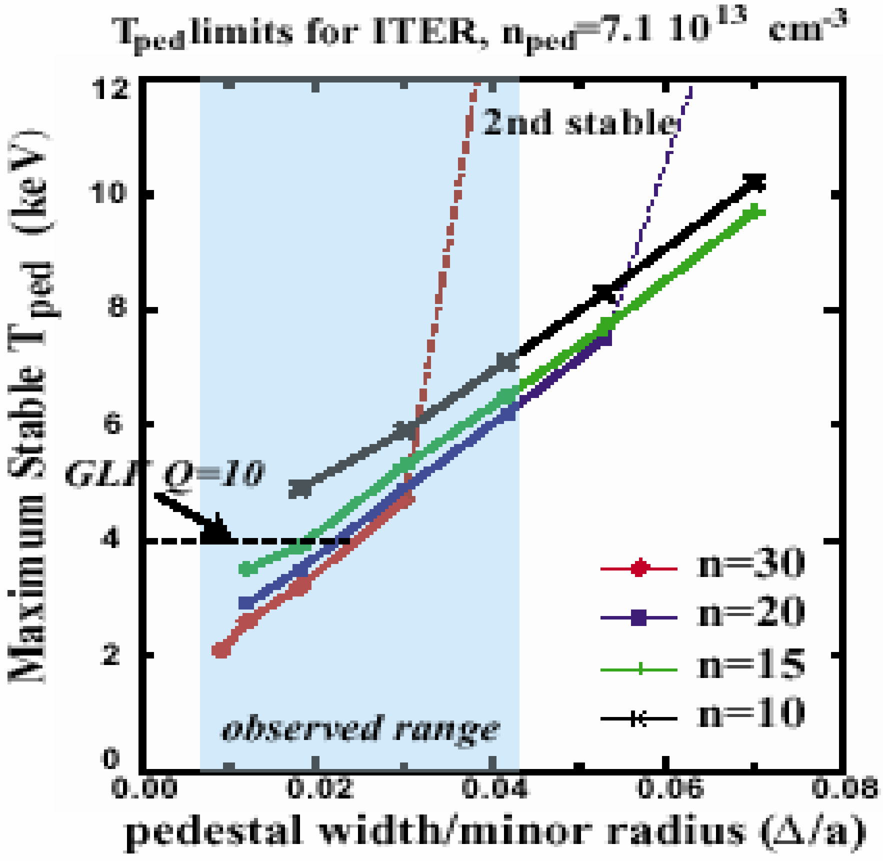
Can we predict pedestal parameters in ITER?

Shaping,β_p,density(=>bootstrap) are important for stability!

Pedestal width Δ remains a key uncertainty => input : Δ and density profiles, T_{ped} increases until stability boundaries for n=8-40 . High n modes limiting at narrow widths, go second stable at wider widths.

ELITE: Snyder NF '04





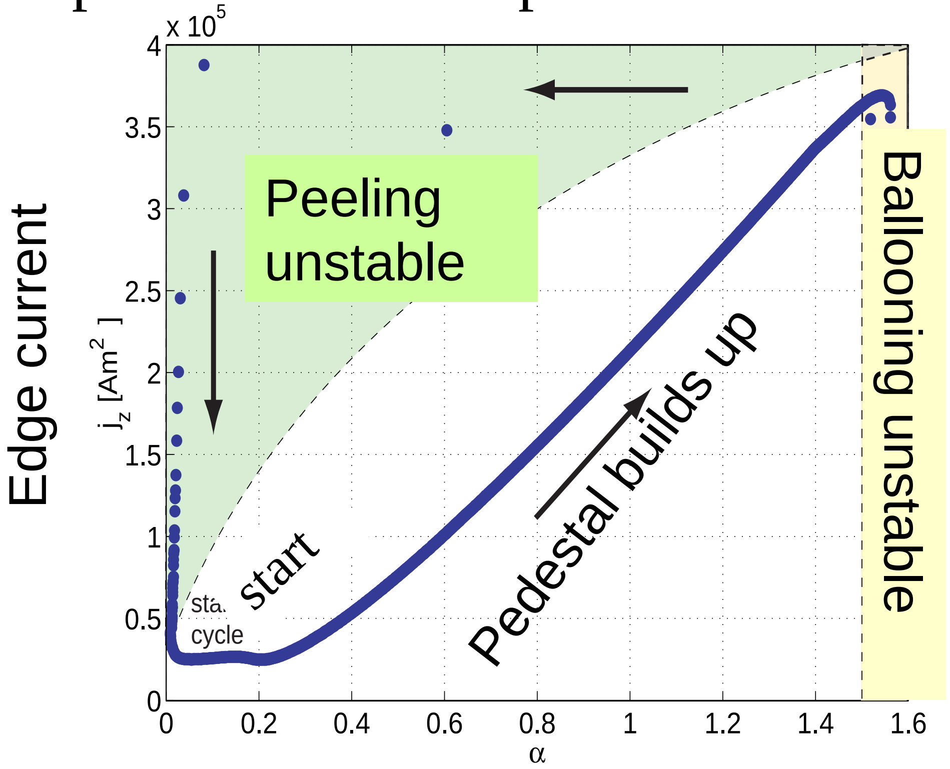
MHD motivated model for Type I ELMs in JETTO.

JETTO-1.5D transport code for $T_{e,i}$, n_e, $j_{//}$ (with bootstrap) diffusion. Transport coefficients in ELM area (~ETB) are proportional to the peeling and ballooning modes amplitudes, estimated from linear MHD theory.

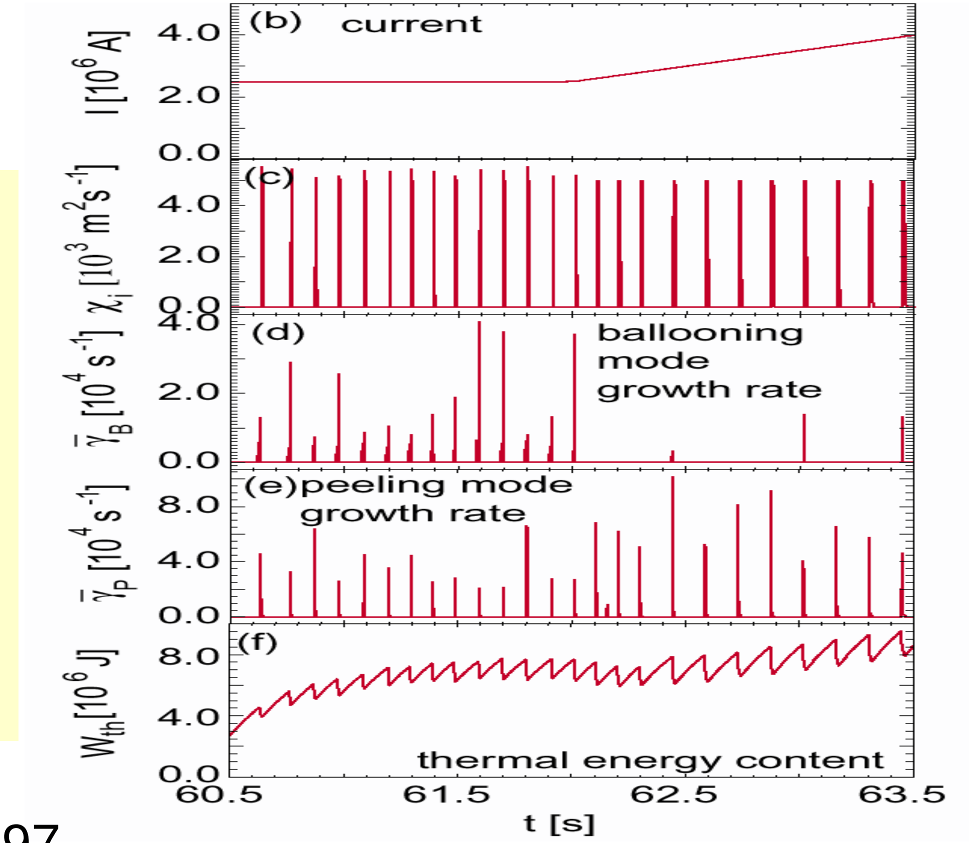
$$\partial_t \xi_{bal} = \gamma(\alpha - \alpha_{crit})\xi_{bal} + \ldots$$

$$\partial_t \xi_{peel} = \gamma_1 (j - j_{crit})\xi_{peel} + \ldots$$

$$\delta\chi^{ETB}_{\perp ELM} \sim (\xi_{bal} + \xi_{peel})e^{-(\frac{r-r_o}{\Delta})2}$$



Normalised pressure gradient α at ρ=0.97



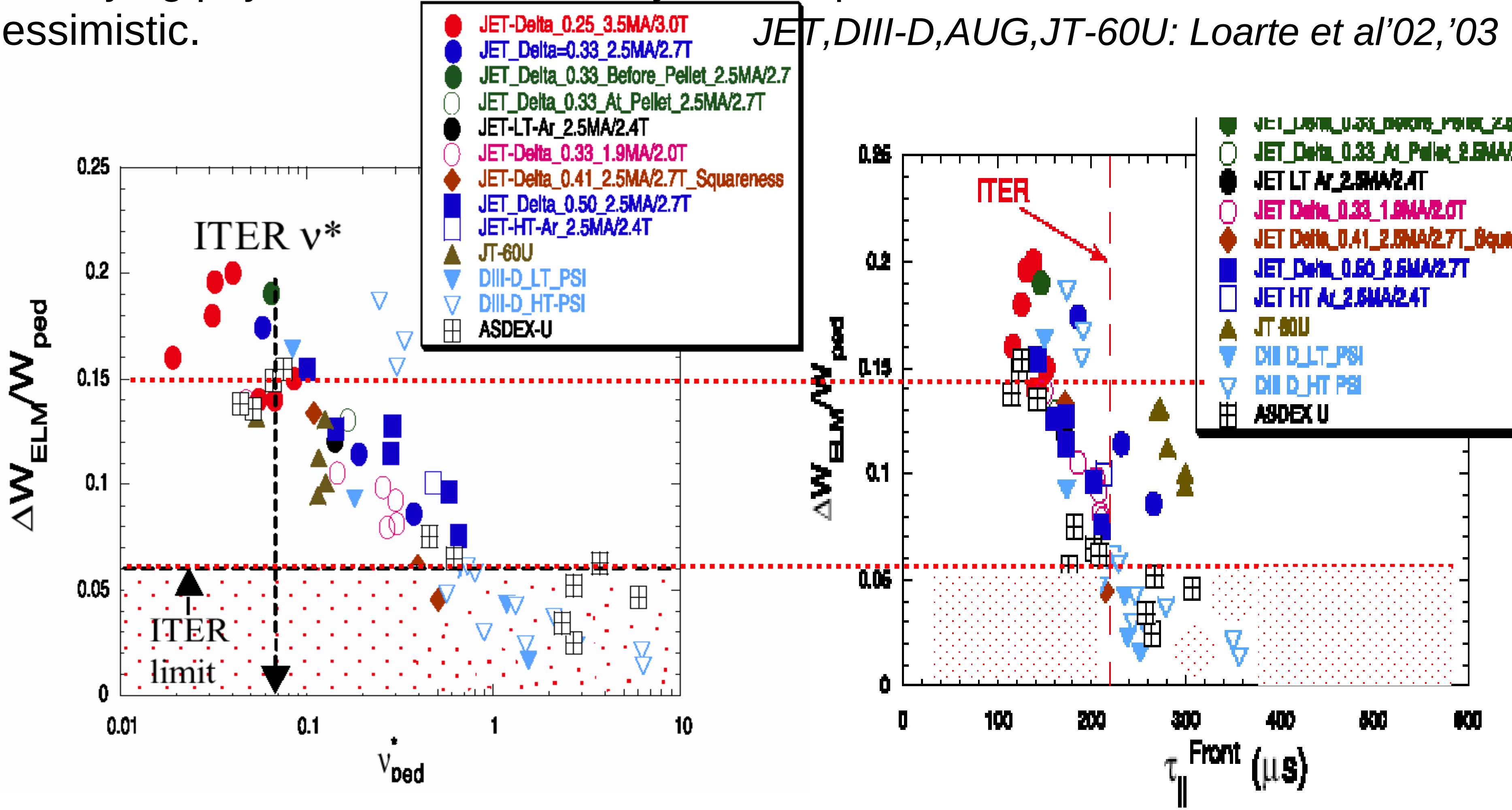
JET(JETTO): Lönnroth, Parail '04

Type I ELM size

Present theoretical models can't predict self-consistently losses in ELMs.

Experimental scaling: $\Delta W/W_{ped}$ decreases with $(n_{ped}, \nu^*_{ped}, \tau_{//}^{ion}, \ldots ?)$

Underlying physics is not identified yet. Extrapolation for ITER is more or less pessimistic.



JET,DIII-D,AUG,JT-60U: Loarte et al'02,'03

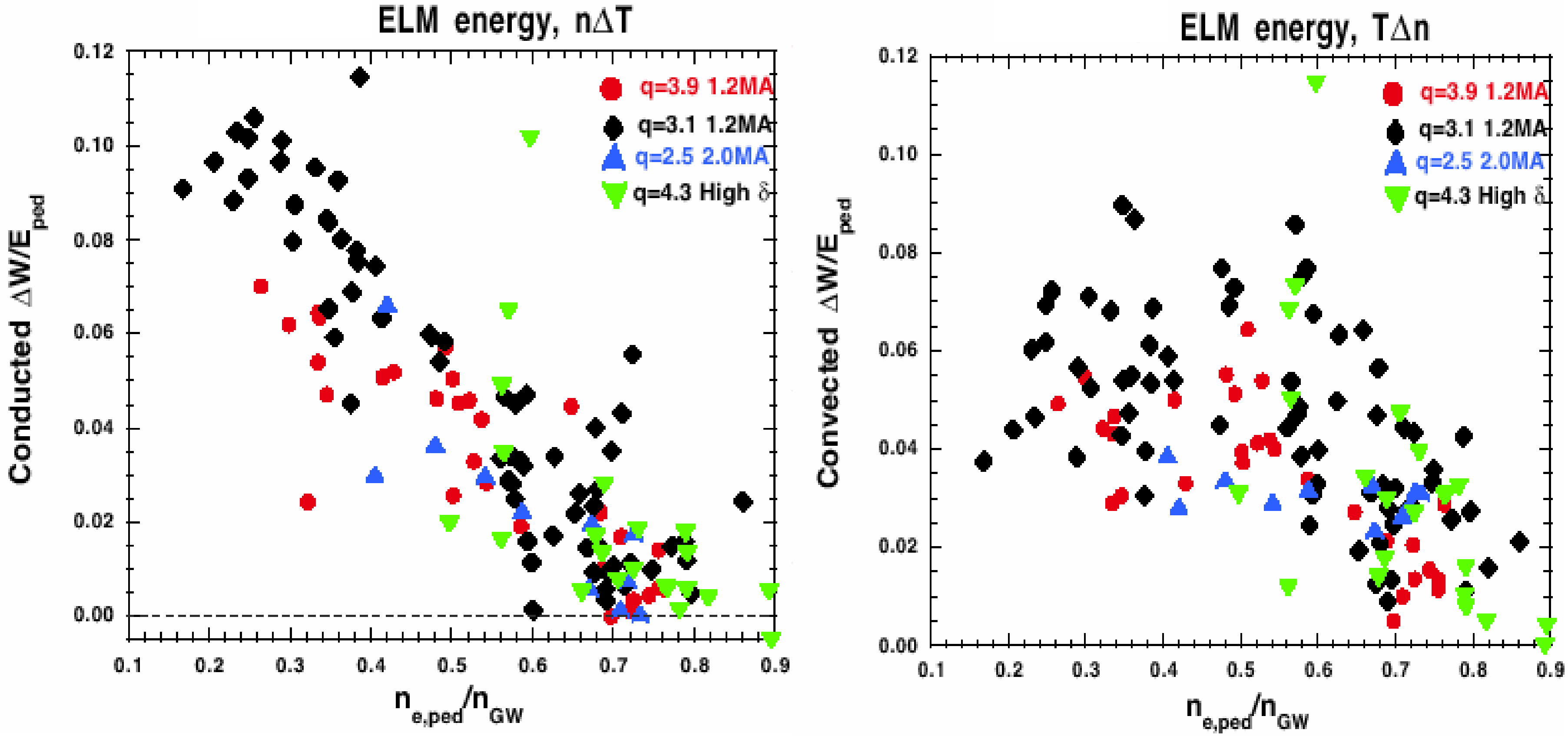
Conductive and convective losses.

$\Delta W_{ELM} \sim n\Delta T_{ELM}$ (conductive) + $T\Delta n_{ELM}$ (convective).

decreases when n_{ped} ↗ ~small change with n_{ped},

At high density (ν^*?): only particle “minimum” Type I ELMs *(DIII-D, JET, MAST, JT-60U).* Not explained by theory.

DIIID: Leonard’01, similar JET Loarte’02



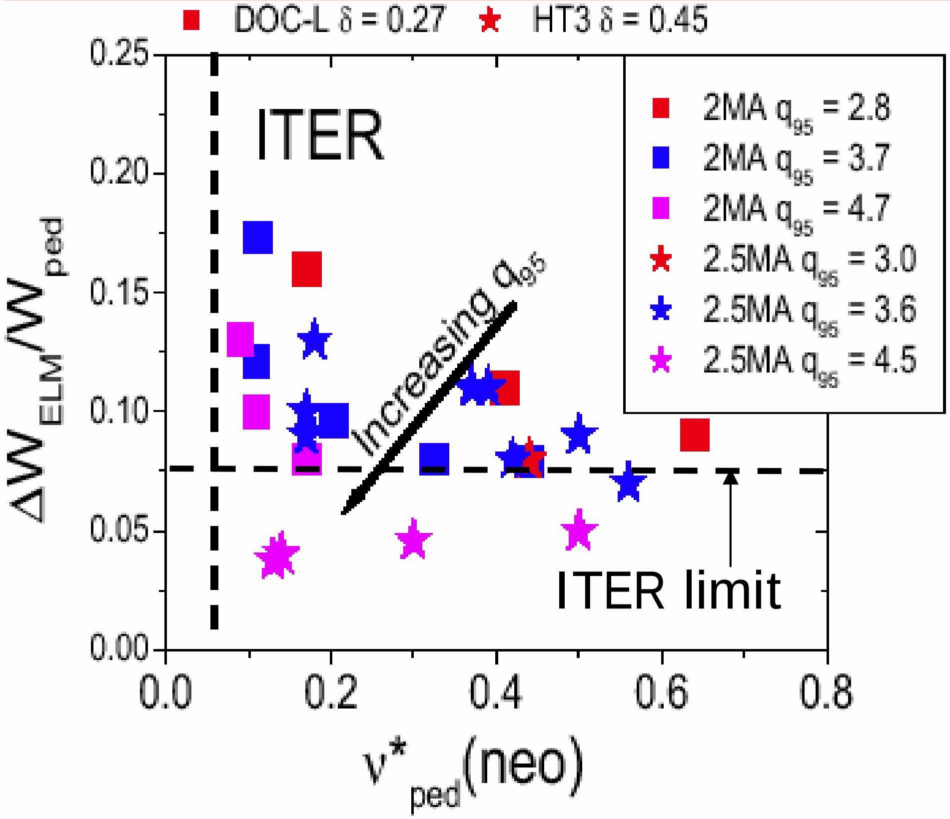
Minimum convective ELMs at high q_{95} or(and) high n_{ped}.

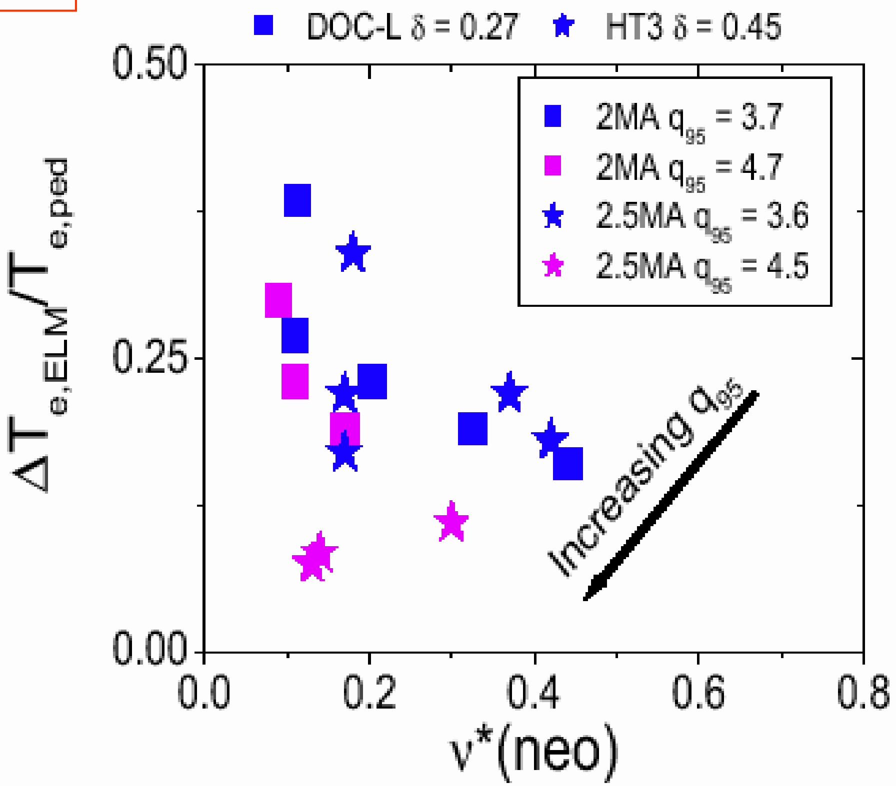
Conductive losses $\Delta T_{ELM}/T$ decreases:

- with density (ν*?)
- at higher q_{95} (=4.5) + high δ~0.45 even at low ν*~0.1!

Small convective ELMs: $\Delta W/W_{ped}$<5%.

JET: Loarte'04

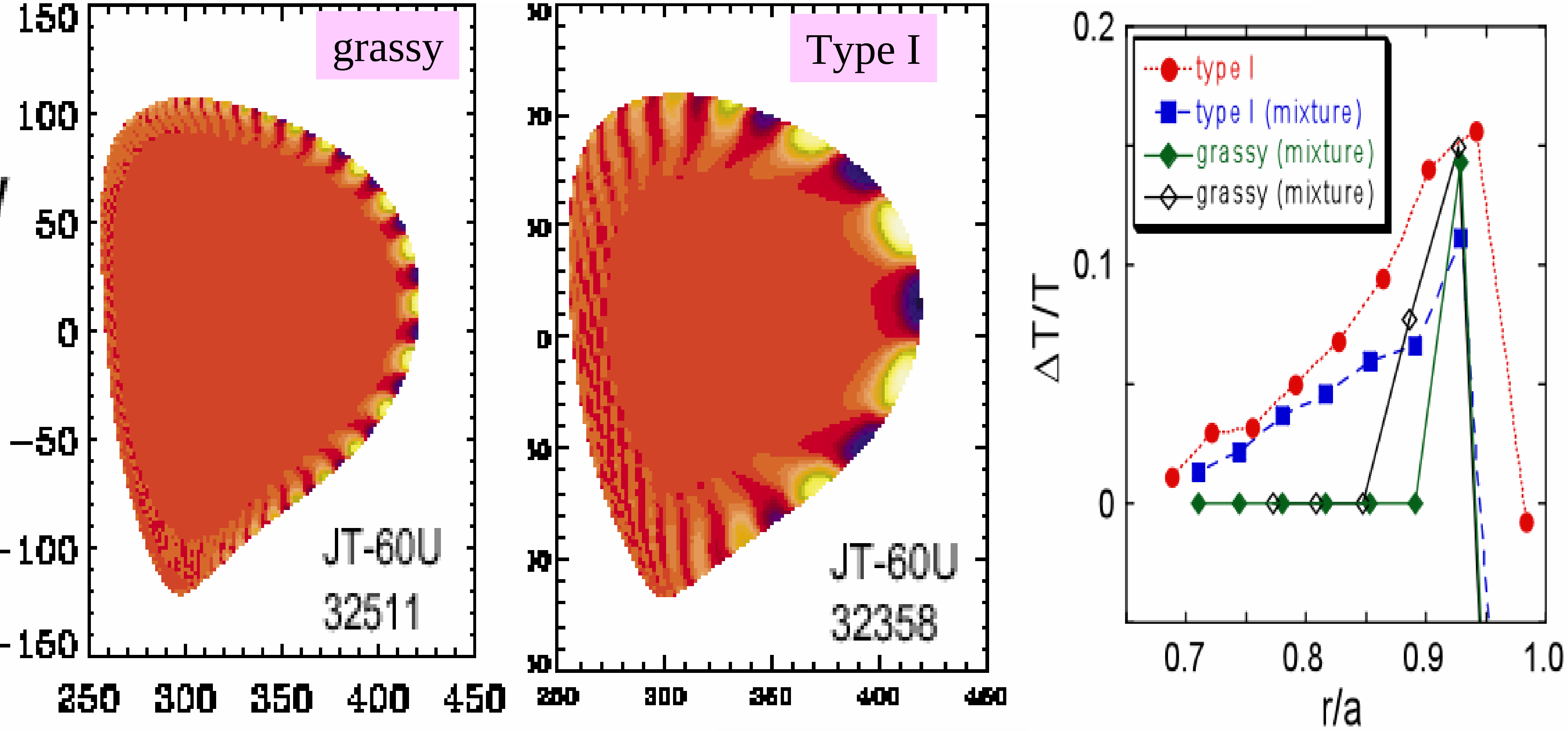




Smaller affected area =>smaller ELMs?

Ideal MHD stability codes+ experiments (JT-60U, AUG, JET, DIII-D)=> Factors decreasing ELM area: high triangularity δ, high q_{95}, high edge magnetic shear, high density. Density effect: bootstrap current is lower, increased transport through ETB, pedestal widths?…

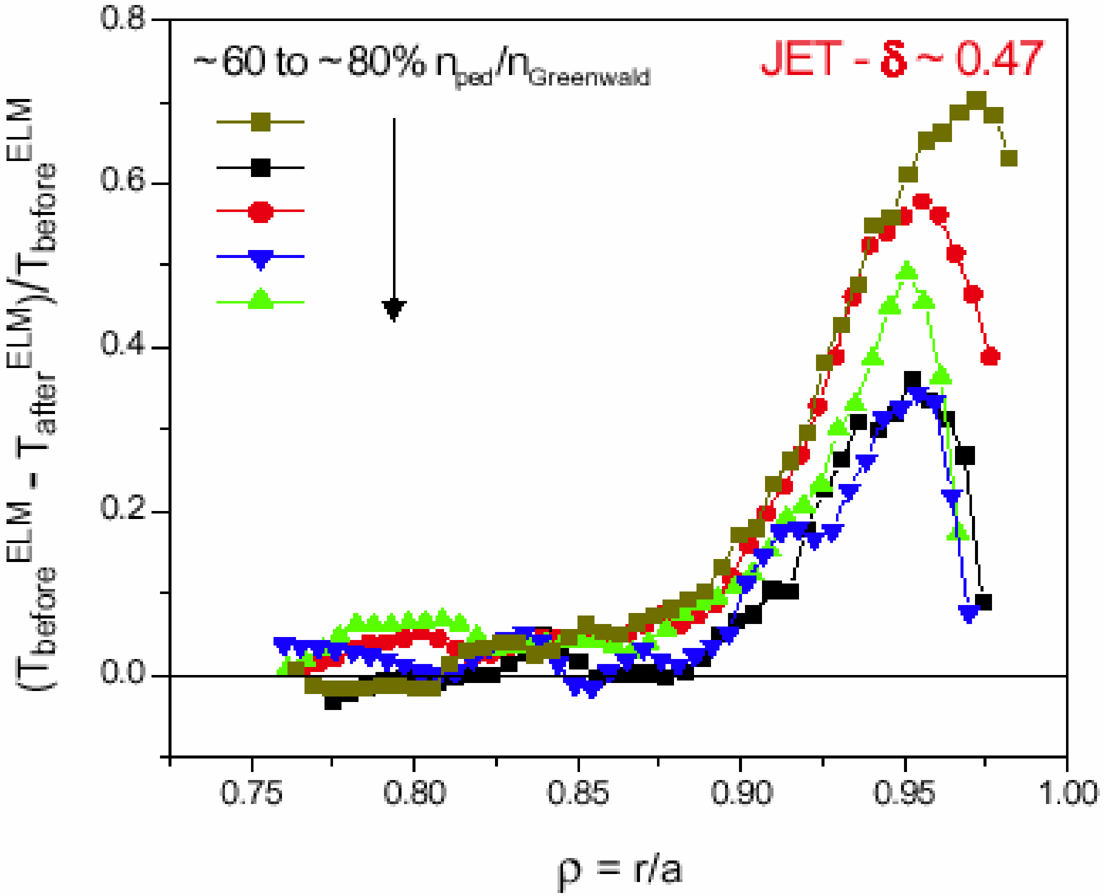
JT-60U(ELITE):Lao’00, Snyder,’02, Kamada’02, Oyama’04



ELM affected area <=≠>energy and particle losses.

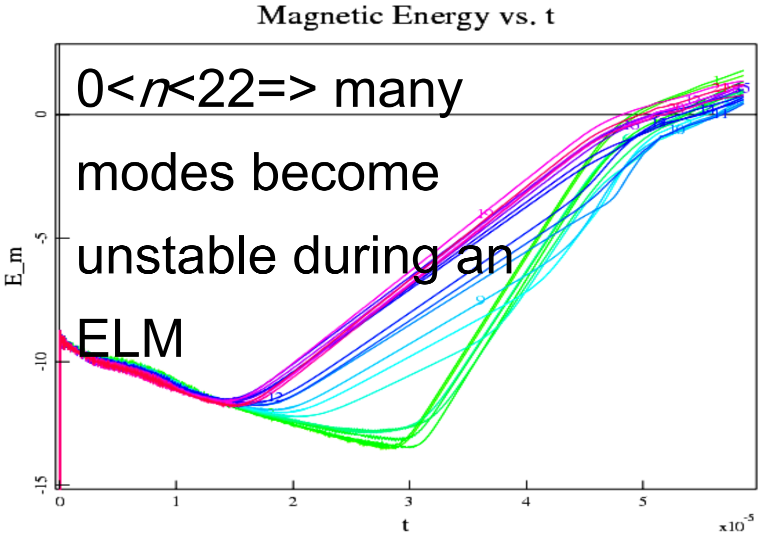
ELM energy loss is not connected with ELM area in a simple way. Mainly $\Delta T_{ELM}/T$ decreases for smaller ELMs. Challenge for theory.

JET: Loarte'03



Non-linear MHD:

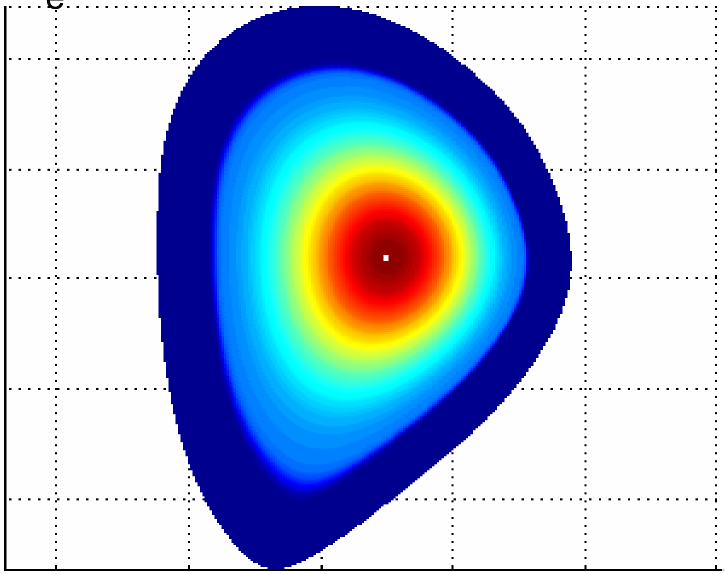
NIMROD *(A. Pankin)*



0<*n*<22=> many modes become unstable during an ELM

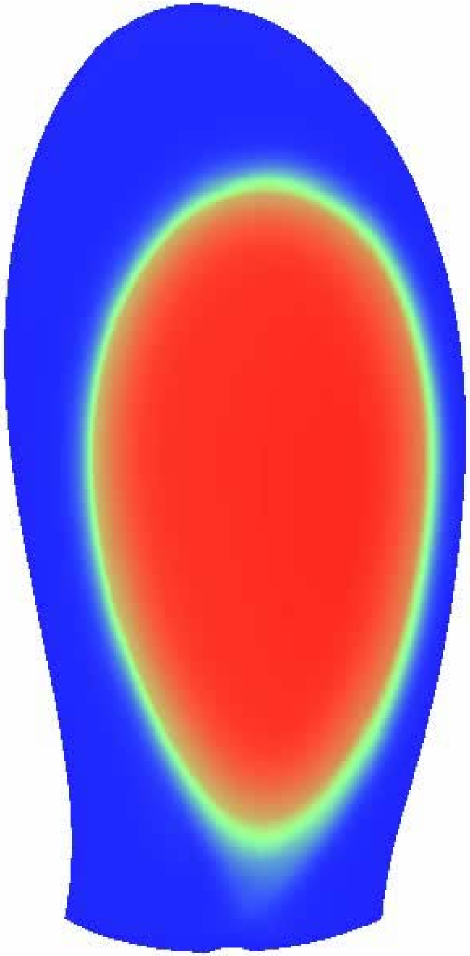
time

T_e: conductive « blobs »



JOREK *(G. Huysmans)*

n_e: convective (due to EXB) « blobs »



TELM*(Becoulet):*MISHKA+non-linear heat transport

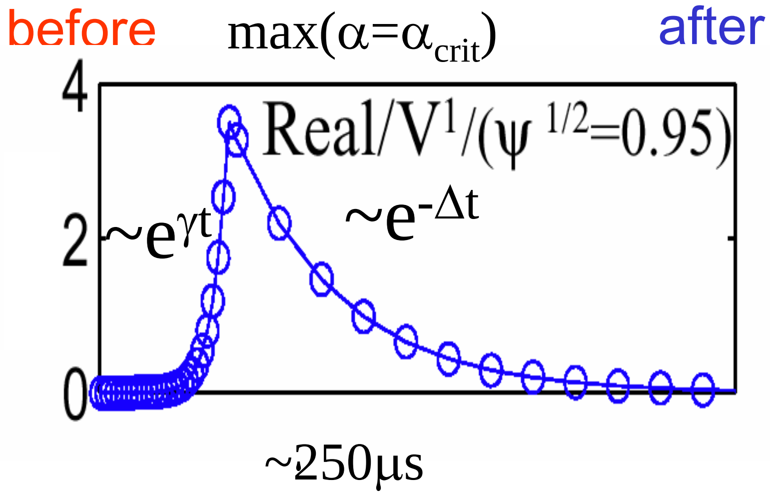
$$\frac{3}{2}\frac{\partial n_e T_e}{\partial t}+\vec{\nabla}\cdot\vec{\Gamma}=S_{loss}$$

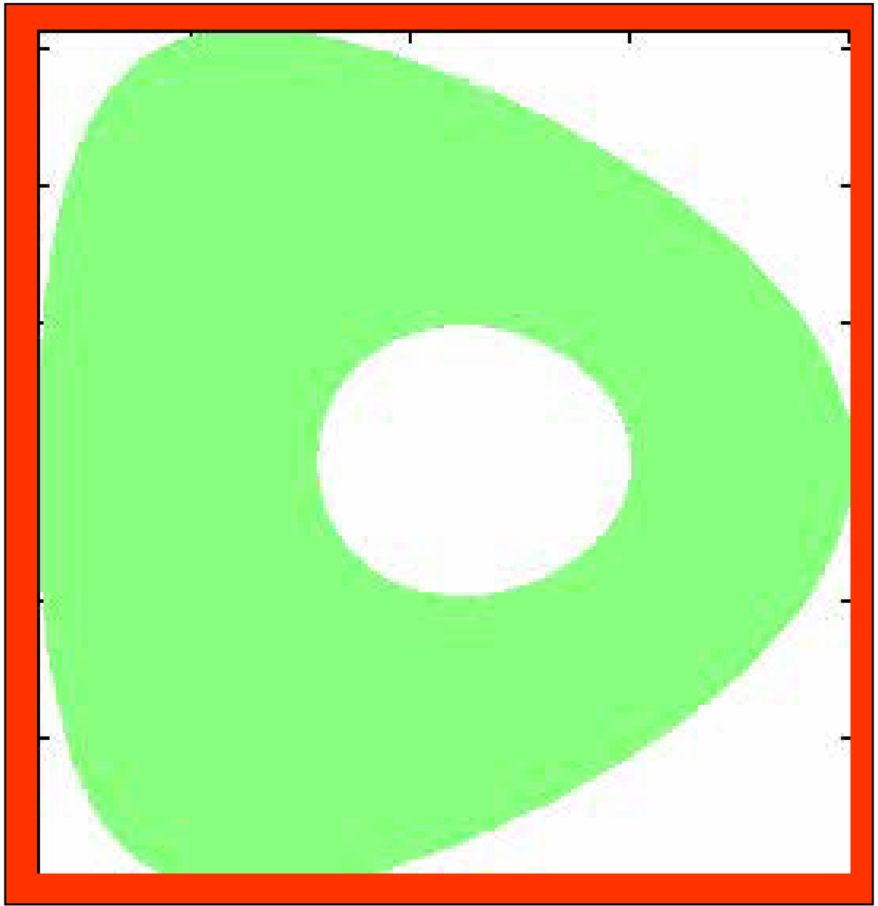
$$\vec{\Gamma}=-\chi_{//}\cdot\vec{\nabla}_{//}T_e-\chi_{\perp}n_e\cdot\vec{\nabla}_{\perp}T_e+\vec{V}_{MHD}\cdot\frac{3}{2}n_eT_e$$

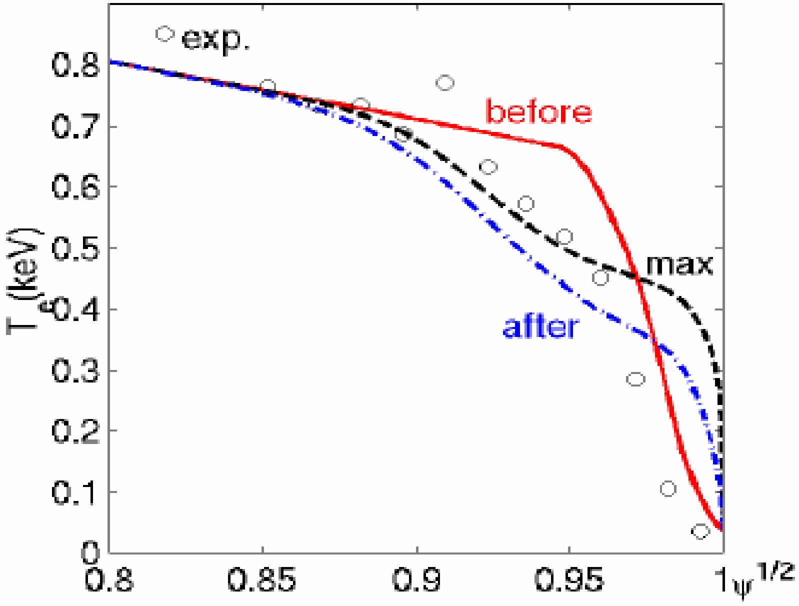
Conductive

Diffusion

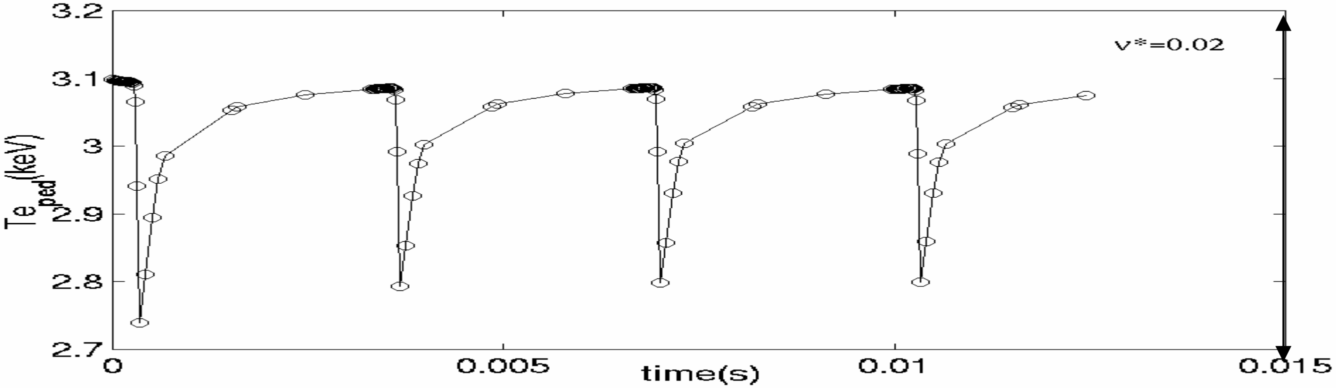
Convective

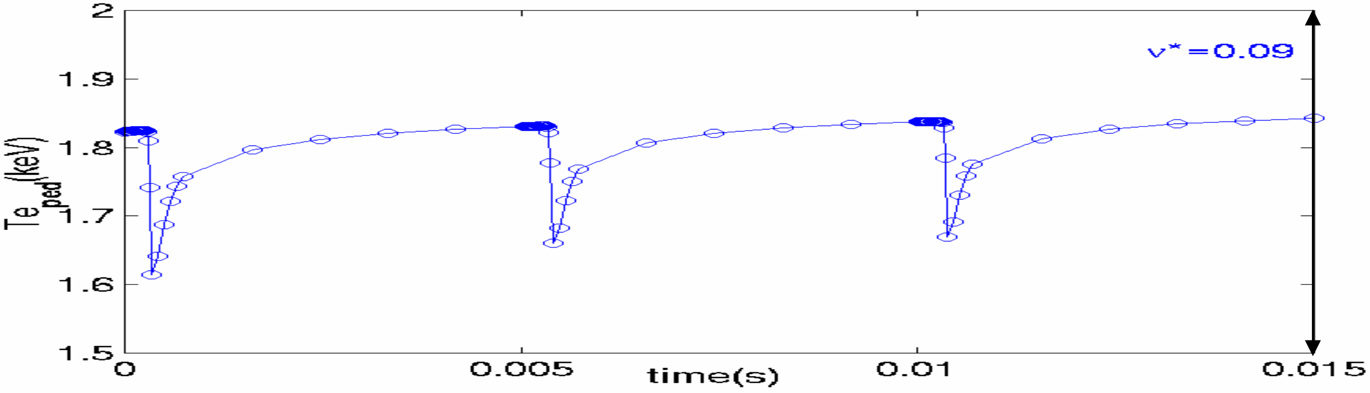


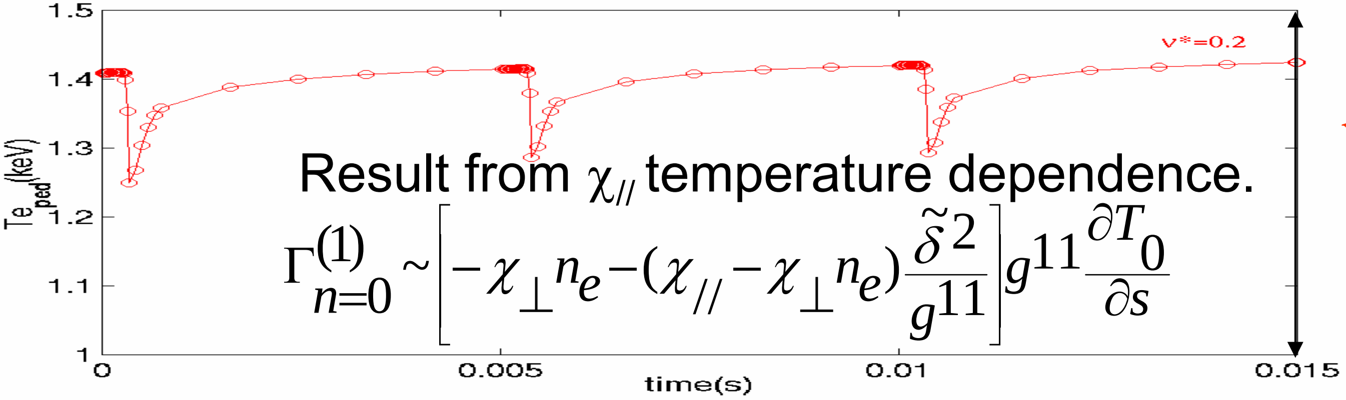




Conductive losses in ELM decreases with ν^* ↗







Result from $\chi_{//}$ temperature dependence.

$$\Gamma^{(1)}_{n=0} \sim \left[-\chi_{\perp} n_e - (\chi_{//} - \chi_{\perp} n_e)\frac{\tilde{\delta}^2}{g^{11}}\right] g^{11}\frac{\partial T_0}{\partial s}$$

ν^* increases

time(s)

ELMs control: understanding=>integrated modelling?

External control of ELMs.

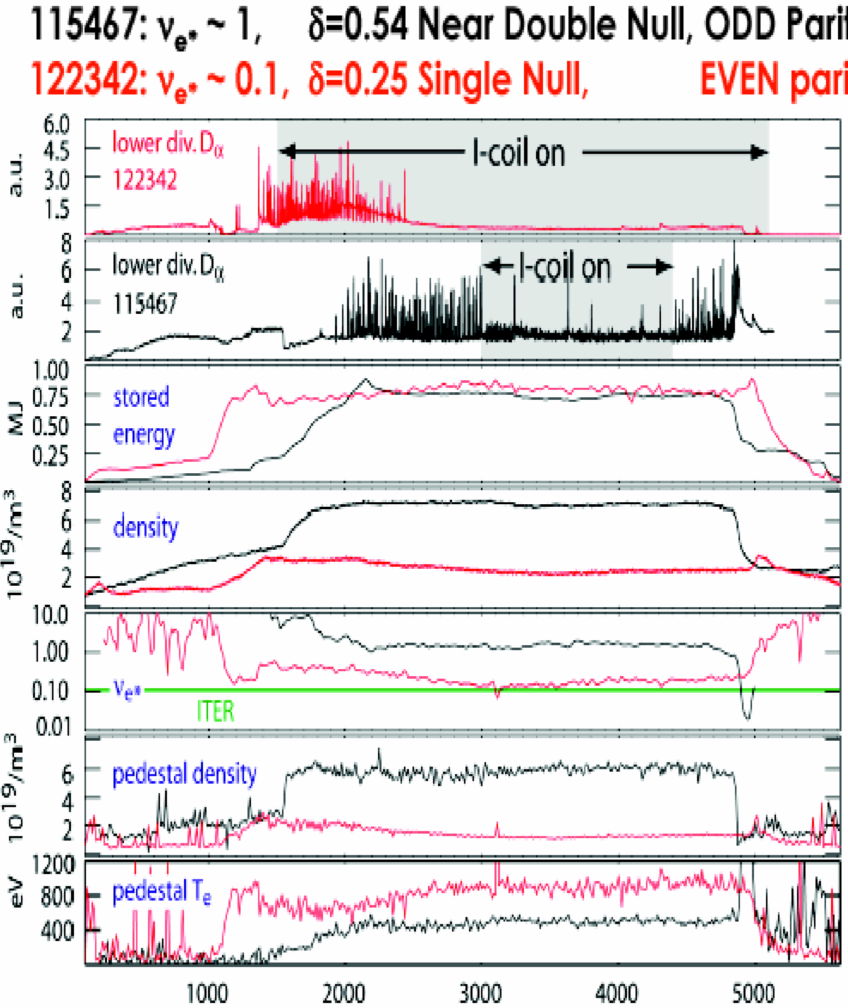
-Stochastic boundaries (DIII-D,pre-project for JET,ITER);
-Magnetic ripple (JT60-U,JET,ITER?);
-Pellet injection (AUG, project for JET,ITER?);

Understanding? =>Integrated Modelling? =>Tests on JET before ITER?

Understanding of DIII-D ELM suppression?

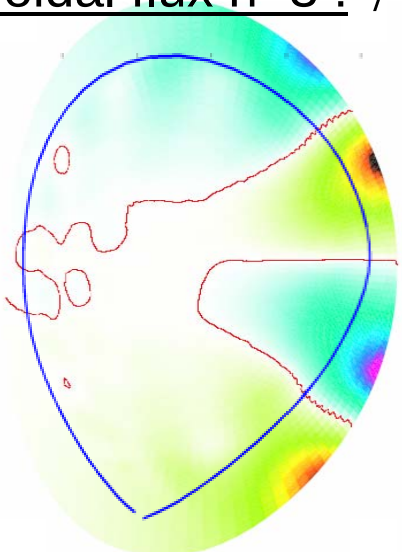
Why not heat $\chi_{erg}^{eff} \sim \chi_{//} \sum_{mn} (B_{mn}^{(1)})^2$,but particle (EXB?) transport?

Role of rotation?

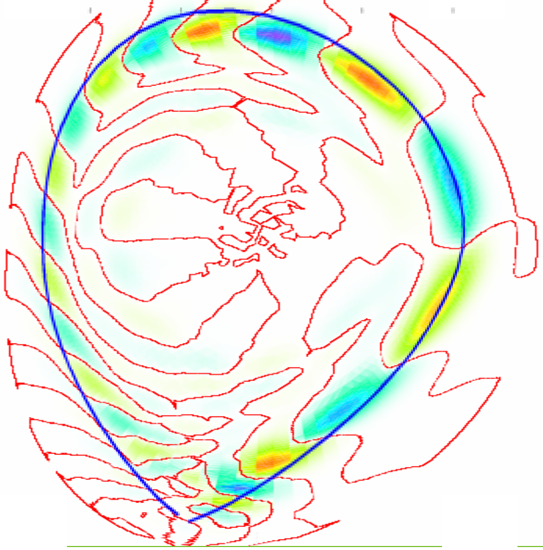


- Stored energy and H factor remain high
- In contrast to ordinary ELM free H-mode, no density or radiation run away
- In contrast to QH-mode, co-NBI-injection was used and no edge harmonic oscillation observed

Poloidal flux n=3 : $\psi_{pol}^{n=3}$



Density n=3 : $n_e^{n=3}$



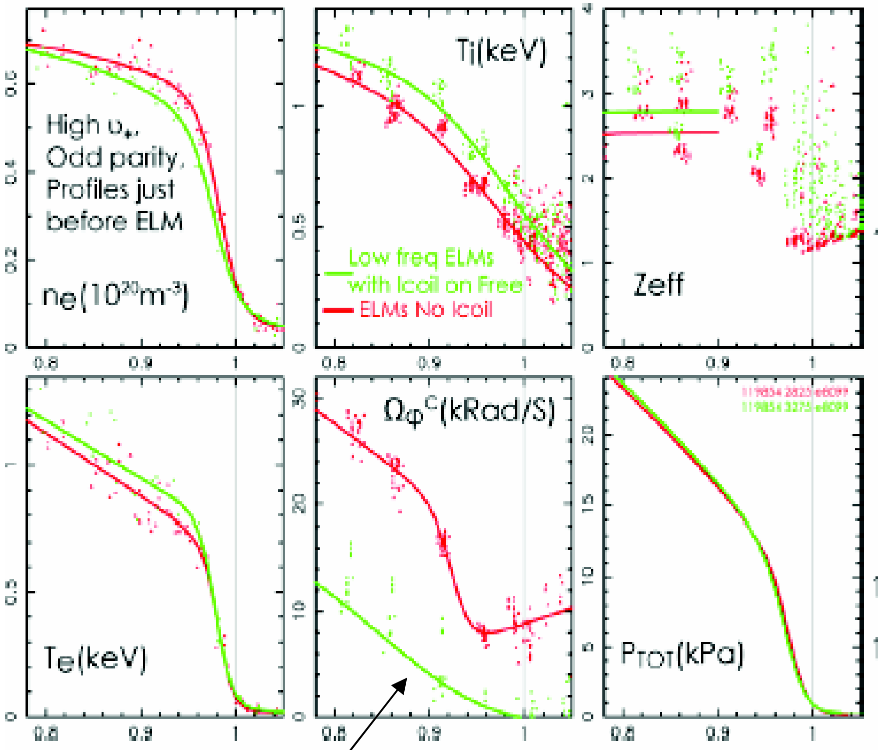
E. Nardon, JOREK(G. Huysmans)

Role of rotation and ν*? Comparison with TEXTOR?

Osborne EPS2005

High ν*

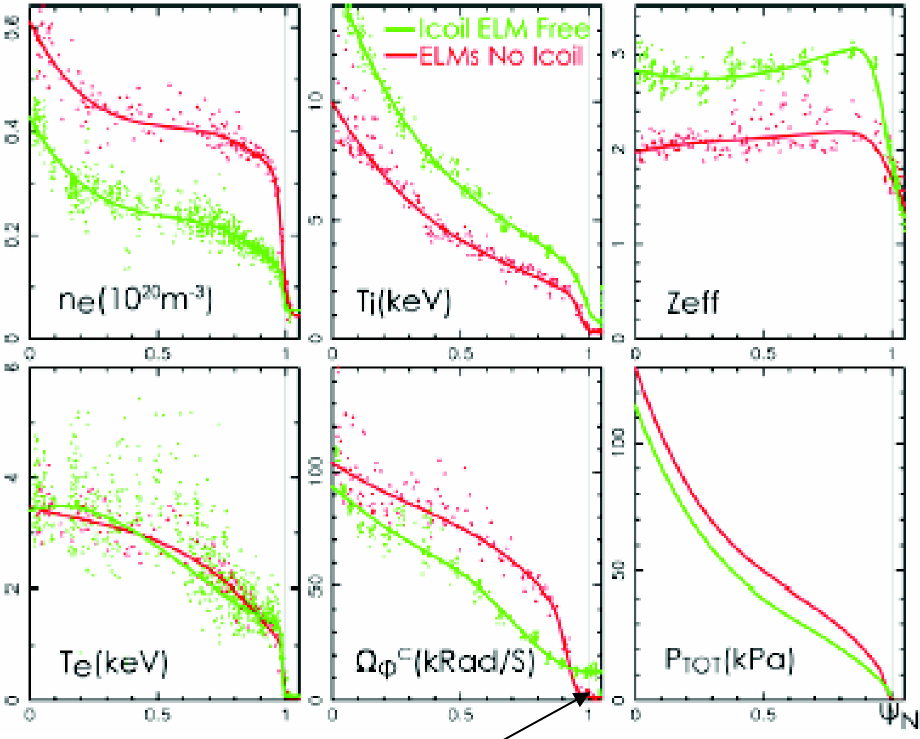
- Except for toroidal rotation, all profiles similar
- ELM frequency reduced by a factor of 5
- Profiles are average over last 20% of inter-ELM phase



Plasma braking in the core

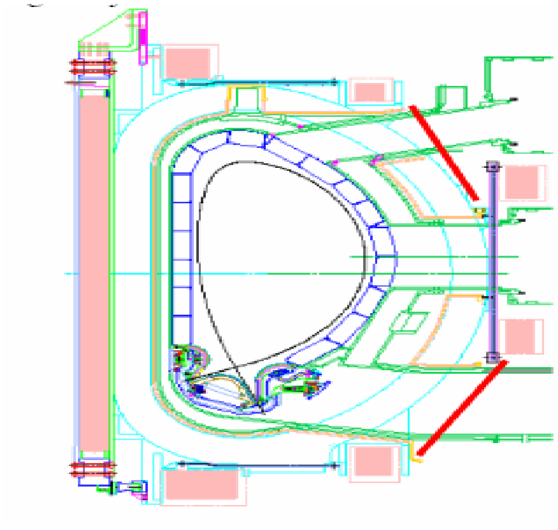
Low ν*

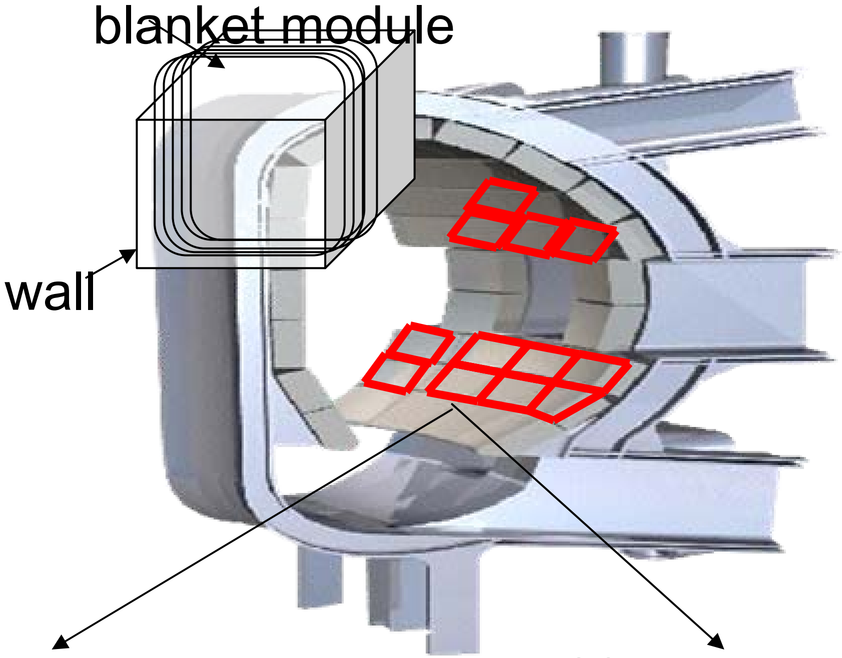
- Primary affect on profiles with Icoil is reduced n_e
- Plasma stored energy and H not reduced as strongly as p_{ped} due to increase in T_i at low n_e



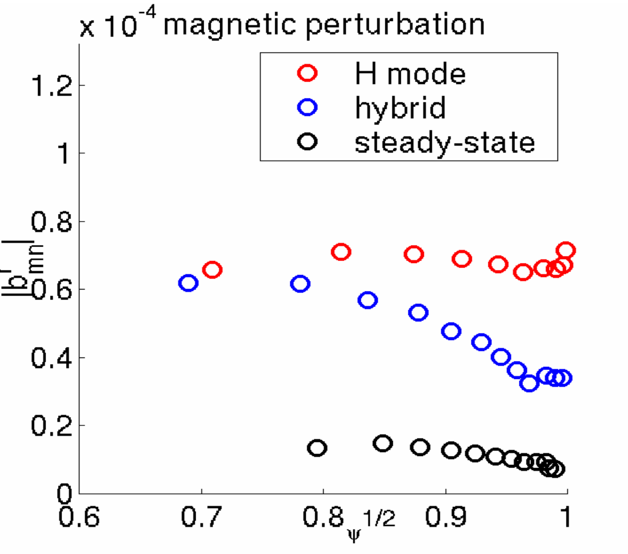
Acceleration in the edge,braking in the core

Design of ergodic coils for ITER: external or inner coils?

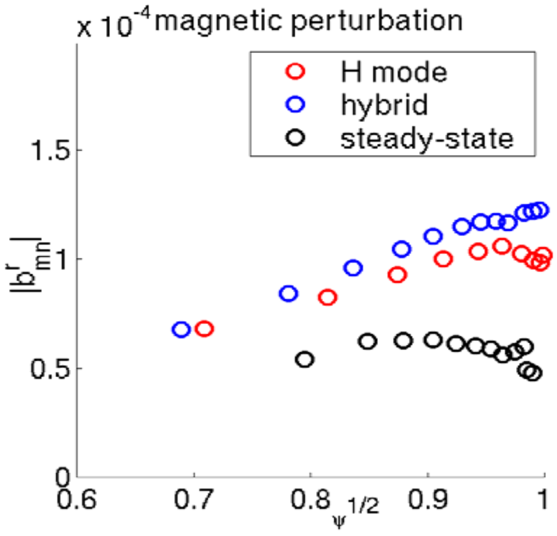




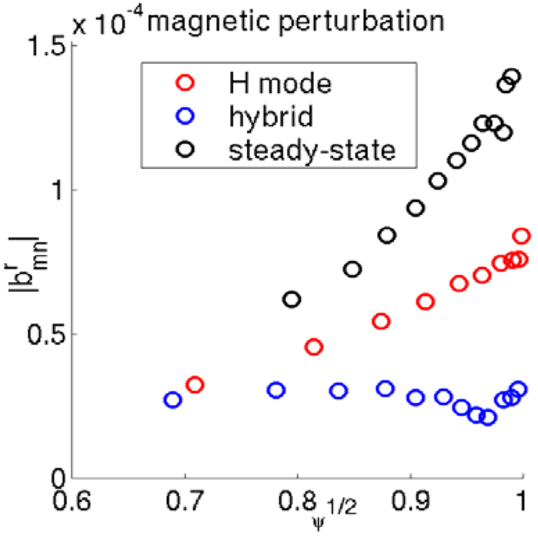
External coils: 400kA for H-mode,
Not adapted to hybrid and ITB.



Inner coils: 20kA « ++++ »

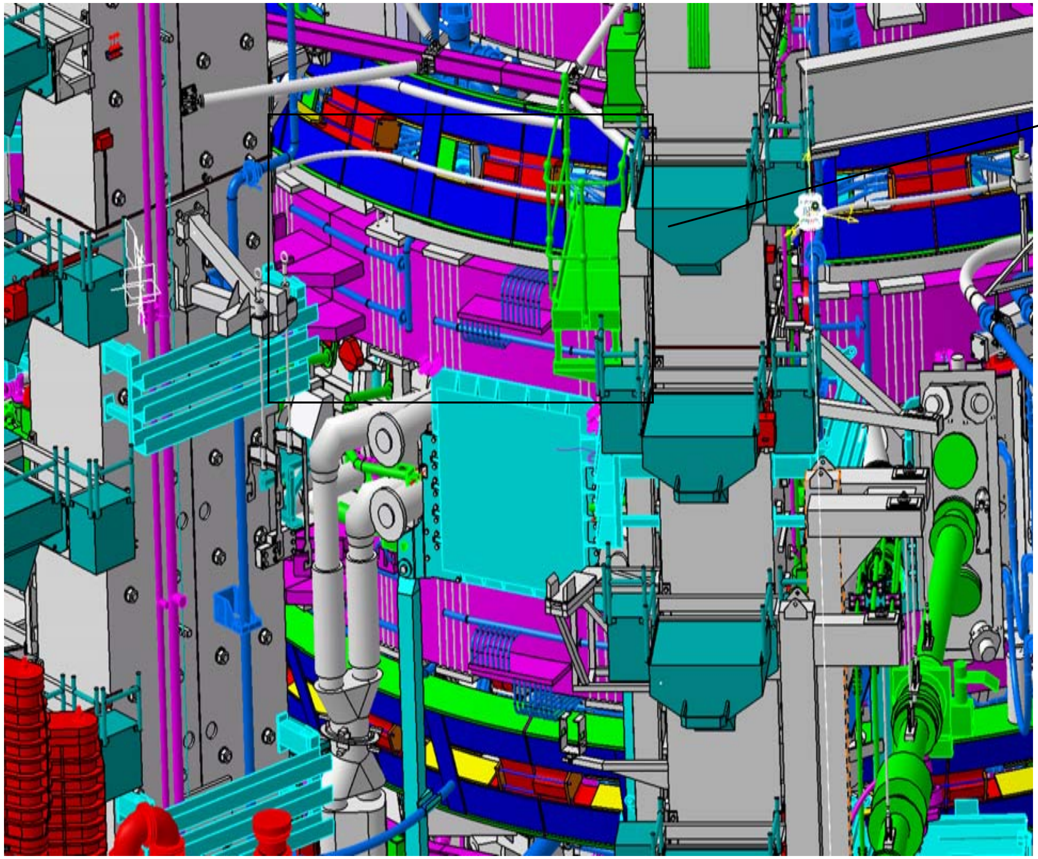


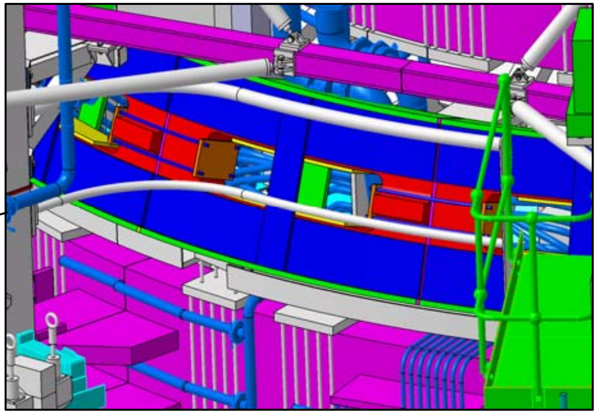
20kA« +--+ »

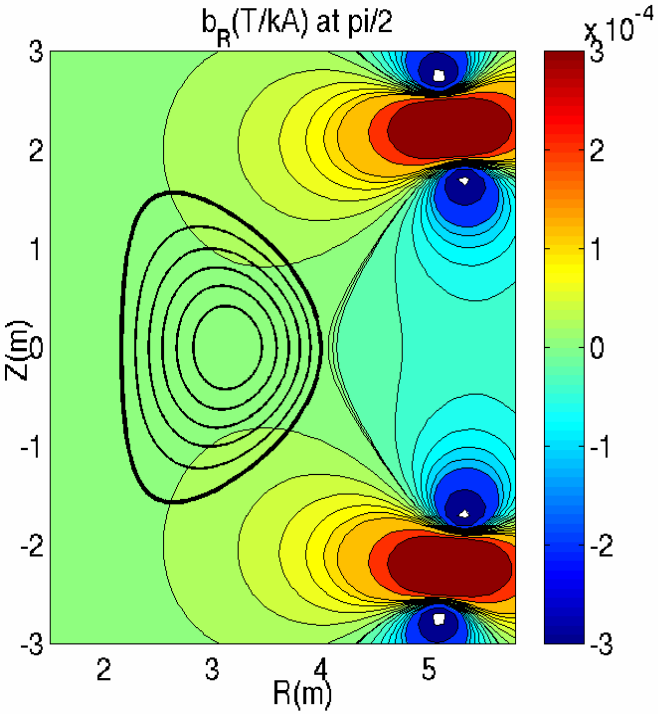


Ergodisation Coils for JET – Pre-Engineering Phase

P. Thomas,, G.Agarici A.Saille, J-M Verger



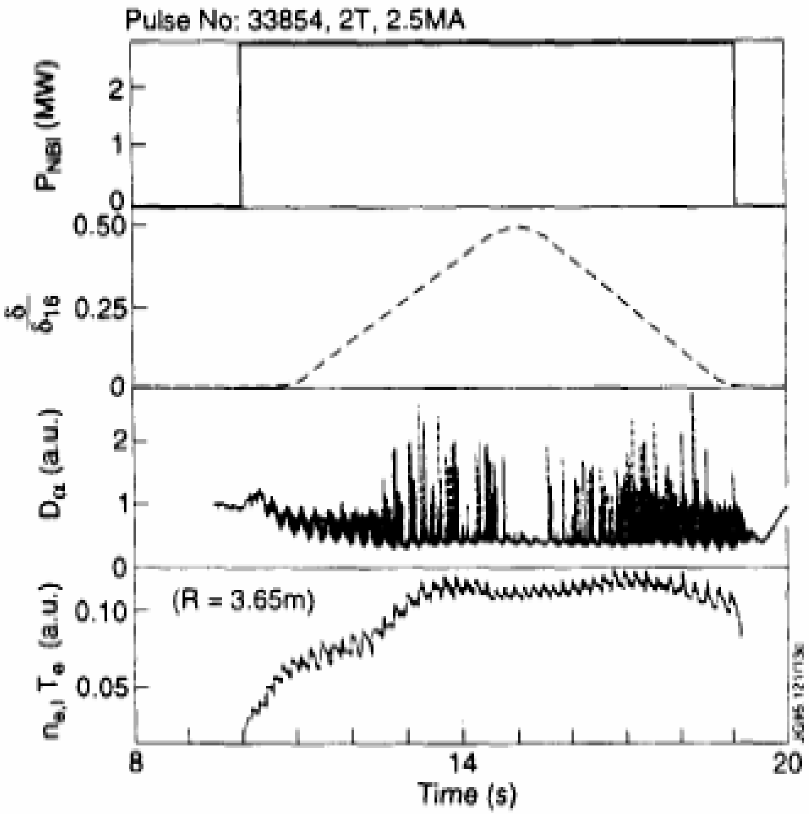


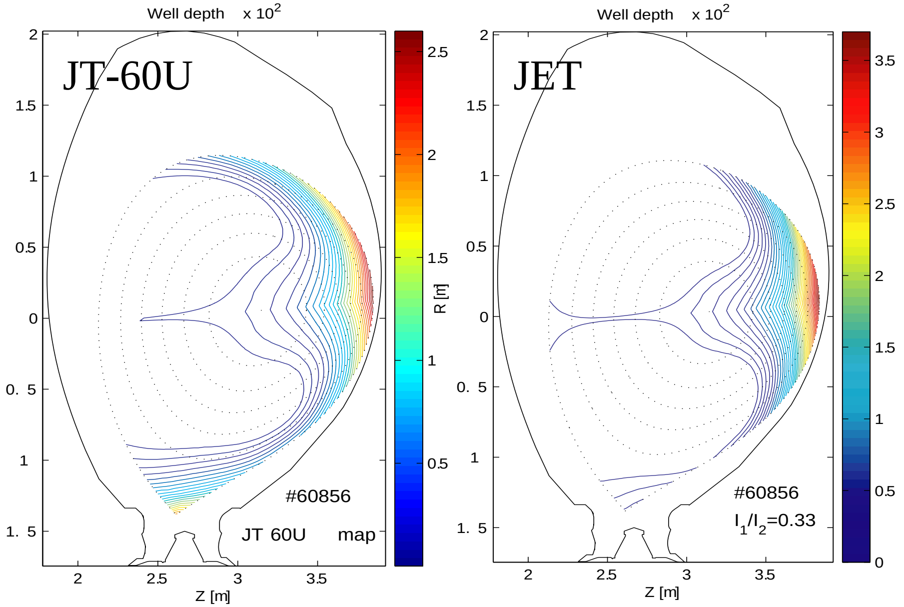


Magnetic Ripples to control ELMs? Can it be used in ITER?

JET experiment 1995,comparison JT60-U and JET *(G. Saibene ,N. Oyama et al),*
JETTO,ASCOT modelling (*V. Parail et al)*

$$\chi_{i,th} \sim \frac{0.5\delta^{3/2}}{\upsilon_i}\left(\frac{Nq\delta}{\varepsilon}\right)^3\left(\frac{T_i}{e_i BR}\right)^2$$





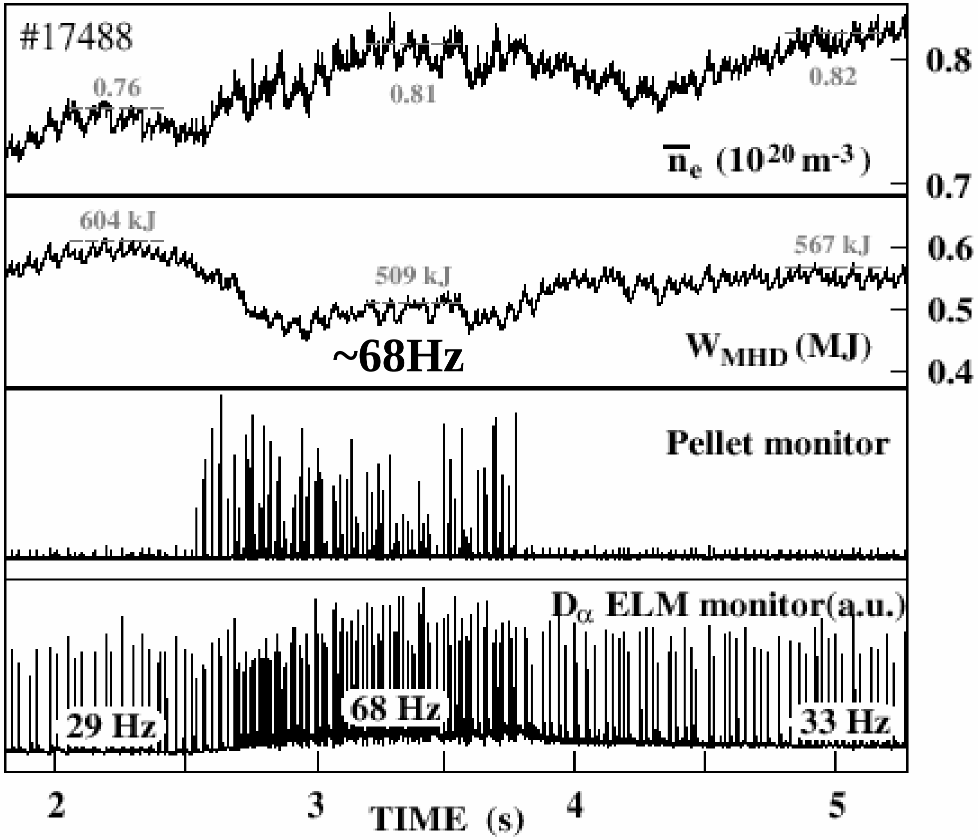
Collisionality regimes:

- High: (these particles oscillate between banana and ripple trapped state in a diffusive way)
- Low: non-diffusive losses . But what about fast particles losses (NBI,alphas?)

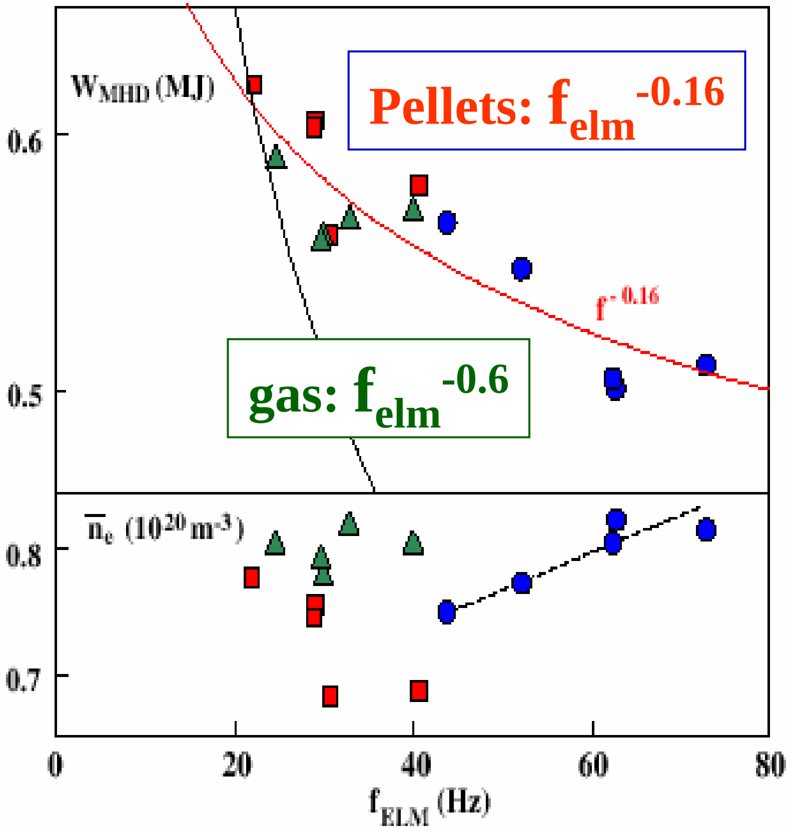
ELM triggering and control by small pellets (AUG).

Pellets trigger ELMs with frequency of f_ pellet injector > f _intrinsic ELM.

AUG:Lang'03



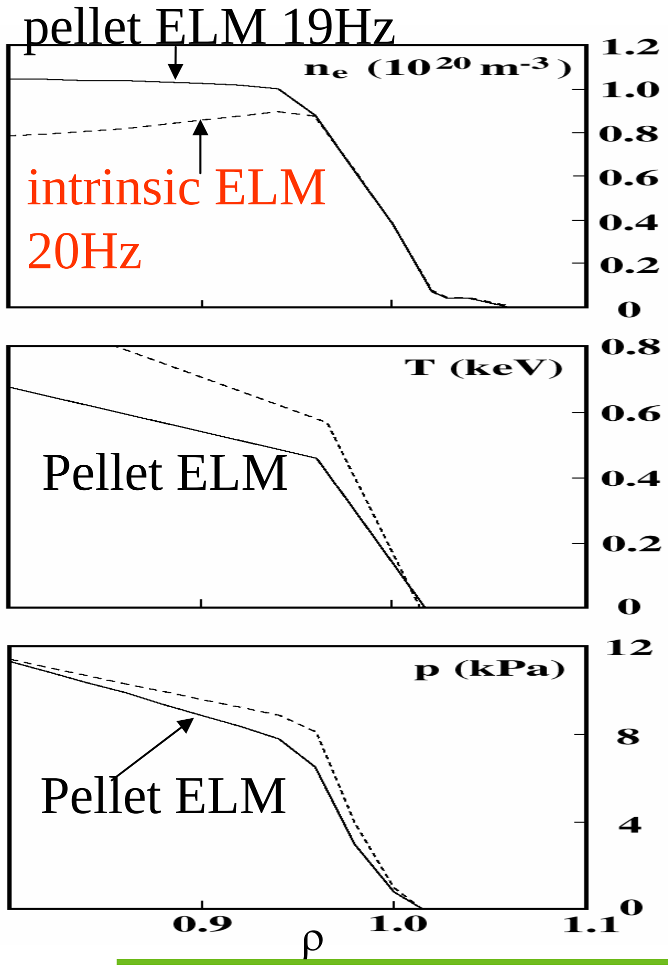
Fuelling can be minimized with pellets as compared to gas leading to small ELMs with higher confinement.

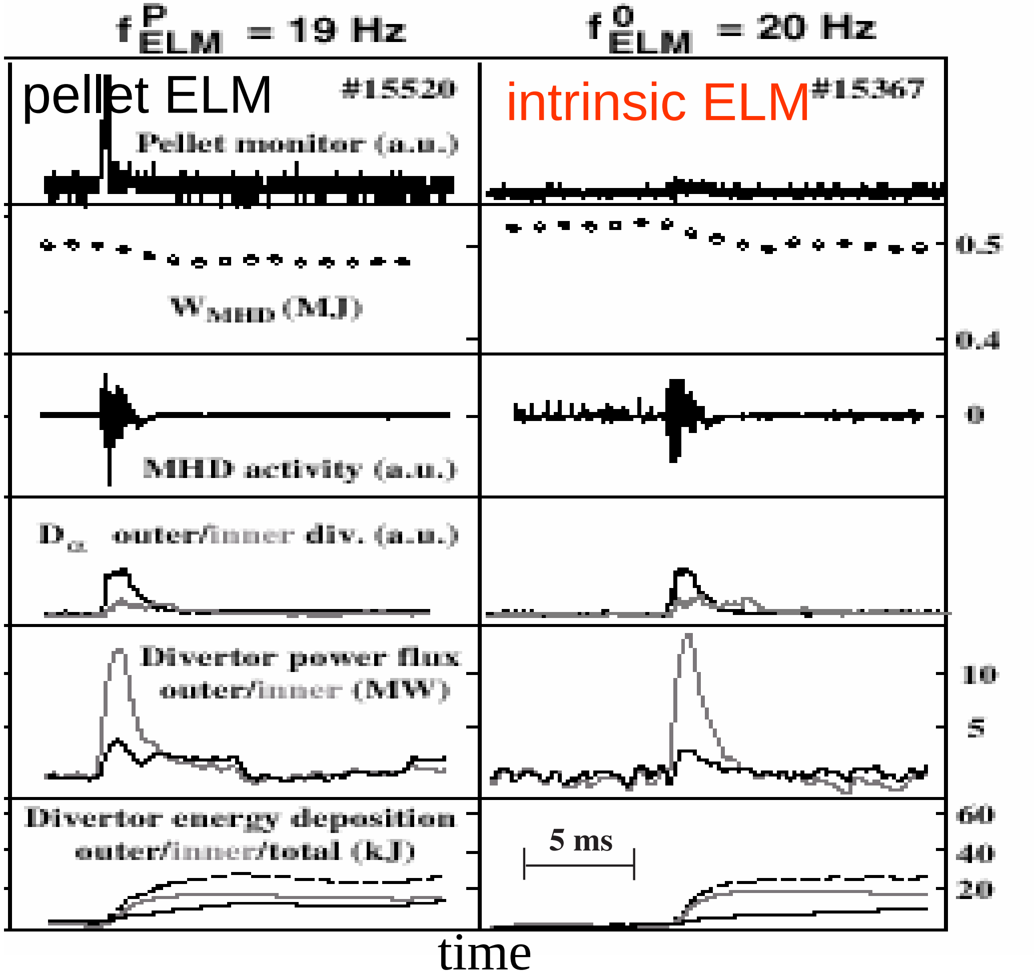


Pellet triggered and intrinsic ELMs are similar if f_{ELM} is the same.

gradP is lower with pellet=>Why pellet triggers an ELM?
ELM is triggered after ~200µs ~20% of pellet mass was ablated =>transient 3D plasmoid=> Linear MHD is limited, but measured MHD activity is similar=> the same peeling-ballooning mechanism?

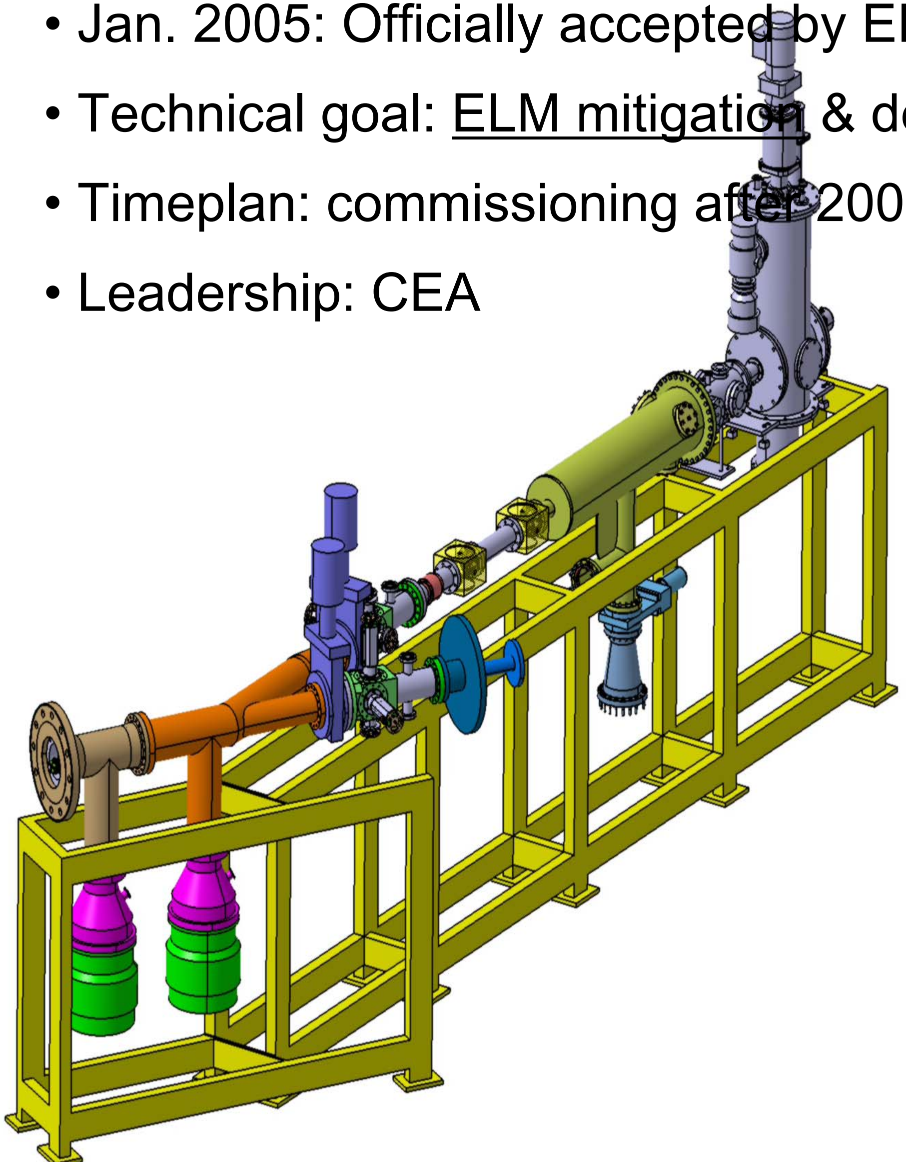
AUG:Lang'03

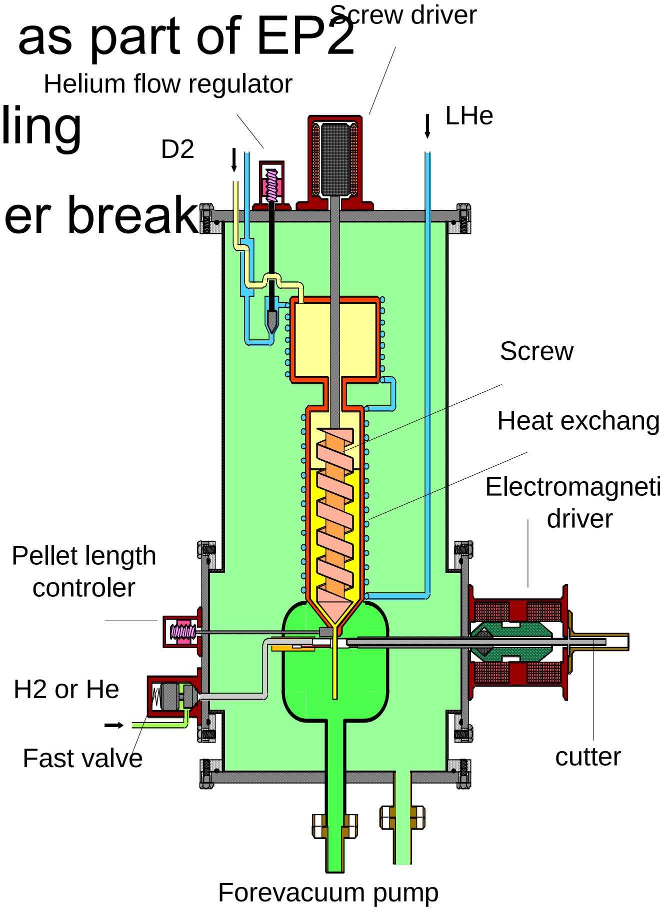




High Frequency Pellet Injector (HFPI) for JET

- Dec. 2004: Welcomed by STAC
- Jan. 2005: Officially accepted by EFDA SC as part of EP2
- Technical goal: ELM mitigation & deep fuelling
- Timeplan: commissioning after 2007 summer break
- Leadership: CEA



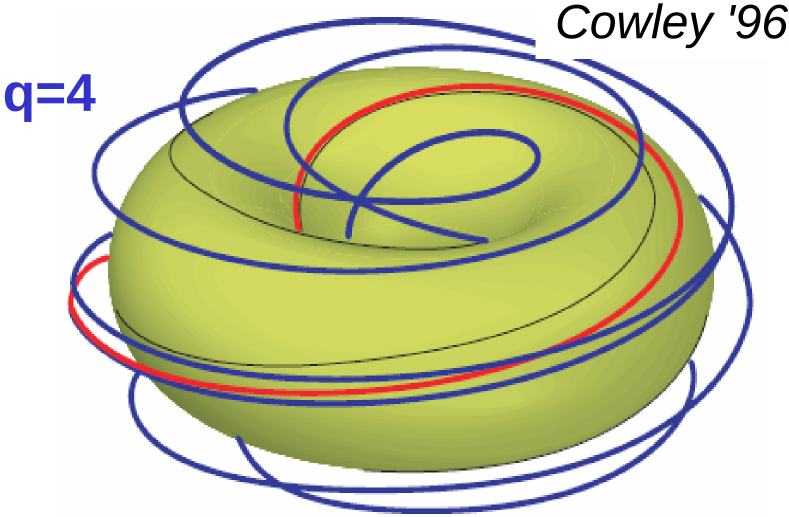


END

Early non-linear phase of ballooning instability.

Finger-like torolidaly localised structure. Explosive time scale: $(\tau_E\ \tau_A^{2})^{1/3} \sim 50\mu s$(JET)

Cowley '96, '03



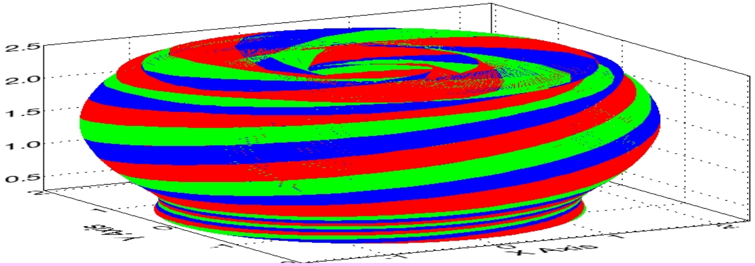
q=2(stable phase)=>q=2(unstable)

$$\partial_t\xi=\gamma(\alpha-\alpha_{crit})\xi+\mu\xi^2-\nu\xi^3+\ldots$$

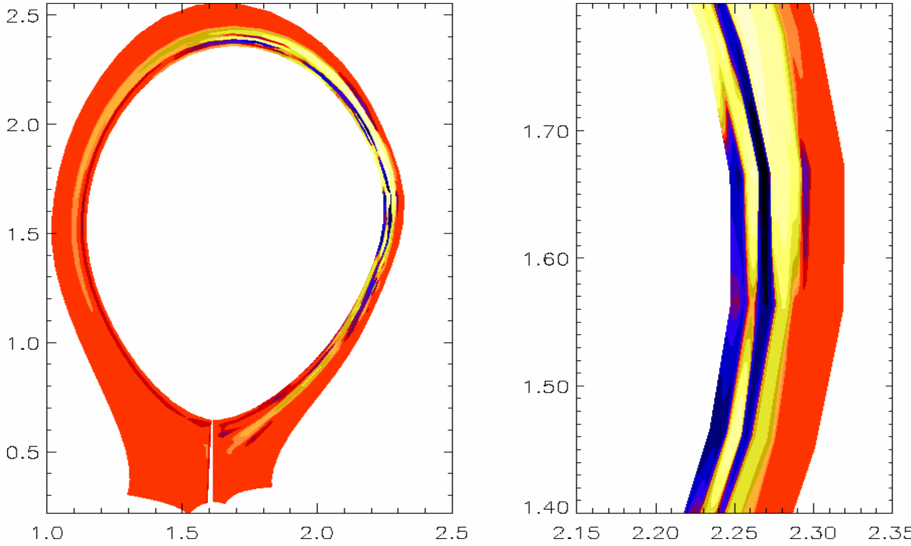
Linear term

If this term is destabilising=> explosive growth of the mode

BOUT -3D Braginskii equations code *Xu'02, Snyder'04*

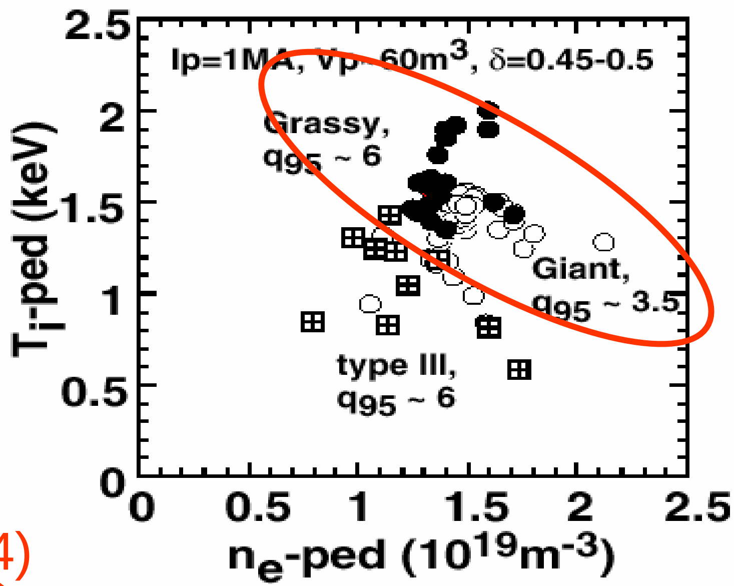


Starting point-unstable P profile. Linear growth followed by a fast burst to SOL.



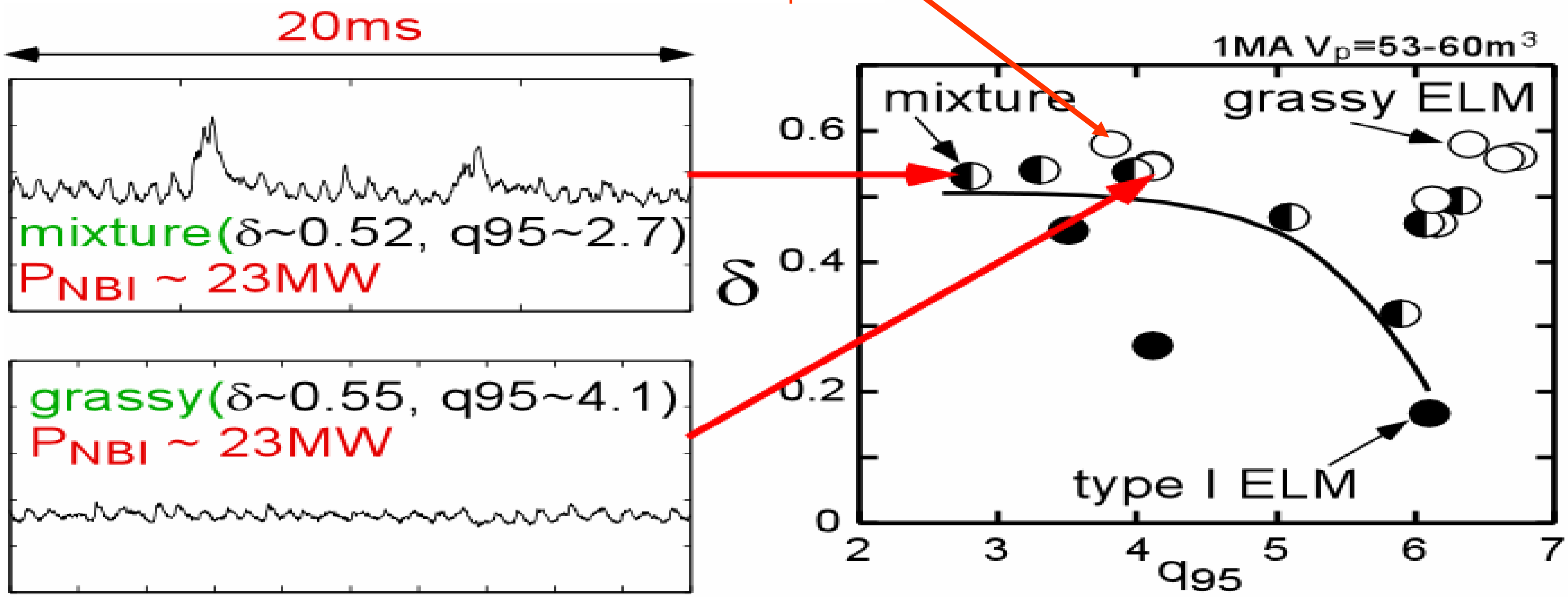
High confinement +small ELMs:Grassy ELMs (JT-60U).

-high triangularity: δ~>0.55;
-high q_{95}=6.4 (ITER: q_{95}~3);
-if high b_p~1.64 (ITER: β_p =0.8)+ high δ~0.6
=> lower q_{95}=3.8;
-ν_{ped}*~0.07-0.16 (ITER: ν^* ~ 0.05)
-high pedestal pressure (like Type I) H_{Hy2}~1.
-heat load to divertor decreases by /4-/5.



JT-60U: Y. Kamada'00,'02, Oyama'04

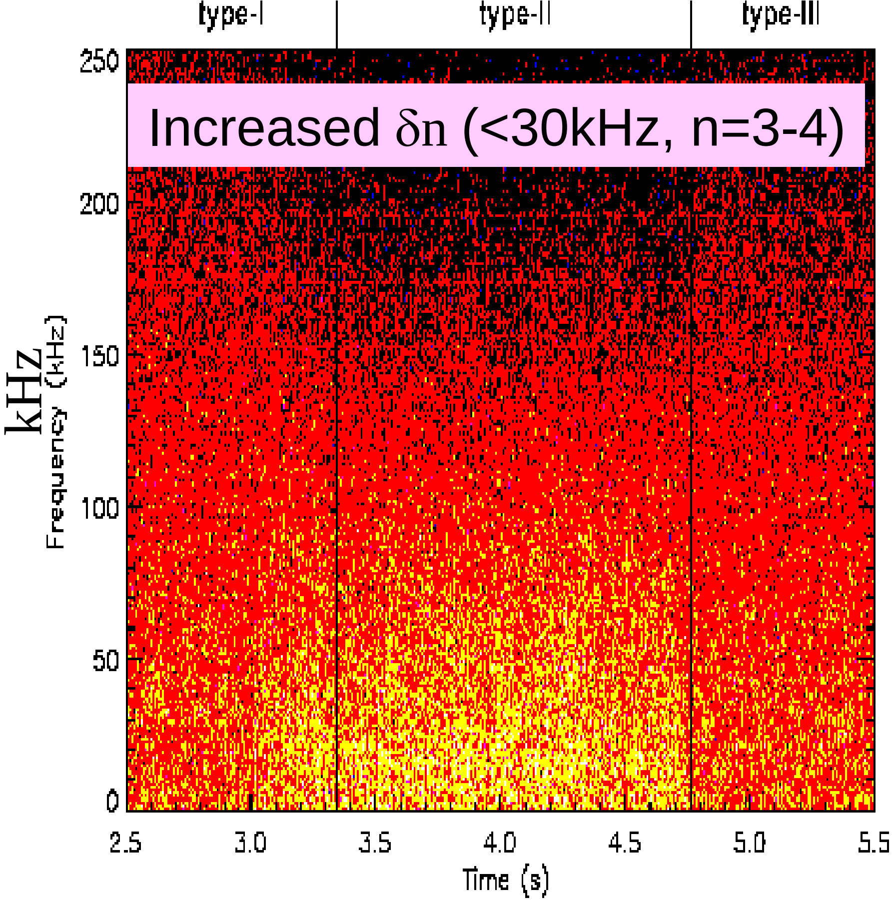
high β_p(~1.64)



Type II ELMs =increased δB and δn => transport in ETB

-high triangularity $\delta>0.4$-0.5; Sensitive to shaping DN (AUG)!
$q_{95}>4.2$ (Type II, AUG) $q_{95}\sim3$ (mixed Type I+II ,JET).
-$n/n_{GR}\sim0.85$-0.95 (medium $\nu^*\sim0.6$-0.8).
-$H_{98y}\sim1$

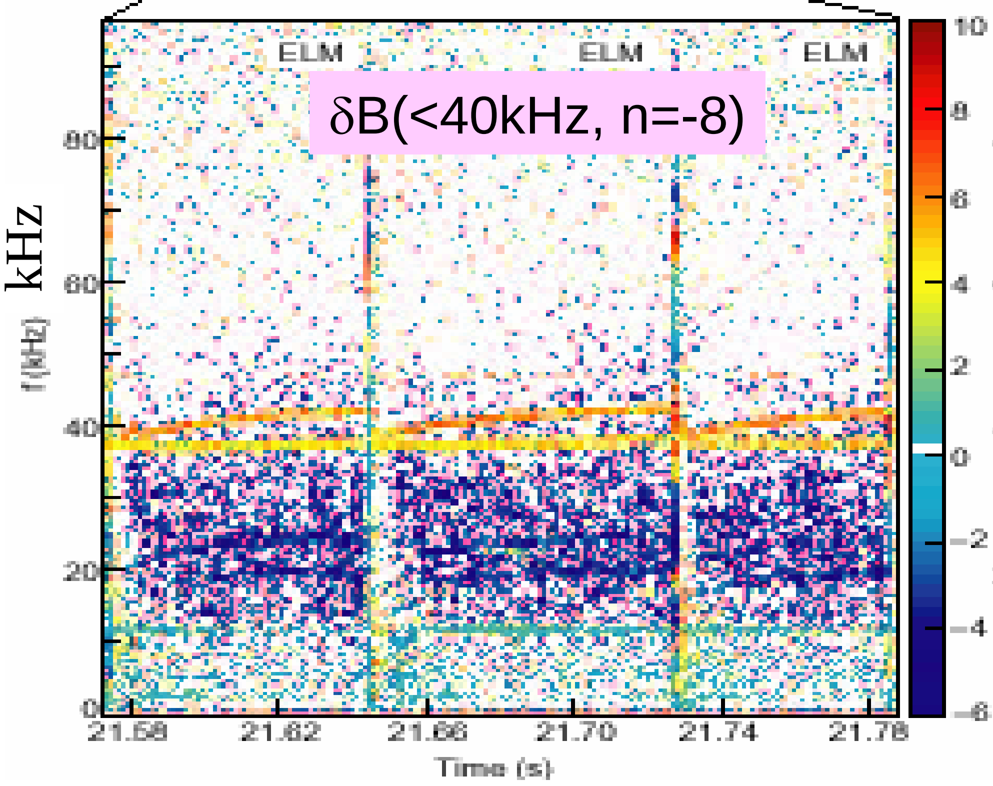
AUG:Stober'01



Increased δn (<30kHz, n=3-4)

Type II= Washboard resistive modes at high density?

JET: Perez'03



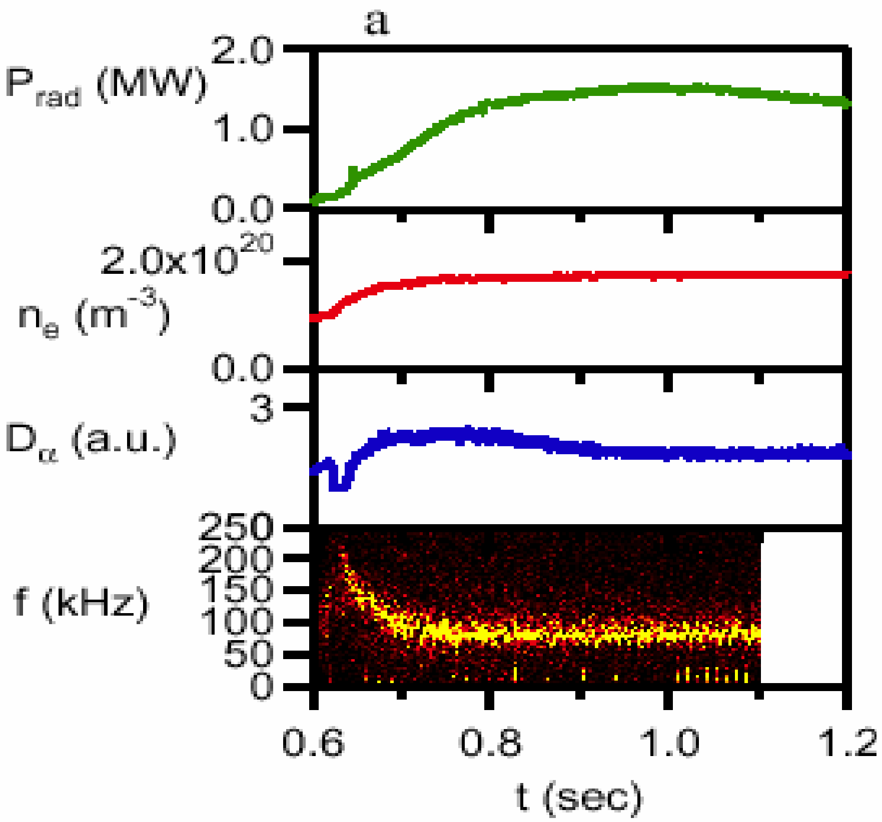
δB(<40kHz, n=-8)

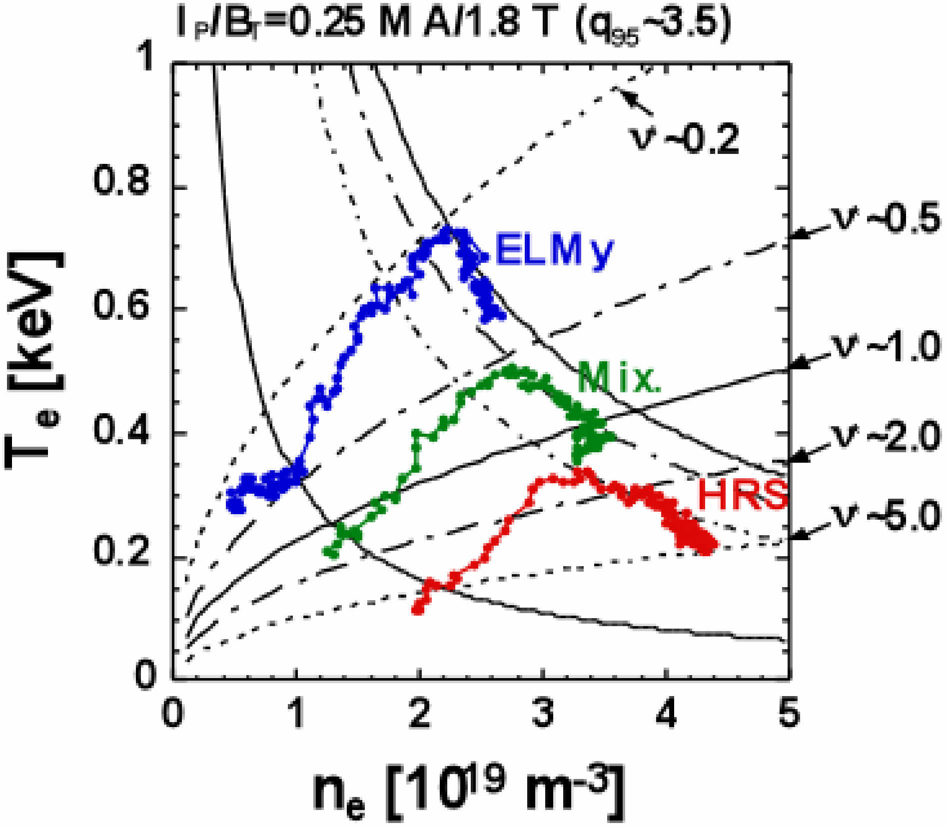
High ν^*(>1.5) regimes w/o ELM : EDA, HRS.

High $\nu^*>1.5-2$ (not achievable in all tokamaks!). EDA*(Alcator C-Mod),*High Recycling Steady *(JFT-2M).* Quasi-Coherent (QC) modes => Enhanced transport through ETB. Pedestal is peeling-ballooning stable ,QC correspond to resistive ballooning mode. But for ITER $\nu^*\sim0.05$!

Alcator-C-Mod:Mossessian, Hubbard '01,'02

JFT-2M:Kamiya, Oyama'04

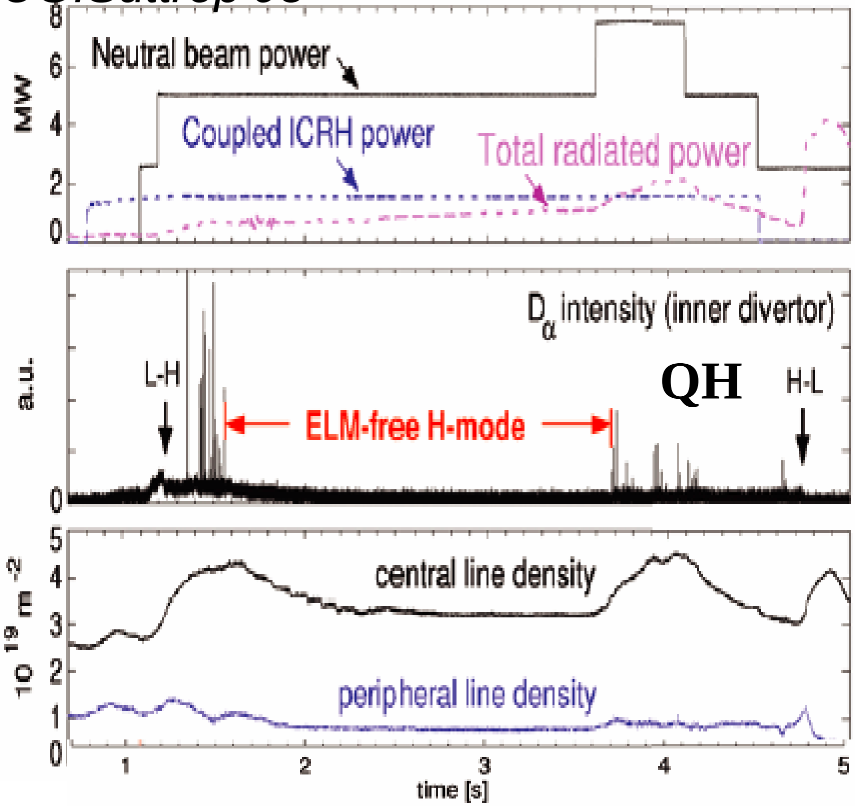




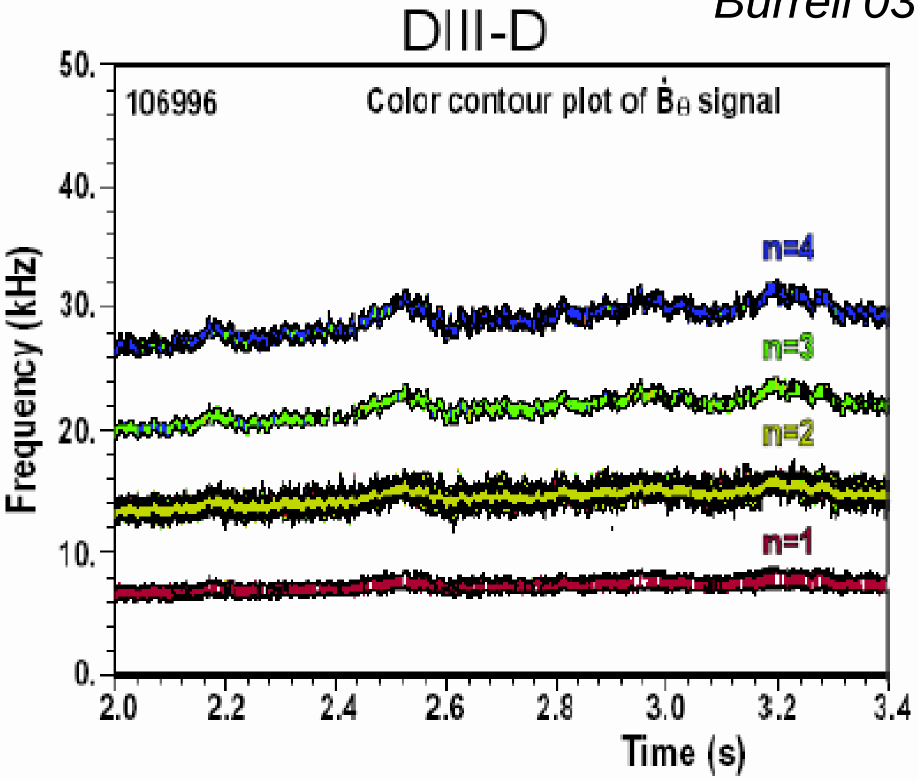
Low ν^*~0.05 QH-mode at counter NBI. *(DIII-D,AUG,JT-60U,JET)*

-high upper clearance, conditioning;but not sensitive to shaping (δ);
-counter neutral beam injection =opposite to I_p (not foreseen for ITER!);
-larger E_r shear at the edge as compared to ELMy H-mode;
-low density: n/n_{GR}~0.1 (DIII-D, strong pumping) -0.5(JT-60U w/o pumping);
-higher Z_{eff}=3.3-5, higher P_{rad};
-edge MHD = Edge Harmonics Oscillations (EHO);

AUG:Suttrop'03



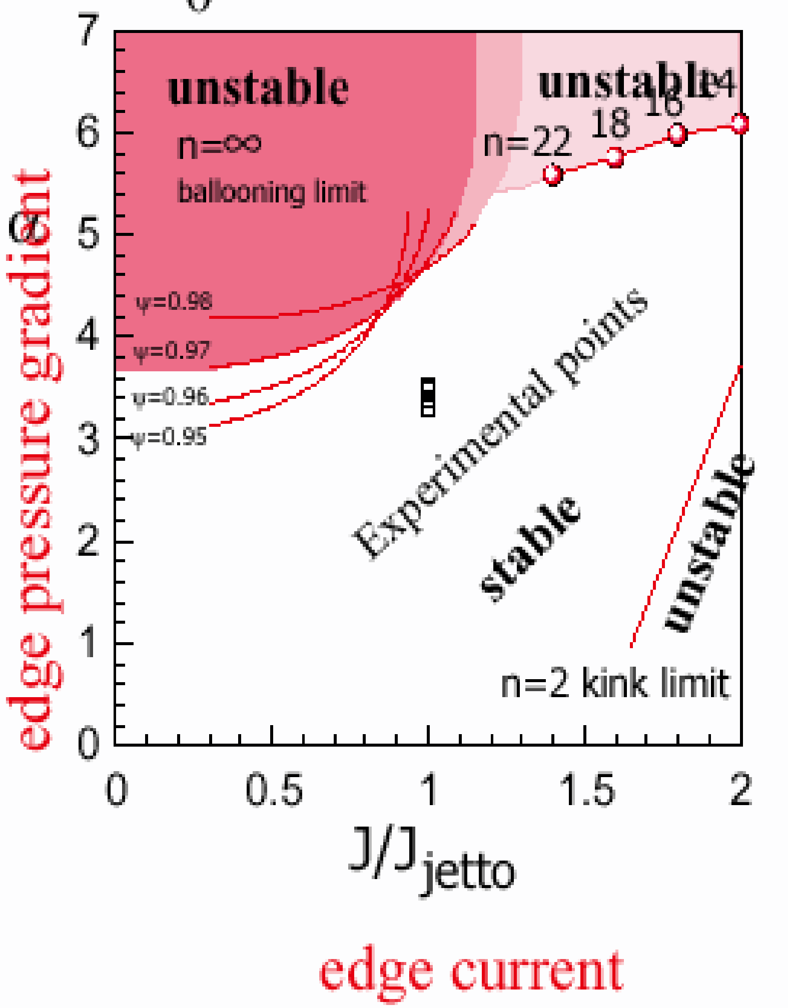
Burrell'03



3. Active control of ELMs.

$$\alpha = \frac{\mu_0 q^2 \nabla P}{\varepsilon B_0^2}$$

JET:Huysmans'01



Type I ELMs =peeling-ballooning modes.

How to control ELMs?

1)Maintain edge in stable region:

$\alpha \sim < \alpha_{crit}$ providing transport mechanism through ETB (artificial Type II small benign ELMs?)=>external magnetic perturbation(COMPASS-D,DIII-D)

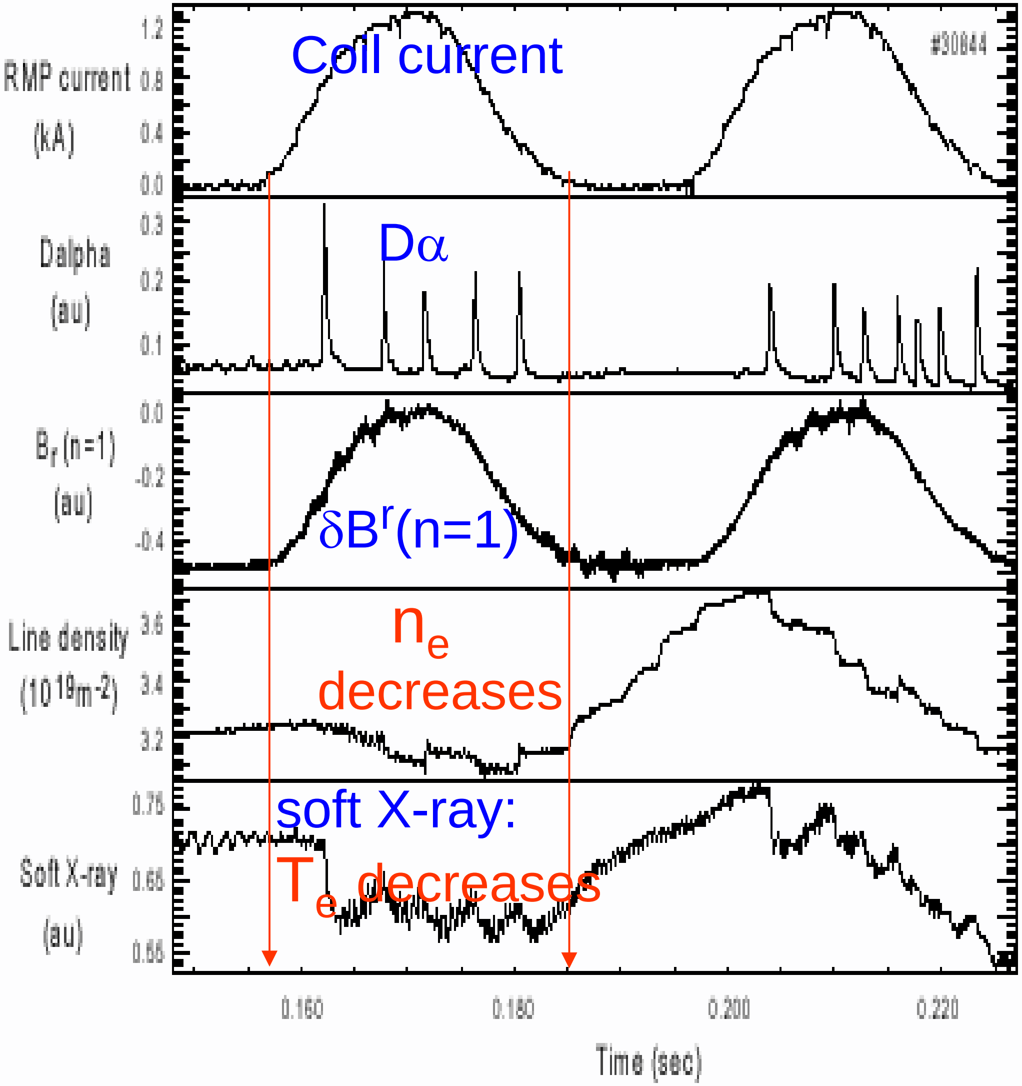
2) Triggering ELMs at given f_{ELM} to avoid large Type I , local change in pedestal ν^*.

-small pellets(AUG);

- edge current (COMPASS-D,JET, TCV);

ELMs triggering by external perturbation in COMPASS-D.

COMPASS-D:Fielding'01.



Resonant (q=m/n) at the edge radial magnetic perturbation n=1, m=4-5.

ELMs are triggered by magnetic perturbation. W/O δB^r –ELM-free.

Radial perturbation δB^r

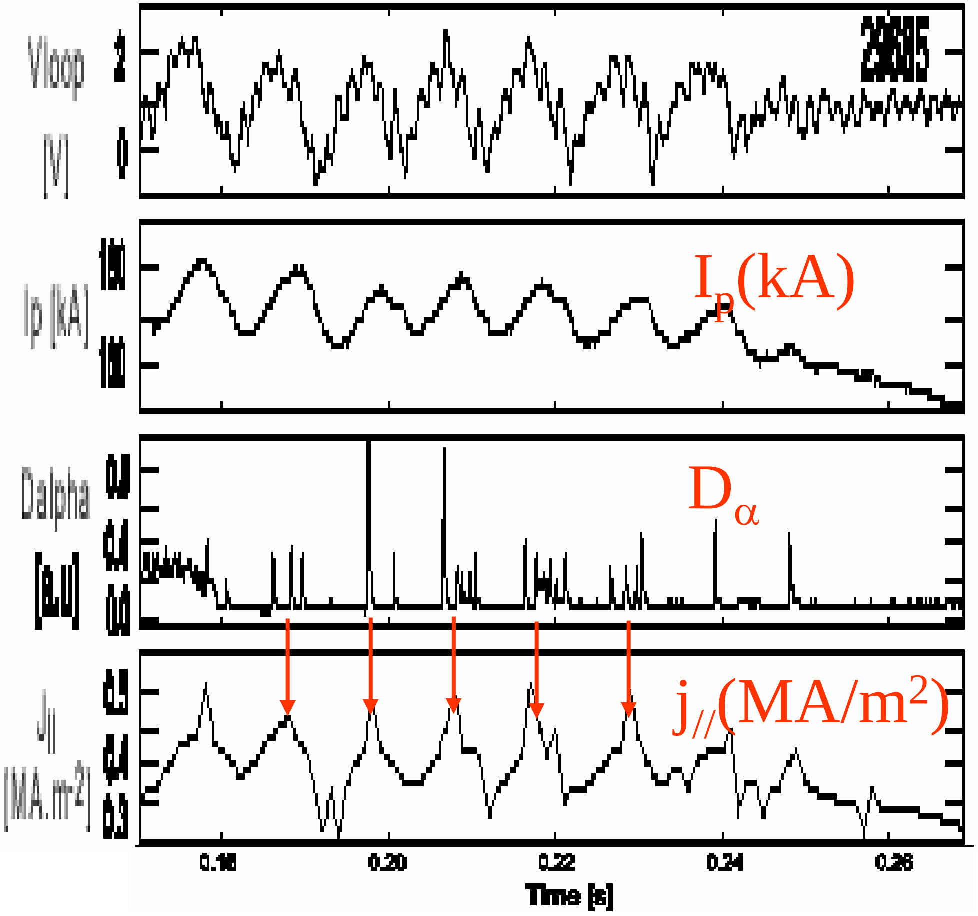
Density decreases with δB^r.
Temperature decreases with δB^r.
Why ELMs are triggered ?

New position in (α-j) MHD stability space, different modes can be unstable?

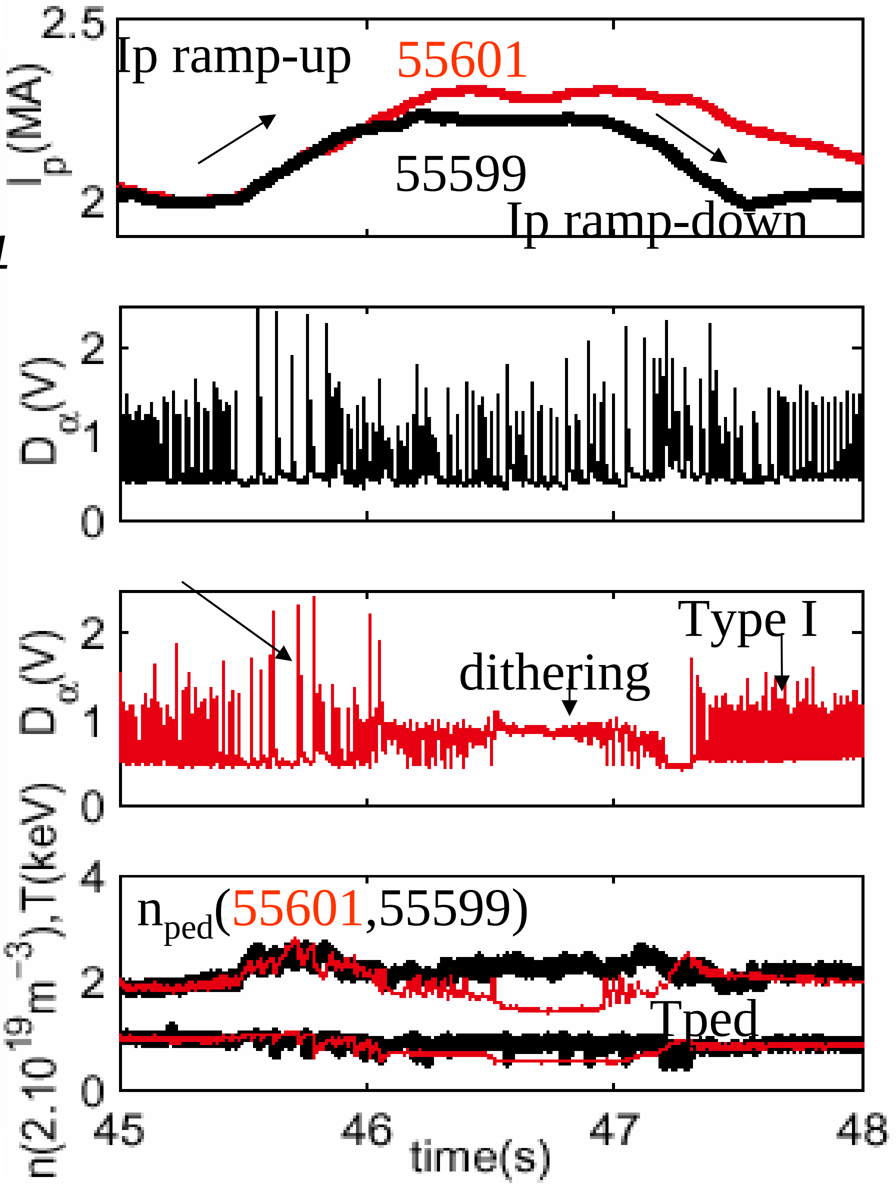
Peeling mode destabilisation in I_p ramps experiments.

Edge current can destabilise peeling modes: Type III ELMs (COMPASS-D,JET) or dithering L-mode(JET).The result is very sensitive to edge Te, ne, dI_p/dt…

COMPASS-D:Fielding'01



JET: Becoulet M.'03

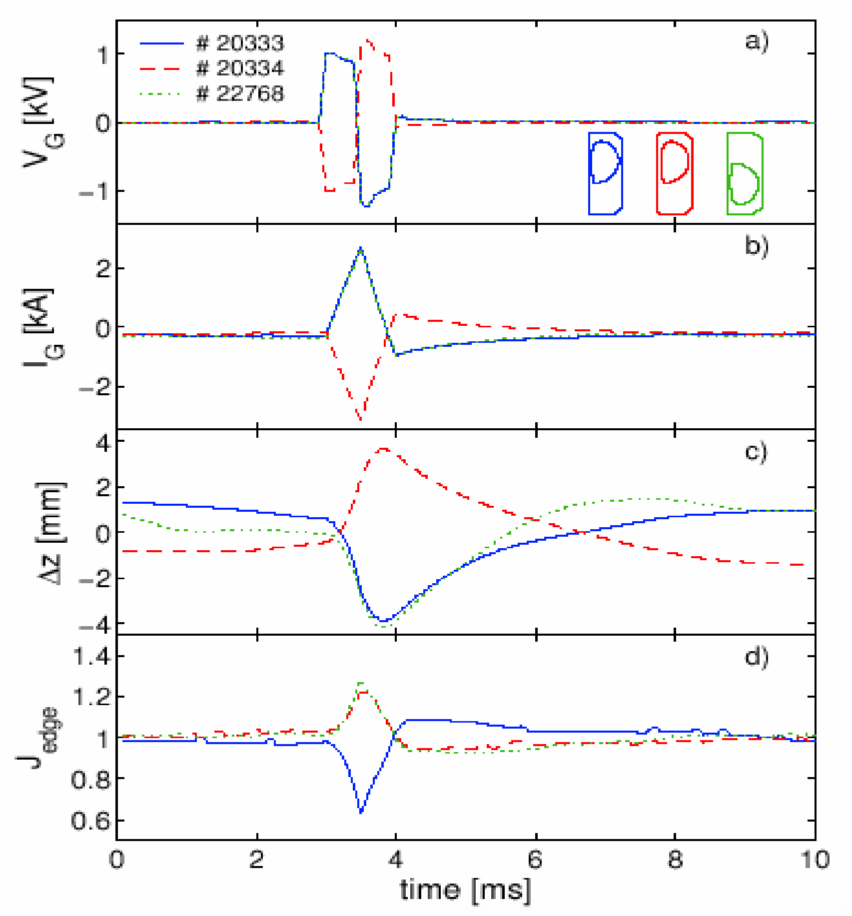


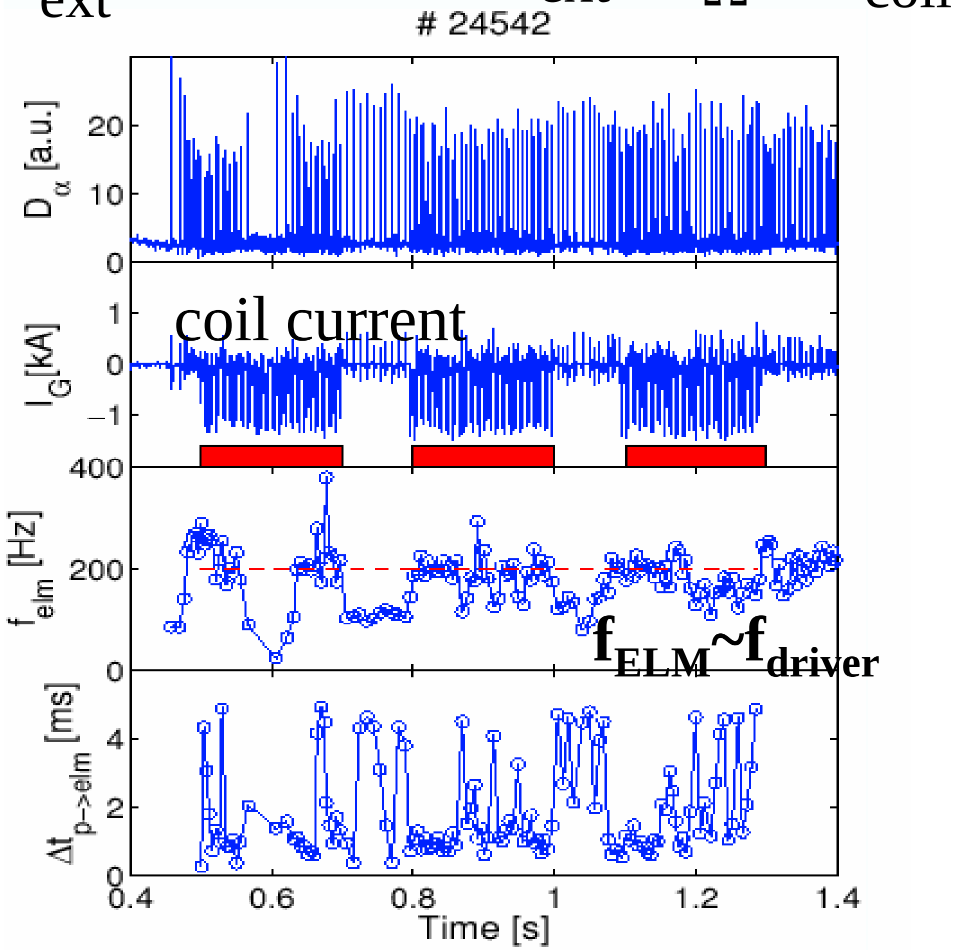
Edge current generation by vertical movements of plasma

Vertical oscillations of plasma column (up-down $\vec{u}=u_z\vec{e}_z$) in inhomogeneous poloidal magnetic flux =>Surface voltage=>Edge current=> Peeling ELMs with f_{ELM}~f_{driver}? *TCV:Degeling'03*

$$V_{surf}=-\frac{d}{dt}<\Psi_{ext}>=-\frac{\partial}{\partial t}<\Psi_{ext}>-<\vec{u}\nabla\Psi_{ext}>$$

$$\Psi_{ext}=\Psi_{\Omega}+\delta\Psi_{coil}$$





Conclusions(1)

1.High confinement scenarios for ITER and Type I ELMs.

-Unacceptable ELM losses predicted for ITER at low pedestal ν^* ~0.05 : $\Delta W_{ELM}/W_{ped}$~20%, acceptable losses ~5% -15%.

-Conductive losses decreases at high δ,high n_{ped}, high q_{95}. Small ($\Delta W_{ELM}/W_{ped}$~5%) only convective Type I ELMs at high density n/n_{GR}>0.8 or high q_{95}>4.5.

2. Progress in ELM theory.

-Ballooning-peeling linear MHD *(MISHKA,ELITE,GATO,..)* predicts LFS localisation, pedestal P_{max}, effect of δ, ELM area => triggering mechanism of Type I ELMs is identified. Type I ELMs are predicted for ITER pedestal *(ELITE, n=10-30).*

-Transport codes model pedestal pressure profile relaxation due to the peeling-ballooning modes destabilisation, ELM cycle, ELM-time. Present models cannot predict ELM loss self-consistently.

-Early non-linear stage of ELM: explosive evolution of ballooning mode=>finger-like structures; particles and energy bursts into the SOL *(BOUT-3D).*

Conclusions(2)

3. High confinement (H_{97}~1) benign ELMs (continuous edge MHD instead of burst transport in ETB) were demonstrated in present machines, but their relevance for ITER parameters *(H-mode: ν^*~0.06, β_p~0.8, q_{95}~3)* is still questionable.

-Grassy ELMs *(JT-60U):*low ν^*=0.07-0.16, but high q_{95}~6, q_{95}~3.8 at high β_p~1.6;

-Type II and mixed: too high ν^*>0.6; sensitive to shaping DN*(AUG)*, high q_{95};

-EDA*(Alcator-C-Mod)* , HRS*(JFT-2M):* too high ν^* ~1-10 regimes;

-QH and QDB*(D-IIID, AUG,JT-60U):* low ν^* ~0.05 regimes; but high upper clearance, counter NB injection, low density, high Z_{eff};

-Type III in impurity seeded discharges. ITER at 17MA?

4. Active control of ELMs is in progress.

-Stochastic boundaries: ELMs can be suppressed at const confinement *(DIII-D).*
-Small pellets can trigger ELMs with given frequency and size *(AUG).*
-Edge current density can be controlled and trigger “peeling” ELMs.
(current ramps *(JET, COMPASS-D)* ,vertical oscillations of plasma*(TCV)*)