Control of Transport Barriers

Edge transport barriers (20 mins. + discussion)

Internal transport barriers (20 mins. + discussion)

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Scope and outline

Need for control of edge and internal transport barriers comes from:

I. requirements for the next step (e.g. ITER-FEAT).

II. desire to obtain, optimise and sustain improved confinement.

A: Control of edge transport barriers in H-modes, predominantly (I).

B: Control of scenarios with internal transport barriers, predominantly (II).

⇒ Review and compare the techniques that are used.

Highlighted by some (unique) examples.

Show alternatives (e.g. Hybrid scenario).

Review their relevance, for burning plasmas *(R)*.

Indicate points for discussion *(D)*.

A: Control of Edge Transport Barriers

Posters with this Topic:

D5: H. Meyer,	Formation of transport barriers in the MAST spherical tokamak.
D6: Y. Sakamoto,	Impact of toroidal rotation on ELM behaviour in H-mode and ITB plasmas on JT-60U.
D7: R. Maingi,	Effect of Gas Fuelling Location on H-mode Access in NSTX.
D8: H. Urano,	Impact of H-mode pedestal on ELMs with and without pellet injection in ASDEX Upgrade.
D9: K. Jain,	Study on generation of radial electric field with various biased electrode ring configurations in a toroidal plasma.
D10:M. Yoshinuma,	Observations of Edge Radial Electric Field Transition in LHD Plasma.

Poster presentations indicated during this talk : *(P)*

Control of edge transport barriers: Requirements

Driven by requirements for the next step:

- To access H-mode (in Tokamaks), Power threshold for ITER-FEAT 37–68 MW, D_2 at $\langle n_e \rangle = 5.0\times10^{19}\ m^{-3}$. Installed power ~ 73 MW.

- The energy losses during type I ELMs are a considerable concern when scaled to a reactor size device (divertor lifetime):

  Predictions for energy loss per ELM for ITER-FEAT *(D)*:

  ~ $f_{ELM}*\tau_E$ gives: ~ 60 MJ [Herrmann, PPCF **44** ´02, 883].

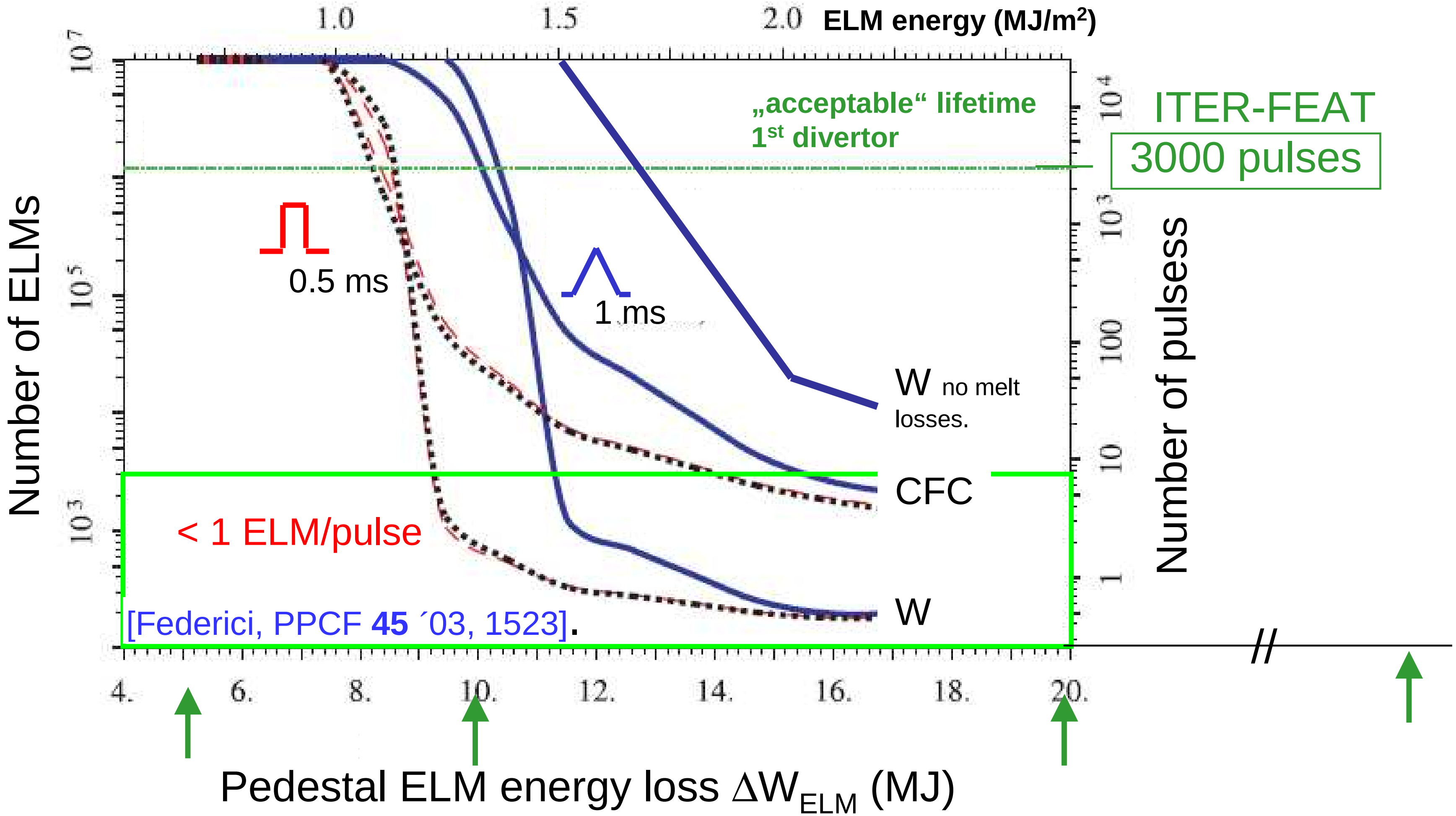
  ~ $\nu_{ped}*$, pedestal collisionality gives: ~ 20 MJ [Loarte, PPCF **44** ´02, 1815].

  ~ $\tau_{//}$, ion transport transit time gives: ~ 10 MJ [Loarte, PPCF **45** ´03, 1549].

  ~ n_e/n_{GW} scaling gives: ~ 5 MJ [Leonard, PPCF **44** ´02. 945].

  (H. Urano, AUG *(P)*).

Control of edge transport barriers: Requirements



Loss power due to ELMs: f_{ELM} x $\Delta W_{ELM,}$

However erosion, strong dependence on ΔW_{ELM} (control ΔW_{ELM} !)

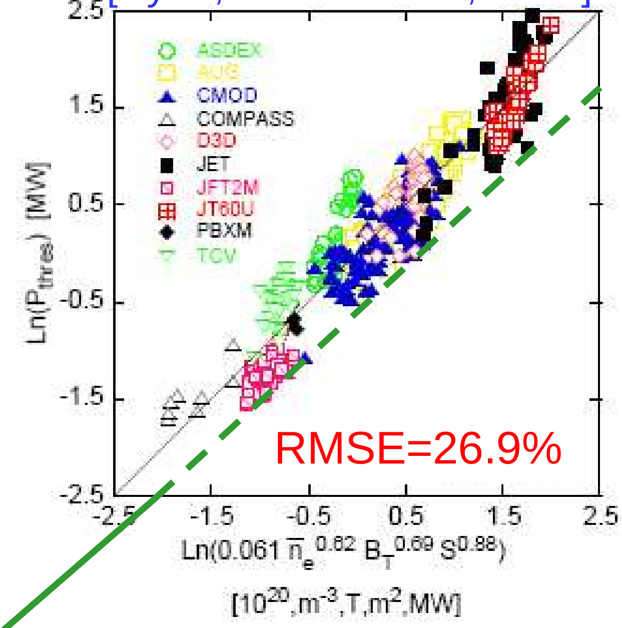
ELMs have non-uniform ΔW_{ELM} distribution: So $\Delta W_{ELM,}$ **average**. ~ 3-4 MJ

Methods for control of H-mode access

control

P_{thres} (MW) = 0.06 $<n_e>^{0.62}$ $B_T^{0.69}$ $S^{0.88}$ ($10^{20}m^{-3}$,T,m^{-2})

[Ryter, PPCF **44** ´02, A415].



(i) more complicated dependencies of the variables used (density !).

(ii) other "hidden" variables, related to Atomic processes, turbulence and MHD.

(iii) To get Type I ELMs (H_{98}~1): P_{in} ~2 x P_{thres}.

Lower P_{thres} using: ?

(1) the effect of fuelling location (Maingi, NSTX *(P)*), pellet injection [Compass-D, Volvic, PPCF 44 ´02, A175, DIII-D, Gohil, PPCF **45** ´03,601], (Meyer, MAST *(P)*).

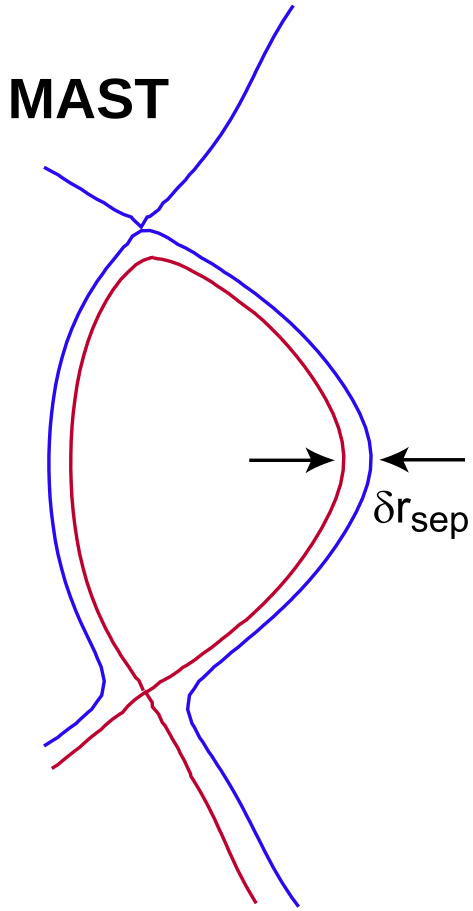
(2) the shape of the divertor or plasma shape [Many !]

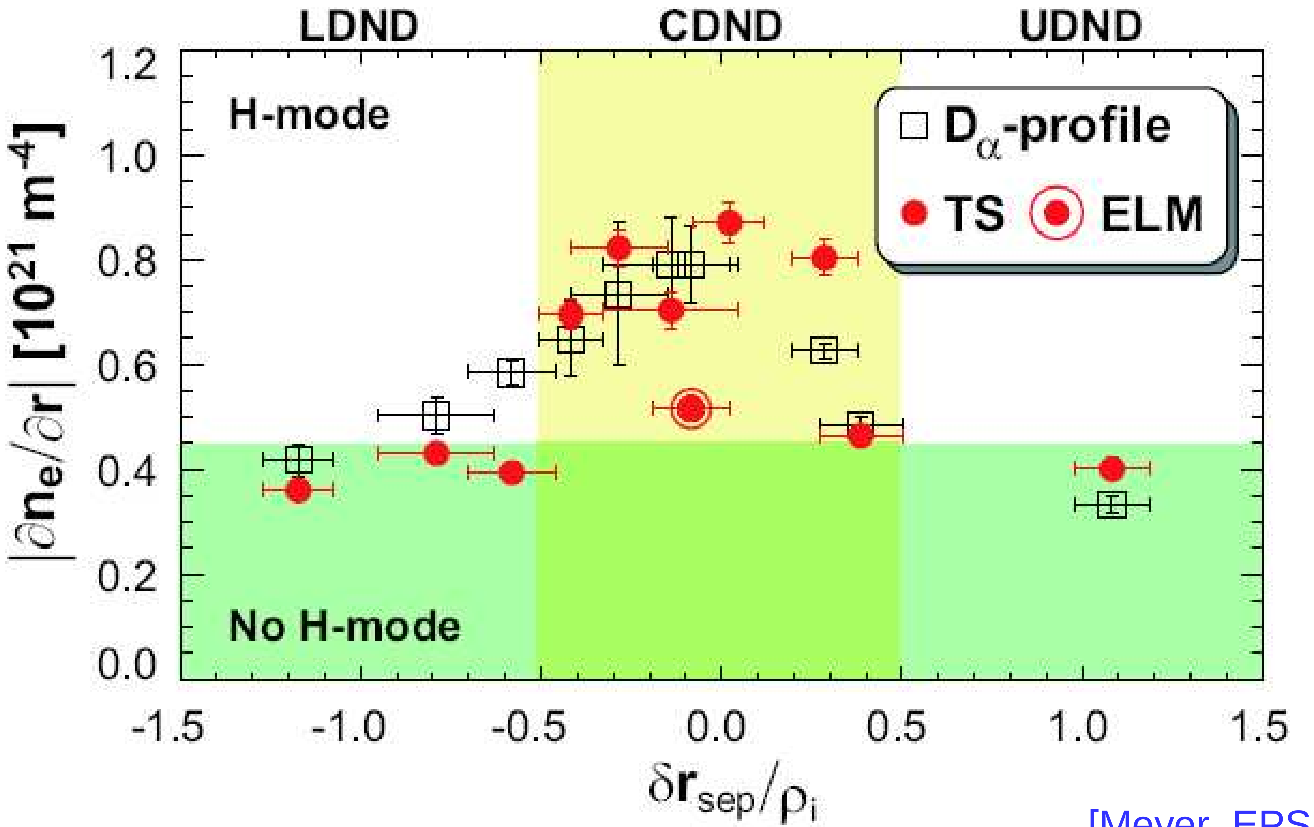
(3) the control of the electric field [T10, Kirnev, PPCF **45** ´03, 337], (Jain *(P)*, Yoshinuma LHD *(P)*, Minami CHS *(P)*).

Methods for control of H-mode access - Example

The shape of the plasma: Results from MAST (Meyer, *(P)*)

Low threshold in double null configurations:





[Meyer, EPS´02]

Applicable to tokamak (reactor) ? (*D*)
(DIII-D + recently AUG).

Methods for control of Type I ELMs

Impurity seeding:

Benefit in maintaining H_{98} ~ 1 at reactor relevant n_e (JET,JT-60U).

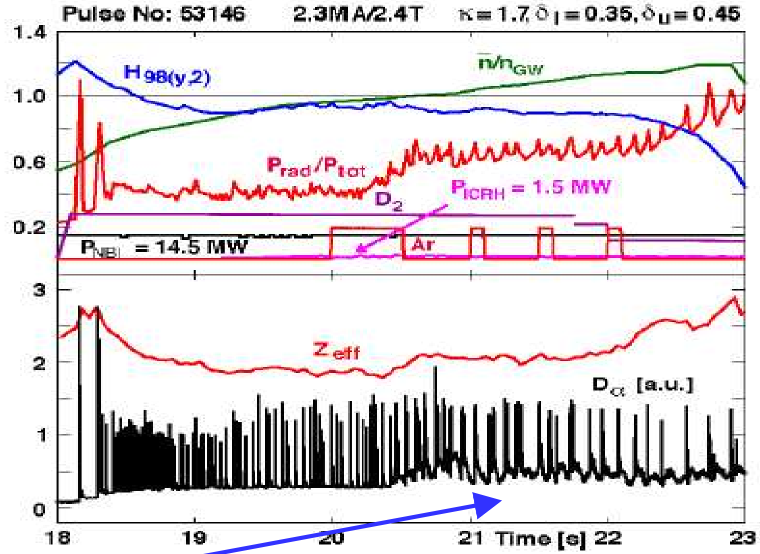
Critical to maintain low temperature in the divertor (reactor without CFC).

Reduction in f_{ELM} , but may not eliminate large energy fluxes.

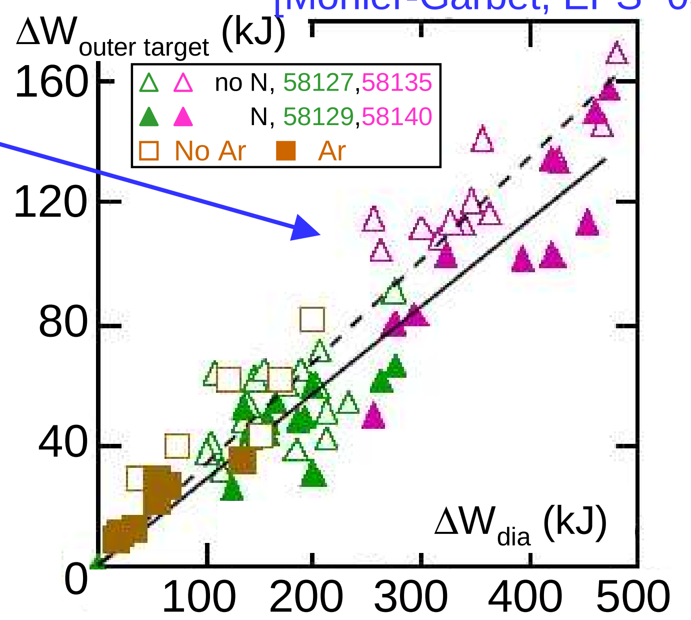
At high seeding levels, long ELM free phases, not stationary in confinement.

Likely to be used in conjunction with other mitigation schemes. *(R)*

[Ongena, IAEA ´02]

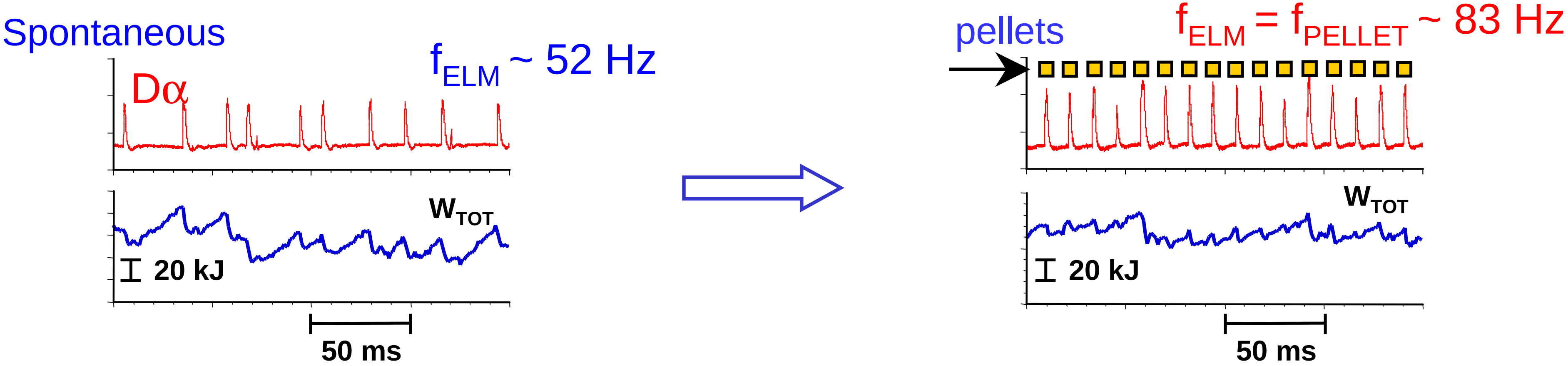


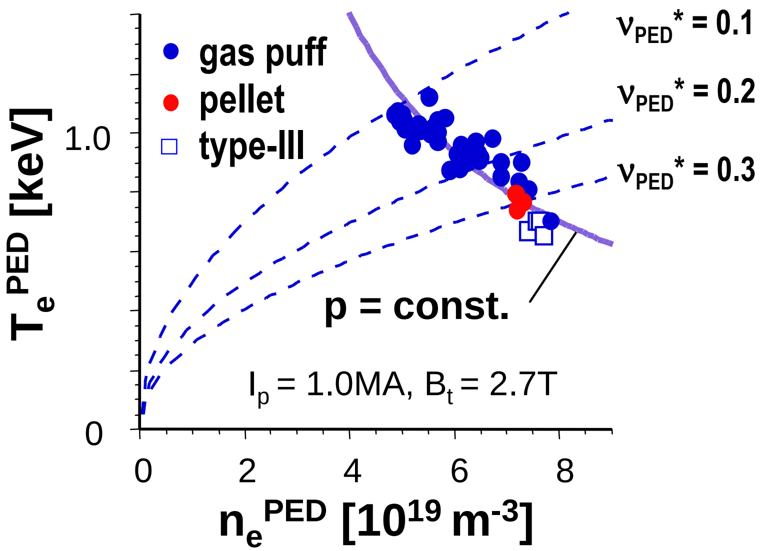
[Monier-Garbet, EPS ´03]

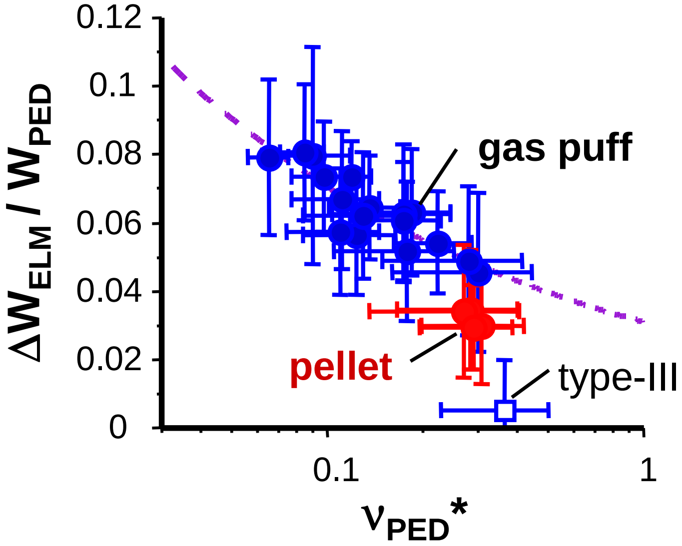


Methods for control of Type I ELMs

Pellet triggering of ELMs: (H. Urano, AUG *(P)*)



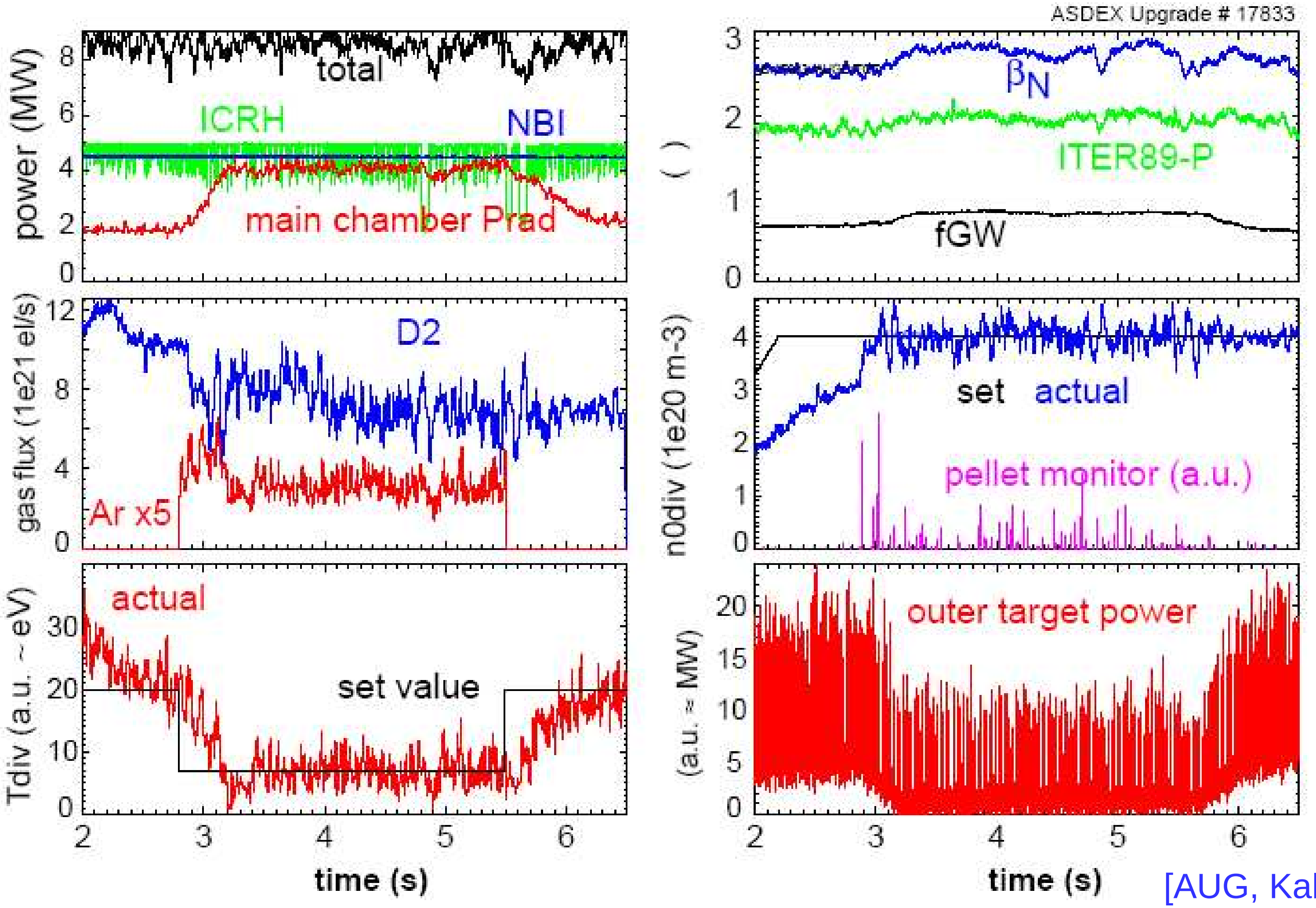




Pellet injector: Easy extrapolation to ITER. *(R)*

Methods for control of Type I ELMs - Example

Combined techniques: Impurity seeding + Pellet triggering of ELMs



[AUG, Kallenbach, ´03]

Add pellets to avoid radiation „run-away“ with Ar-seeding

Methods for control of ELMs

Edge current variations:

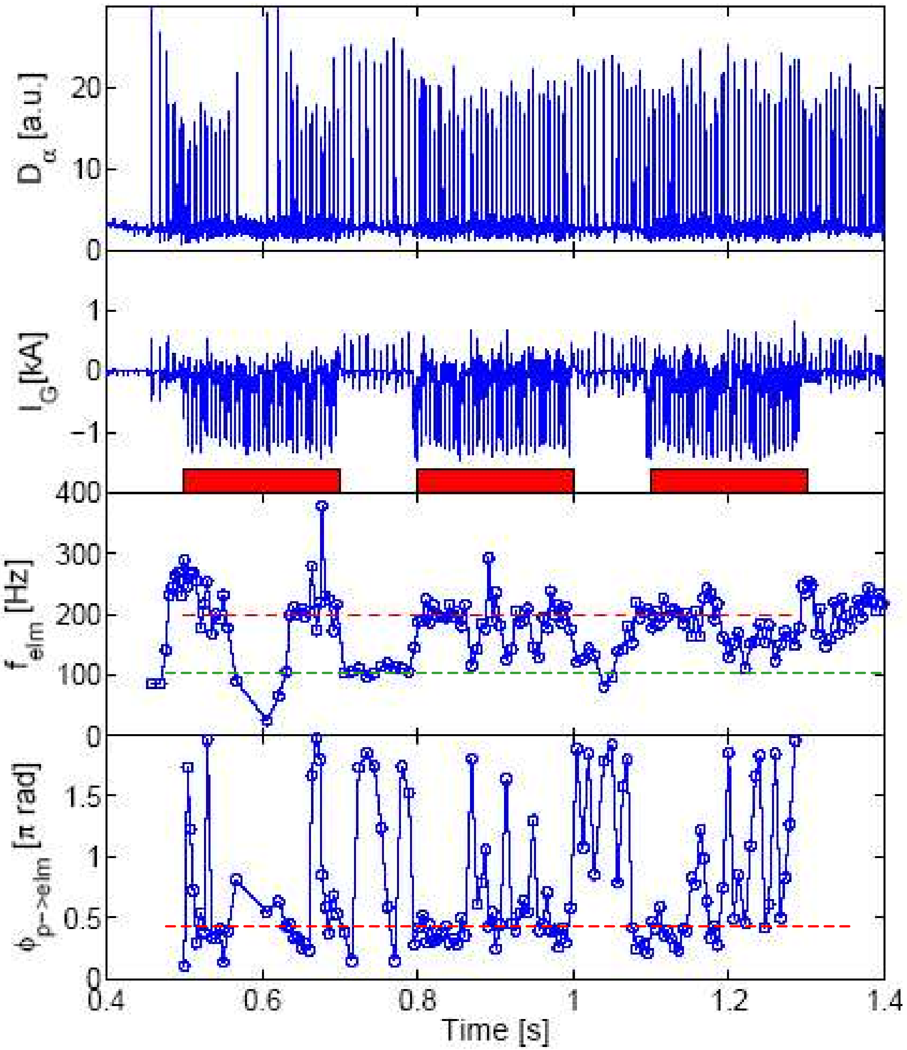
Change the stability of the ELMs.

Results from COMPASS-D, JET and JT-60U with Ip ramps report f_{ELM} ↑, at higher edge currents.

BUT, TCV demonstrates control of $f_{ELM.}$+ model + prediction for use in larger devices.

Oscillations on ~ 1 s. timescale would be enough in ITER-FEAT with external coils (AC losses ?).***(R)***

[Degeling, PPCF **45** ´03, 1637] **TCV, #24542**



But, Type III ELMs

Methods for control of Type I ELMs

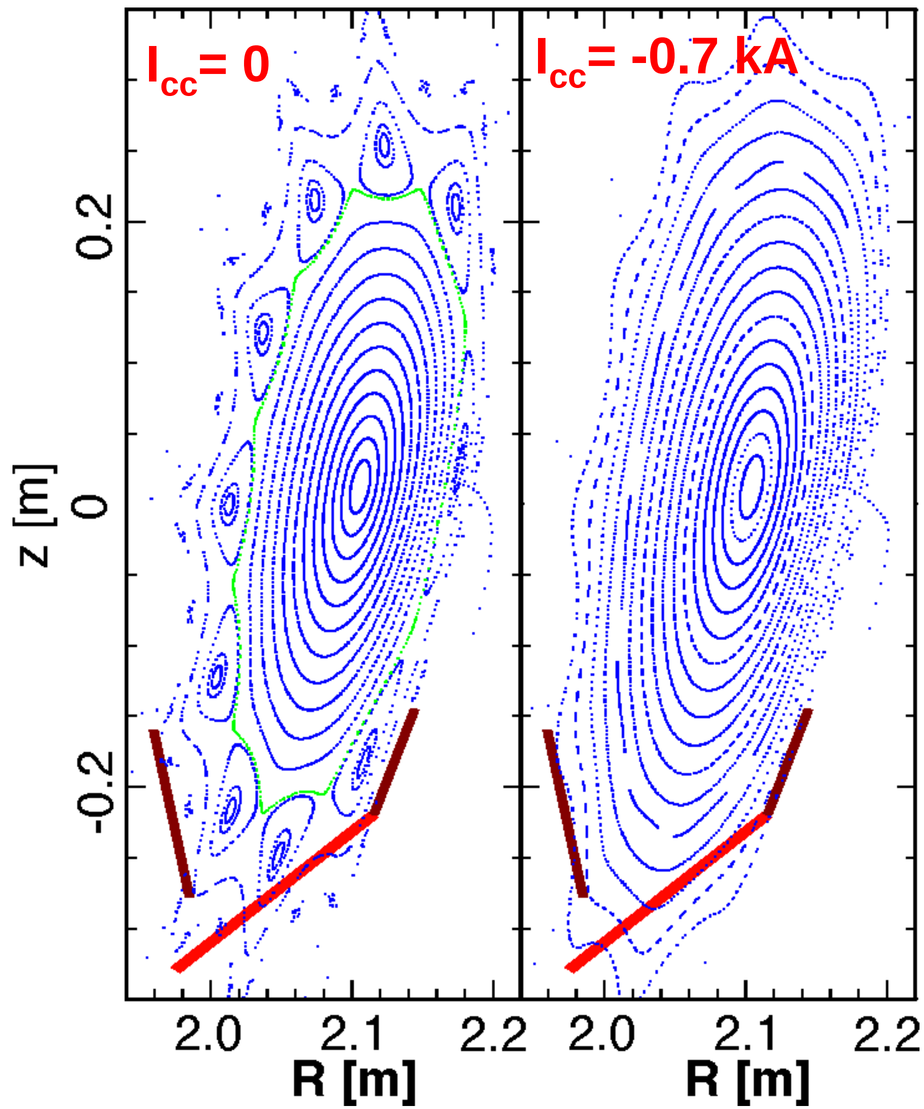
Ergodisation of the edge:

- Technique for limiter machines (Tore Supra) or helical devices
- W7-AS, high density H-mode. without ELMs.
- Combination of poloidal divertor and ergodic edge (JFT-2M, COMPASS-D).
- Very recent results of DIII-D, ELMs suppressed completely [PRL to be submitted]:
- To start: TEXTOR-DED.

Ergodisation in a reactor ? (*D*)

[W7-AS, Weller, EPS´03]

Calculated Vacuum Surfaces



Regimes without Type I ELMs (see also Topic B)

High ν^* ← Today´s experiments → Low ν^*

Type II ELMs (AUG):
Control of plasma shape near DNX, $n_e/n_{GW} > 0.85$, $q_{95} > 3.5$.

Quiescent H-mode (DIII-D):
counter NBI, no ELMs at all.
Rotation control
(Sakamoto, JT-60U, ***(P)***)

EDA Mode (C-Mod):
High recycling with reactor relevant heating. No ELMs at all.

Type III + ITB (JT-60U, JET):
Requires ITB to keep $H_{98} \sim 1$ with all their control issues.

at lower ν^* ?

at higher n_e/n_{GW} ?

Are these our safeguard against a worst case scenario ? ***(D)***

Edge barrier control in burning plasmas - Discussion

Edge barrier control, reactor relevance (mainly focussed on Type I ELMs):

- Impurity seeding in conjunction with other mitigation schemes.
- Pellet trigger of ELMs has easy extrapolation to ITER.
- PF current oscillations at ~ 1 s. $\rightarrow$ ITER-FEAT with external coils.
- Edge ergodisation is technical challenge, but RWM stabilisation for advanced scenarios is taken for granted in ITER-FEAT.

Edge barrier control, discussion points

1. Predictions for energy loss per ELM for ITER-FEAT
2. Spherical tokamaks, L $\rightarrow$ H in DNX, applicable to tokamak (reactor) ?
3. Is ergodisation a possible ELM mitigation method for a reactor ?
4. Scenarios without type I ELMs, our safeguard against a worst case scenario for a burning plasma (no type I ELMs allowed) ?
5. More discussion points............

B: Control of Internal Transport Barriers

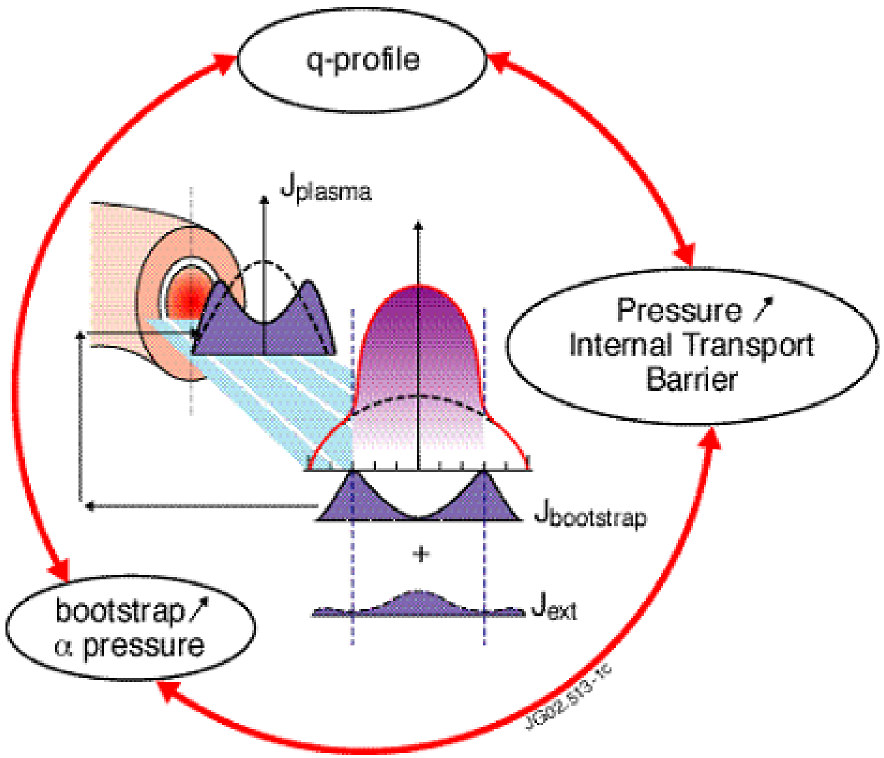
Posters with this Topic:

D1: C. Fiore,	Progress in Alcator C-MOD Internal Transport Barrier Studies.
D2: M. Henderson,	Creation and Control of eITBs in Stable Plasma Conditions on TCV.
D3: T. Minami,	Formation of Neoclassical Internal Transport Barriers under Various Operational Regimes on CHS.
D4: D. Mazon,	Real-time control of the current density profile in JET.
D5: H. Meyer,	Formation of transport barriers in the MAST spherical tokamak.

Poster presentations indicated during this talk: *(P)*

Control of internal transport barriers

Control requirements driven by the desire to obtain, optimise and sustain the improved core confinement to create an advanced scenario.



Areas for active control:

- Avoid global beta limits,
- MHD....resistive wall modes,
- q-profile,
- ITB strength, radius, duration.

Control of the edge as discussed before ? *(D)*

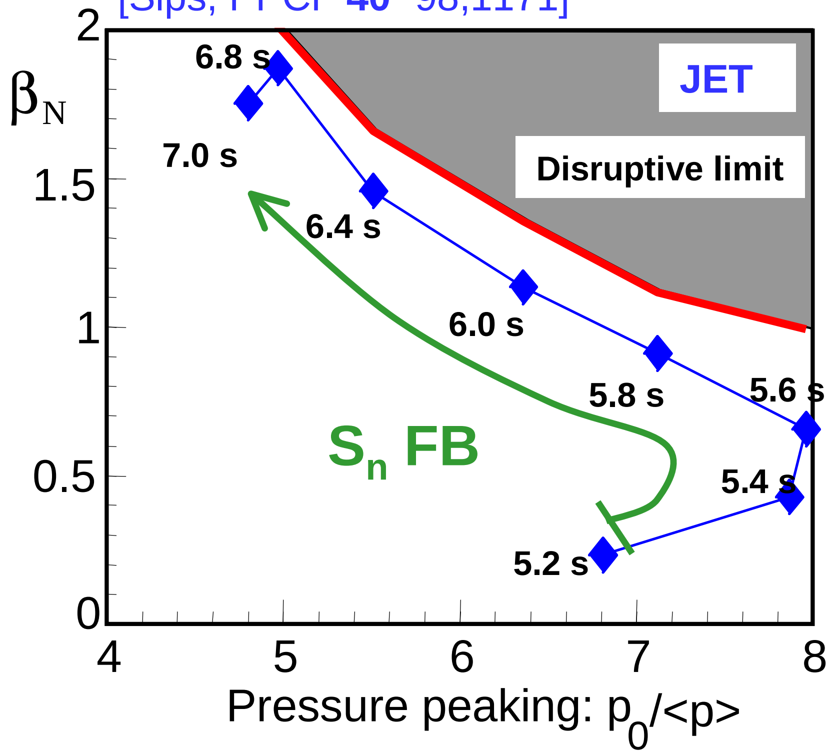
Control of ITB´s: Beta limits

Avoiding global beta limits:

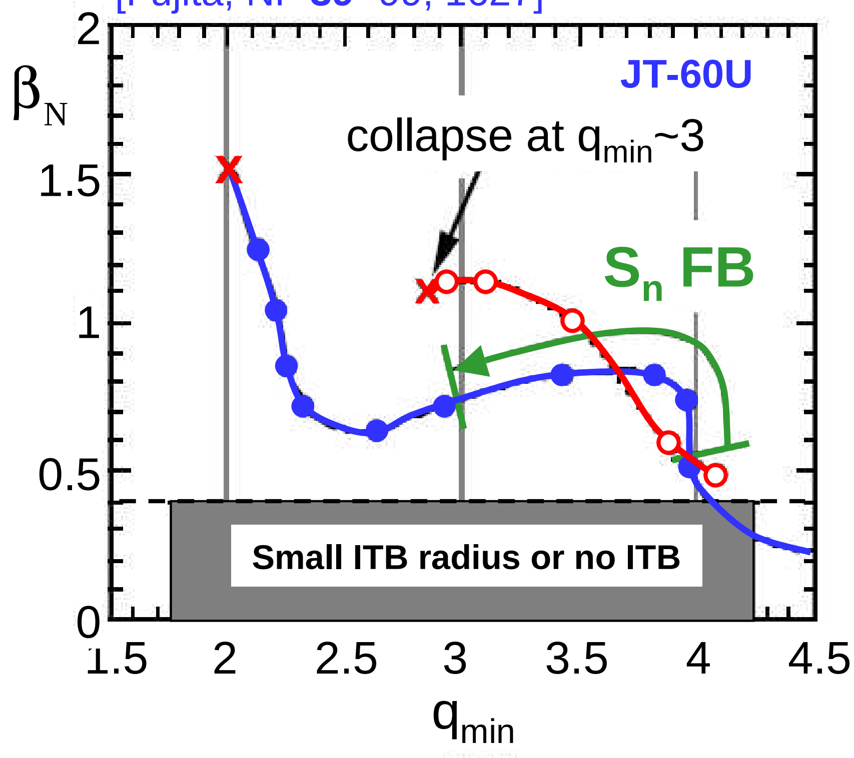
First type of control for ITBs with R_{DD} using input power to avoid disruptions:

Reduce power during peak pressure profiles or when q_{min} crosses rationals

[Sips, PPCF **40** ´98,1171]



[Fujita, NF **39** ´99, 1627]



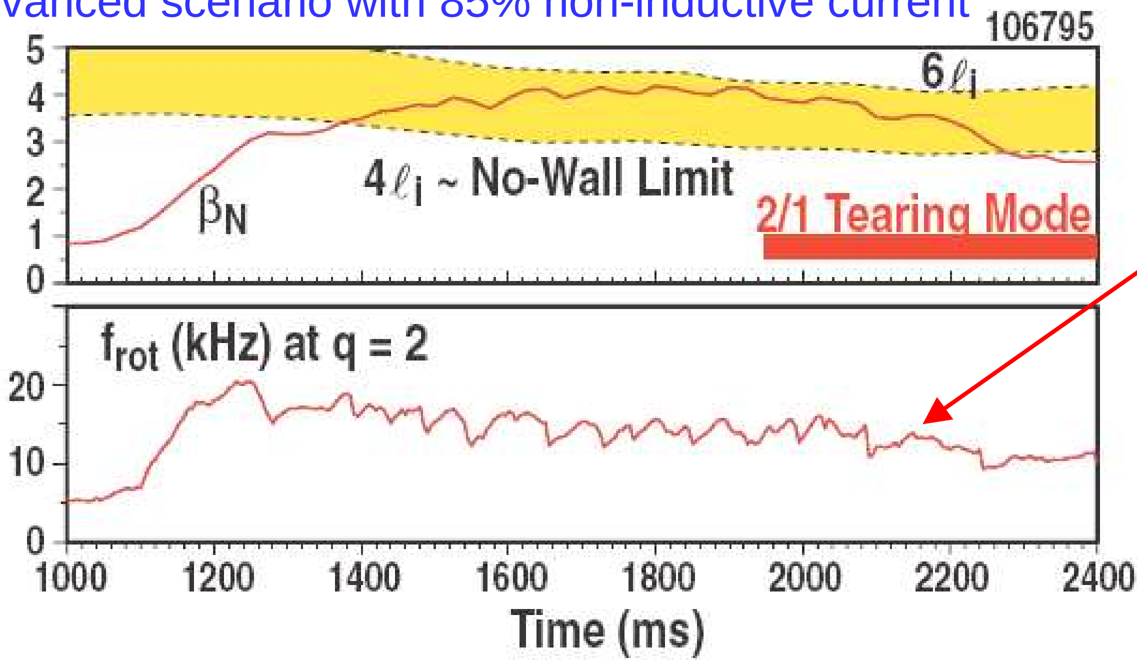
This type of control can not be used when α-power is main heating source ***(R)***

Control of ITB´s: Beta limits

MHD....resistive wall modes,

Feedback control of RWMs by rotational drive or flux conserving intelligent coils are crucial to operate at β_N ~ 3.0–3.5 [Lao, PPCF **45** ´03. 1023].

Advanced scenario with 85% non-inductive current



[Wade, NF **43** ´03, 634]

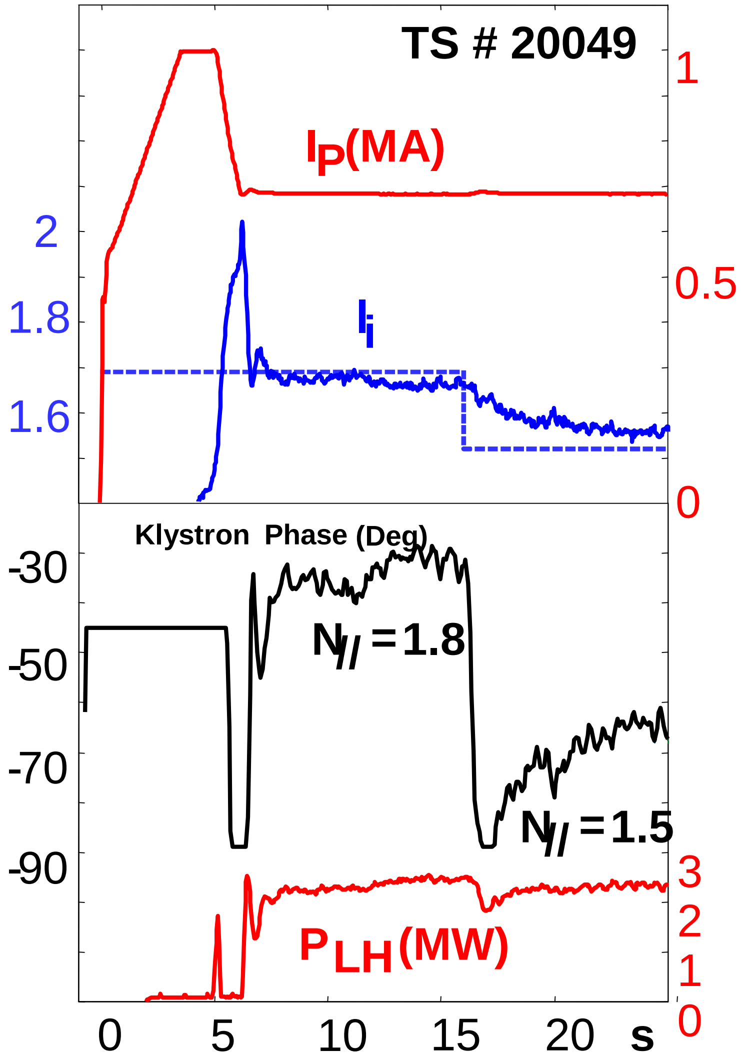
Rotation remains since external coils (C-coils) correct n=1 error fields in feedback (DIII-D).

JT-60U: Plasmas with larger minor radius, $\beta_N \uparrow$ (~10%) [Kamada, NF **41** ´01, 1311].

Conduction wall + control coils for a reactor, difficult but possible ? *(D)*

Control of ITB´s: q-profile control

Control of q(r), with ECCD, (LHCD),NBCD + PF coils:



[Mazon, EPS ´03]

Pre-programmed ⇒ Closed loop systems

Without ITB: Obtain desired q(r) at low β.

Vertical flux ⇔ ohmic generator

Plasma current ⇔ LHCD power

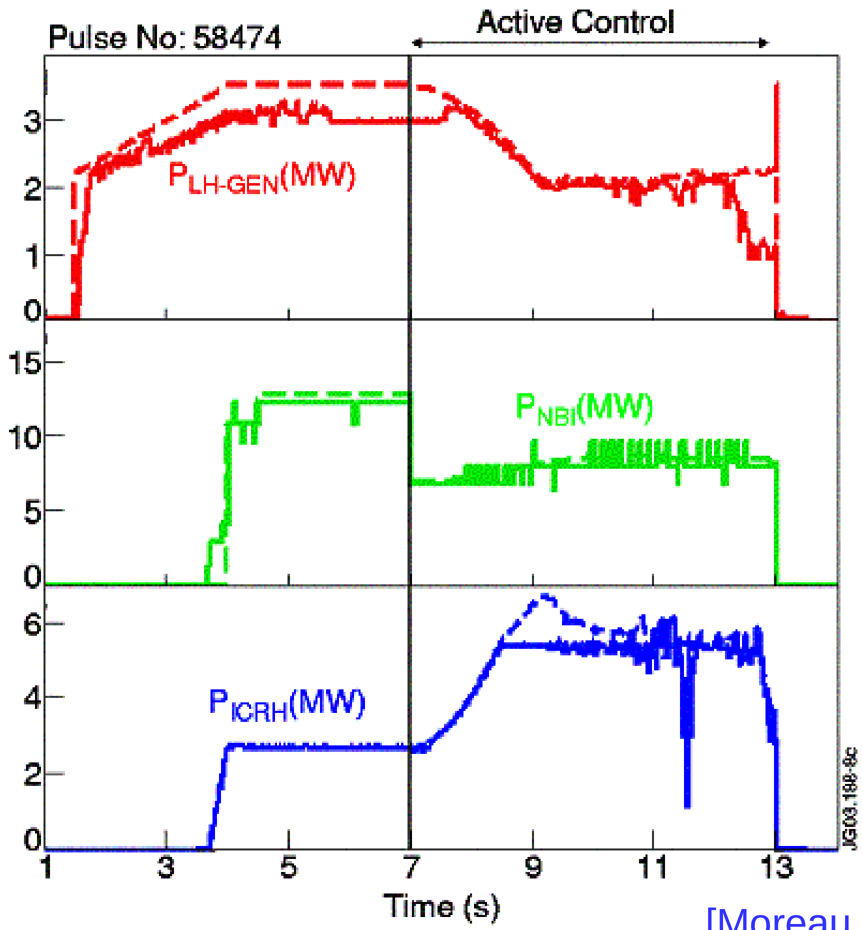
Internal inductance ⇔ LH parallel index

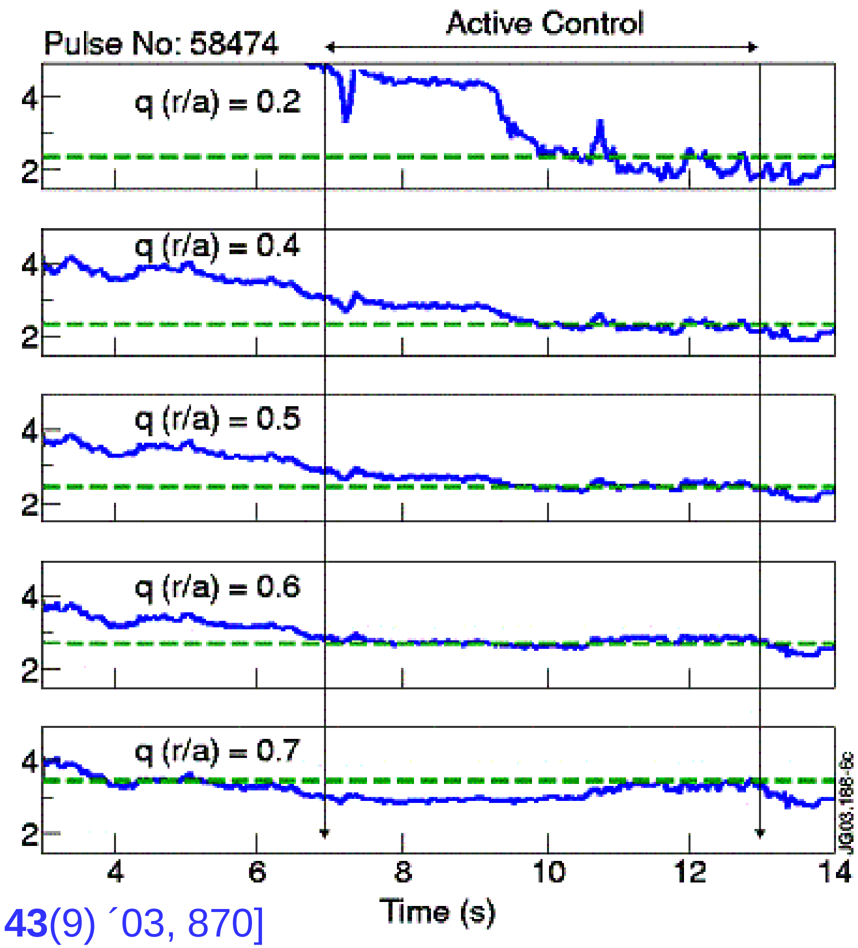
Tore Supra: Unique measurements with hard X-rays of LHCD deposition profile.

Can be combined with control on Tsurf. *(**R**)*

q-profile control - Example

JET: target q(r) or q(r) during weak ITB phase (low β), multiple actuators.





[Moreau, NF **43**(9) ´03, 870]

Control matrices from modelling **or** from step response in experiments ? ***(D)***

Need to control q(r) and p(r) to be reactor relevant ! ***(R)***

Control of ITB radius & strength (see also Topic A)

1. Control of the rotation shear with NBI in TFTR (old result). Similar results for JT-60U using NBI (Sakamoto, *(**P**)*).

2. Strong dependence of type of barrier obtained with q-profile (reversed, flat or weak shear in JT-60U) or rational q-surfaces (JET).

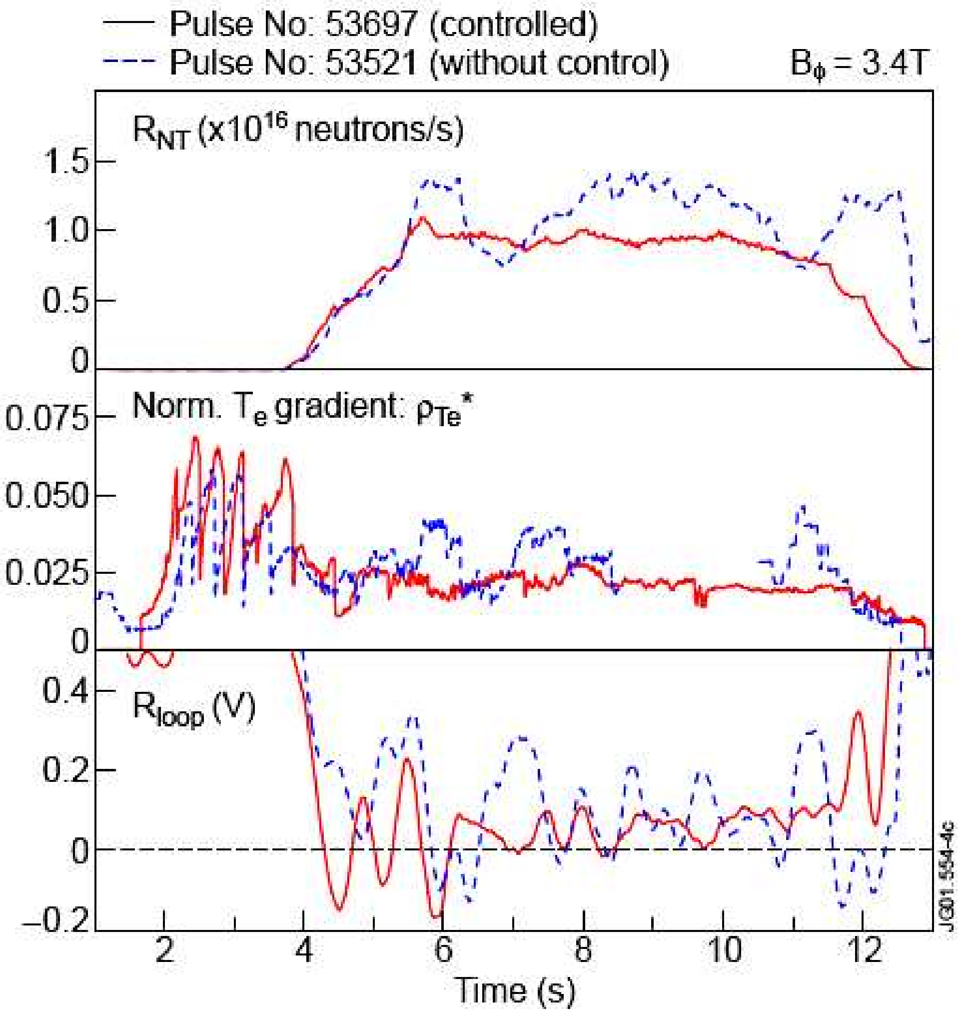
3. Barrier for n_e depends on B_T with off-axis ICRH in C-Mod (rotation increase is observed) (Fiore, *(**P**)*)

4. Quiescent H-mode + ITB (QDB): avoid erosion of ITB due to ELMs, counter NBI. DIII-D: $\beta_N H_{89}$ ~7 for > 3.8 s , need ECCD to control q(r).

Rotation profile control in a reactor ? *(**D**)*

ITB radius, strength and duration - Example

[Mazon, PPCF **44** ´02,1087]



<u>Closed loop control:</u> JET

ICRH ⇔ ρ_T^*

NBI ⇔ neutron rate

LH holds the q-profile

Ion and electron ITB´s,

- More stable at lower beta.
- No impurity accumulation.
- Edge: Type III ELMs.

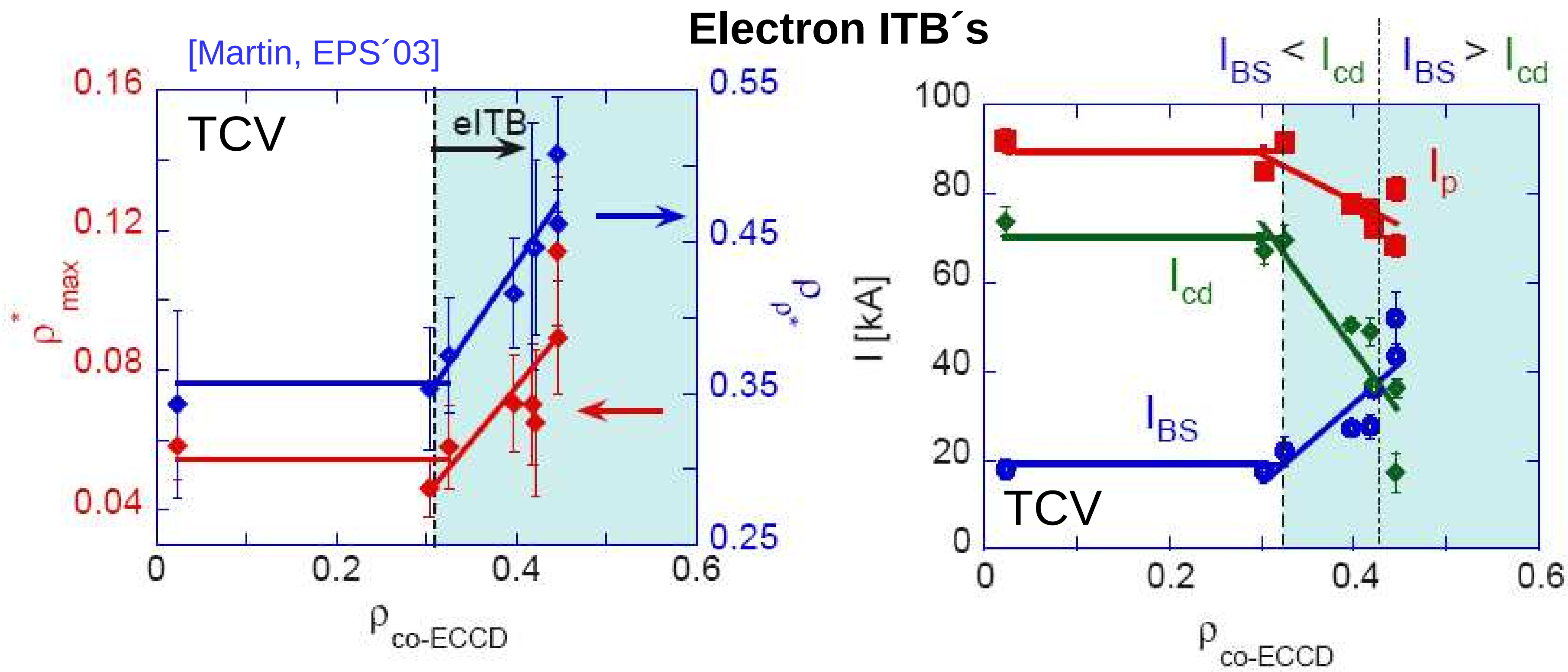
What about higher beta ? *(D)*

What about the ELM type ? *(D)*

Plan: Also control q(r) (Mazon, *(P)*)

ITB radius, strength and duration - Example

Experiments at higher beta: more bootstrap current fraction.



Full non-inductive: Flexible ECCD systems of TCV maximise ITB with off-axis co-ECCD (loses efficiency). Counter ECCD could be used but then, inductive scenario (Henderson, TCV ***(P)***).

How much power for ECCD and NBCD in ITER would you need ? ***(D)***

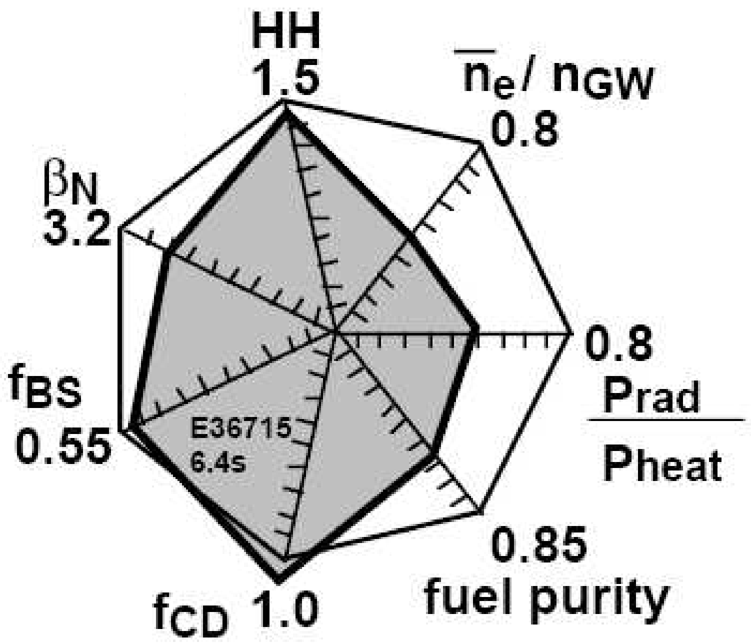
Lets review the situation......

Control of MHD: p_0/<p> and RWM stabilisation, avoid disruptions.

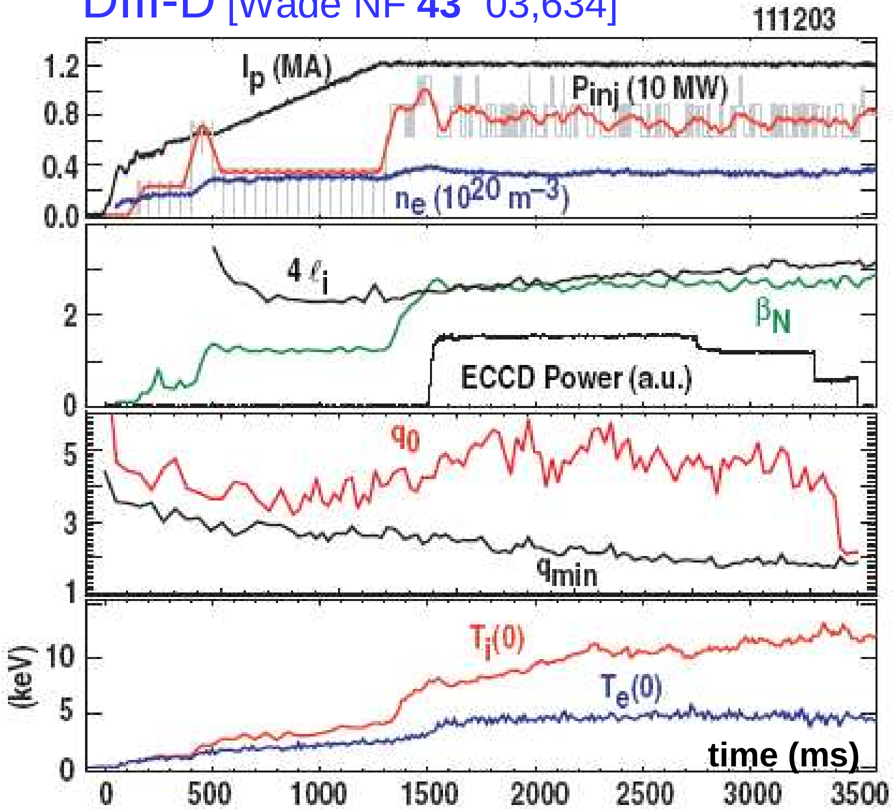
Control of q(r): Target q(r), or keep q(r) at low beta (so far).

Control of ITB: Dramatic improvement of $H_{89}\beta_N$ with control ?

JT-60U [Kamada NF **41** ´01,1311]



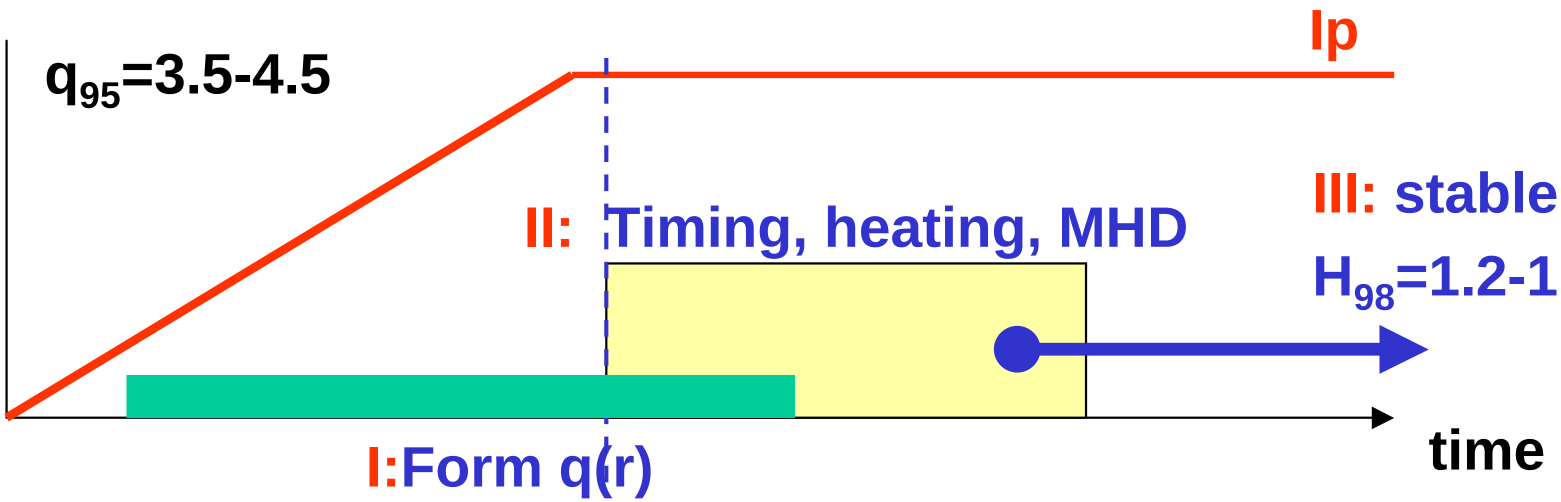
DIII-D [Wade NF **43** ´03,634]



Why not minimise control requirements using self-consistent scenario *(D)* ?

Hybrid scenario:

AIM: Improve core confinement and β, without need for stringent control



I: Obtain low central shear, q_0~1, no sawteeth (no ITB !)

II: Apply main heating to obtain β_N ~ 2-2.5 + mild MHD.

III: Extend heating, raise to $\beta_N \sim 4l_i$ with stationary q(r). Edge: Type I Elms.

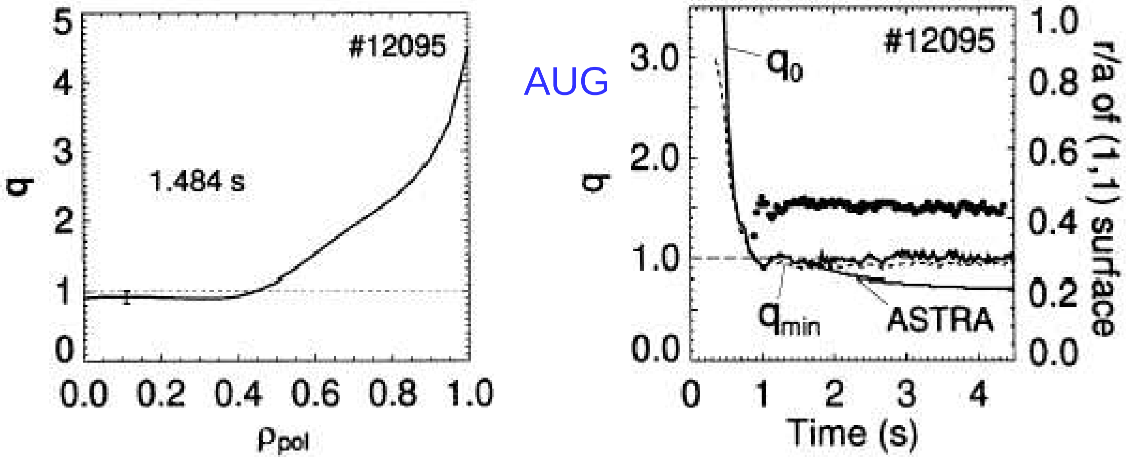
Developed at ASDEX Upgrade and DIII-D: $H_{89}\beta_N$ ~ 7, I_{CD}/I_p~ 50%

[ASDEX Upgrade, Sips PPCF **44** ´02 A151 & DIII-D, Luce NF **43** ´03,321]

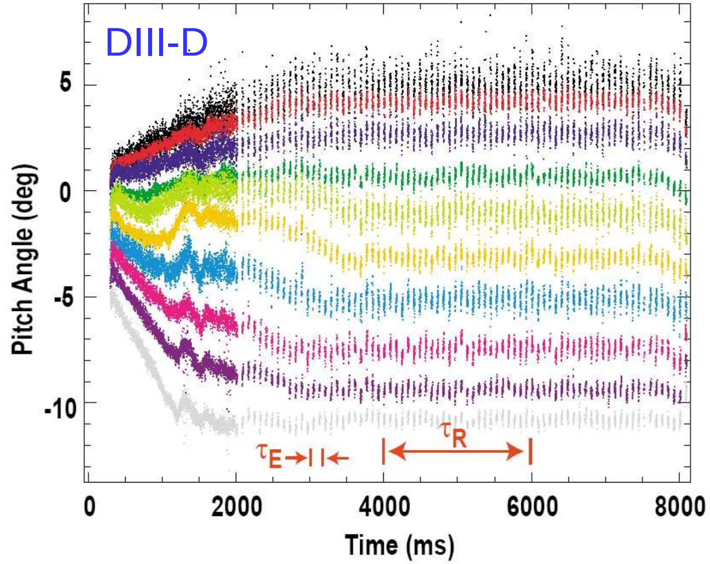
Hybrid scenario: Advanced with minimum control ?

q-profile is stationary without control, MHD events play key role:

Fishbones, [Wolf PPCF **41** ´99, B93]



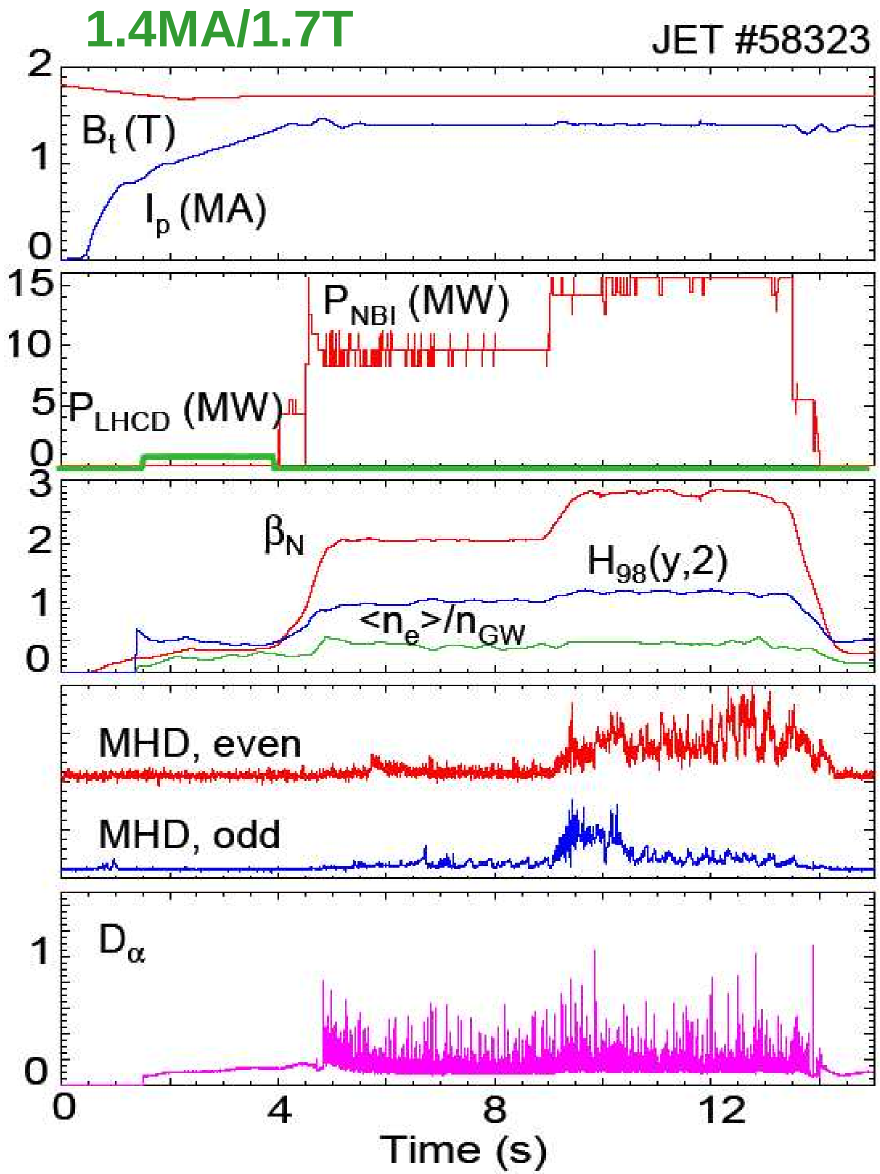
3/2 NTM, [Luce IAEA´02]



High beta (β_N ~ 4l_i) without ITB: Transport analyses in AUG and DIII-D, show that, although profiles are peaked, core transport is driven by ITG and ETG/TEM turbulence (profiles are stiff).

How does this regime extrapolate to a reactor ? ***(D)***

Hybrid scenario: International collaborations (ITPA)



Experiments at JET [Sips EPS ´03].

- establish hybrid scenario, with non-dimensional parameters similar to AUG (DIII-D)
- make them stationary.
- document differences (if any) when going to lower ρ*.

Map existence domain [Luce EPS´03]

- Experiments at AUG & DIII-D.
- For which q_{95} and density (0.3 $<n_e/n_{GW} <1$) ?

With I_{CD}/I_p ~ 50% not steady state ! *(R)*

ITB control in burning plasmas - Discussion

Internal barrier control and sustain (edge control ?):

- Simple control on reaction rate can not be used to avoid disruptions in ITB plasmas when α-power is main heating source in core.
- Need to control q(r) and p(r) to be reactor relevant at high beta !
- Control of profiles with control on Tsurface of first wall.
- Hybrid scenario: minimum control, why $q_0 \sim 1$ without sawteeth ?

Internal barrier control, sustain:

1. Control of the edge (e.g ELMs) for ITB plasmas ?
2. Control matrices: modelling or step responses in experiments ?
3. Rotation profile control in a reactor OR impurity accumulation?
4. Should go to higher beta soon (better ITB$\rightarrow$ impurity accumulation ?)
5. How much power for ECCD and NBCD in ITER would you need ?
6. More discussion points..........