Structure and Dynamics of Internal Transport Barriers.

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Acknowledgements: Clive Challis, Flavio Crisanti, Xavier Garbet, Claude Gormezano, Guido Huysmans, Shunsuke Ide, Emmanuel Joffrin, Xavier Litaudon, Tim Luce, Robert Wolf

Framework

- Discussion of physics mechanisms which trigger and sustain internal transport barriers
- Similarities and differences between machines and magnetic geometries
- Emphasis on ion and electron barriers and the similarities and differences between them
- Include role of MHD in limiting core barrier

Contributed papers for Topic A

- Formation conditions of electron internal transport barriers in JT-60U plasmas, by **T. Fujita**
- Comparison of electron internal transport barrier in LHD Heliotron and JT-60U Tokamak Plasmas, by **K. Ida**
- Cold Pulse Experiments in Plasmas with and without Barrier on LHD, by **S. Inagaki**
- Status of and prospects for Advanced Tokamak regimes from multi-machine comparisons, by **X. Litaudon**
- Observations of core modes during RF-generated ITBs in Alcator C-MOD, by **AG Lynn**
- Study of Internal Transport Barrier in the Initial Phase of Ohmic Discharge in the TUMAN-3M, by **A.S. Tukachinsky**
- Progress in Alcator C-MOD Internal Transport Barrier Studies, by **CL Fiore** *(topic D)*
- Study of Transport Barrier Dynamics with Dual HIBP Systems, by **A. Fujisawa** *(topic F)*

Credits

On top of many works about ITBs, incl. the previous H-mode Workshop, two recent outstanding reviews are to be acknowledged:

- **A Review of Internal Transport Barrier Physics for Steady State Operation of Tokamaks**, by *J. W. Connor, T. Fukuda, X. Garbet, C. Gormezano, V. Mukhovatov, M. Wakatani, the ITB Database Group and the ITPA Topical Group on Transport and Internal Barrier Physics, to appear in Nucl. Fus.*

- **Internal Transport Barriers in tokamak plasmas,** *by R. Wolf, PPCF* ***45*** *(2003) R1-R93.*

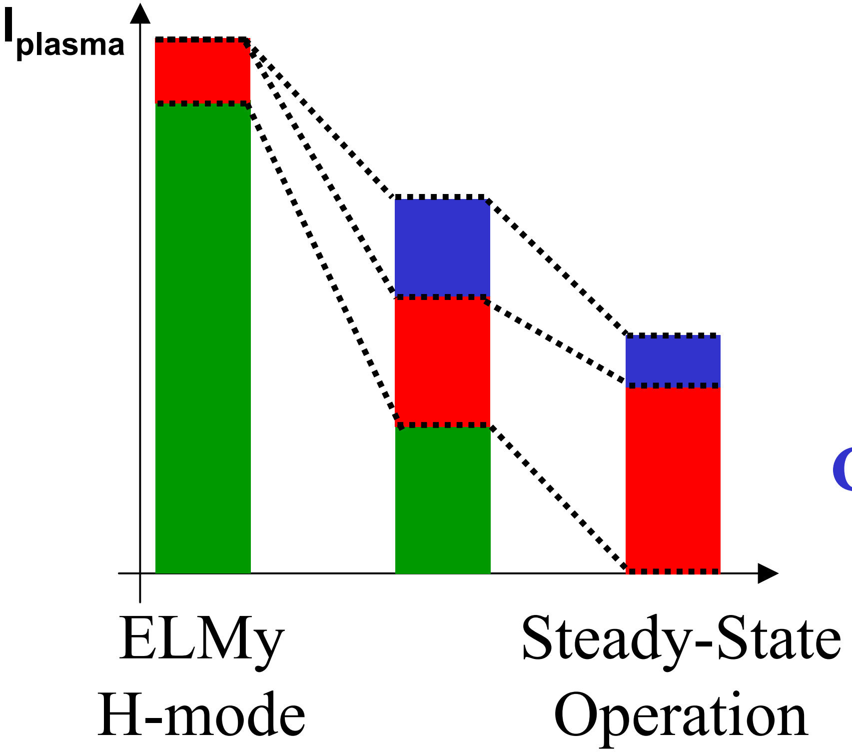
Introduction

$$I_{plasma} = I_{ohmic} + I_{bootstrap} + I_{additional}$$

I_{ohmic} → duration

$I_{bootstrap}$ → $\propto \beta_p$

$I_{additional}$ → Q



Steady-State Operation

=

High Bootstrap Fraction

+

Confinement Enhancement

$$\tau_{E,th}^{ELMy}=0.0562 x I_p^{0.93} B^{0.15} P^{-0.69} n_e^{0.41} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa_{eff}^{0.78}$$

Predictive Transport Model Picture

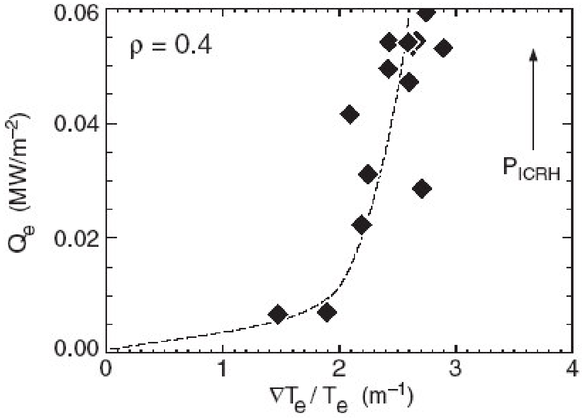
>The plasma transport is dominated by turbulence phenomena

>The plasma turbulence mostly originates in the electrostatic toroidal drift waves (at low β) and/or in MHD high-n ballooning modes (at higher β)

>The most severe modes are "interchange driven", i.e. are unstable when the pressure gradient is aligned with the gradient of the equilibrium magnetic field (LFS, toroidal geometry):

- Long wavelength modes ($k_\perp \rho_i<1$): ITG, TEM
- Short wavelength modes ($k_\perp \rho_i>1$): ETG

>Turbulence appears beyond a Critical Temperature Gradient ("profile stiffness")

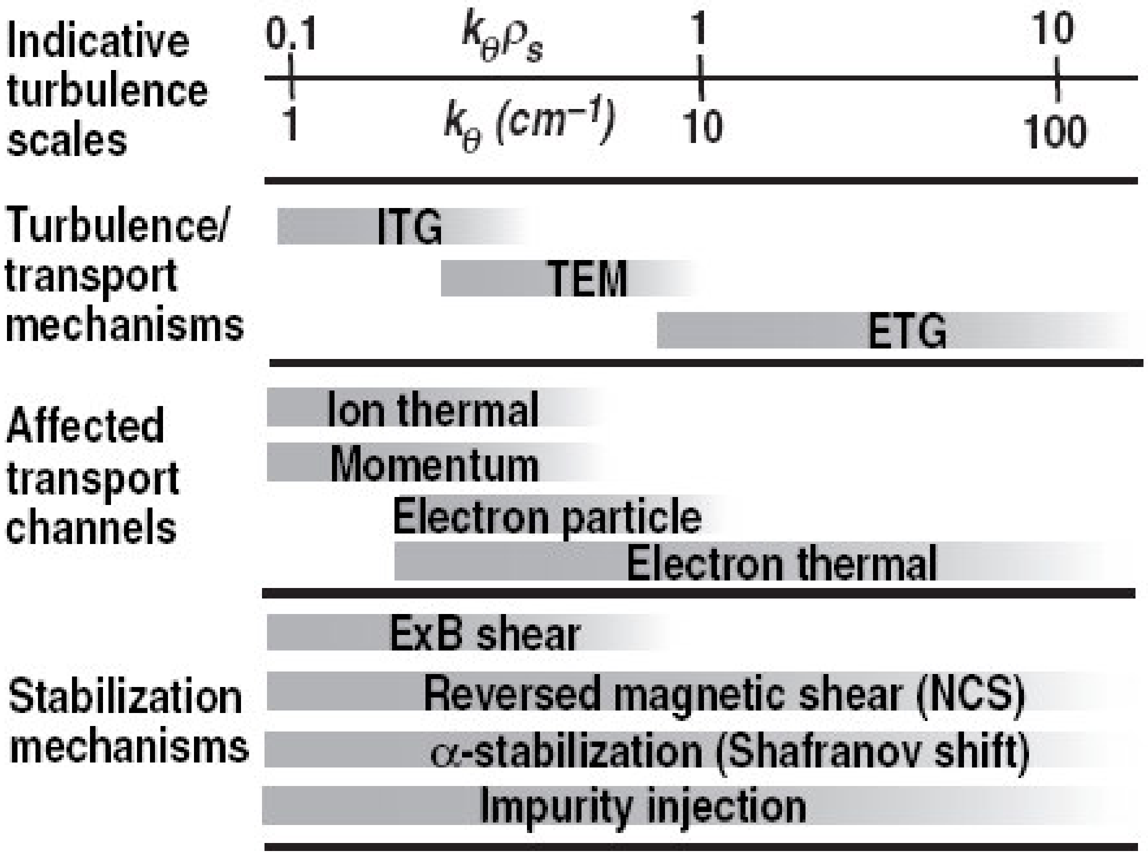


W. Suttrop et al., EPS Conf. 2001

Predictive Transport Model Picture

Several ingredients may act upon the various modes:

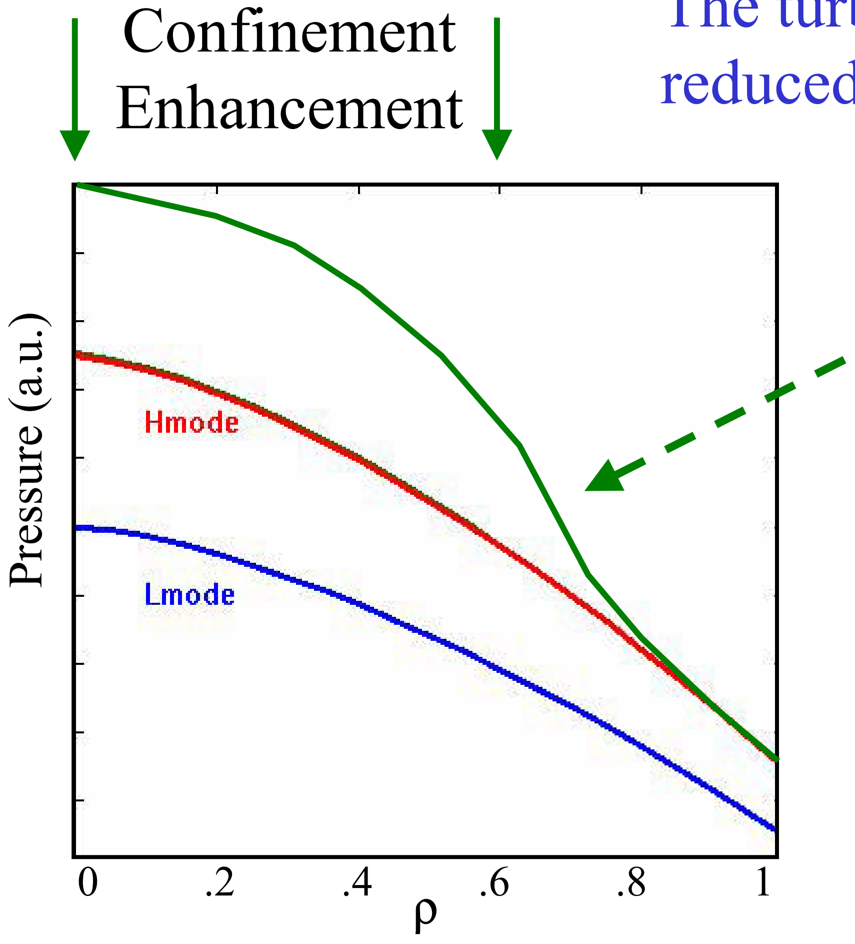
- density peaking $n_{e0}/\langle n_e\rangle$
- magnetic shear $s=\rho/q\ dq/d\rho$
- rotation shear ω_{ExB}
- Shafranov shift $\alpha = -q^2 R_0 \nabla\beta$
- Te/Ti ratio
- impurity content



E. Doyle et al., NF 42 (2002) 333

Internal Transport Barriers

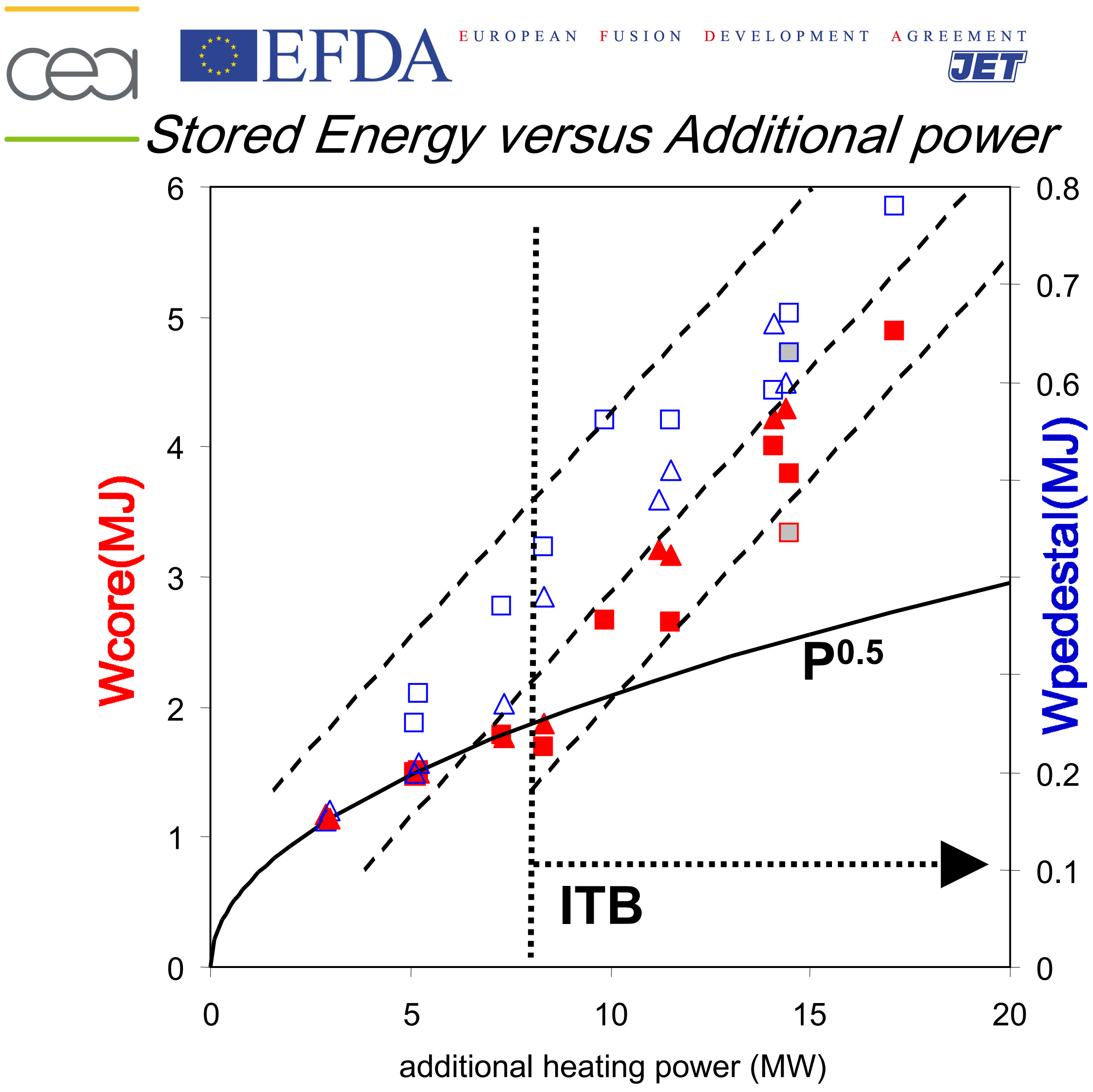
The turbulence-driven transport can be reduced/suppressed in the plasma core



Large pressure gradient
=> High Bootstrap fraction

Triggering & Sustaining ITBs, in principle, allows a Tokamak Steady-State Operation

Confinement Enhancement from ITBs



- ➢ $W_{pedestal}=3 \times vol \times n_{pedestal} \times T_{pedestal}$
- ➢ $W_{core}=W_{dia}-W_{pedestal}$

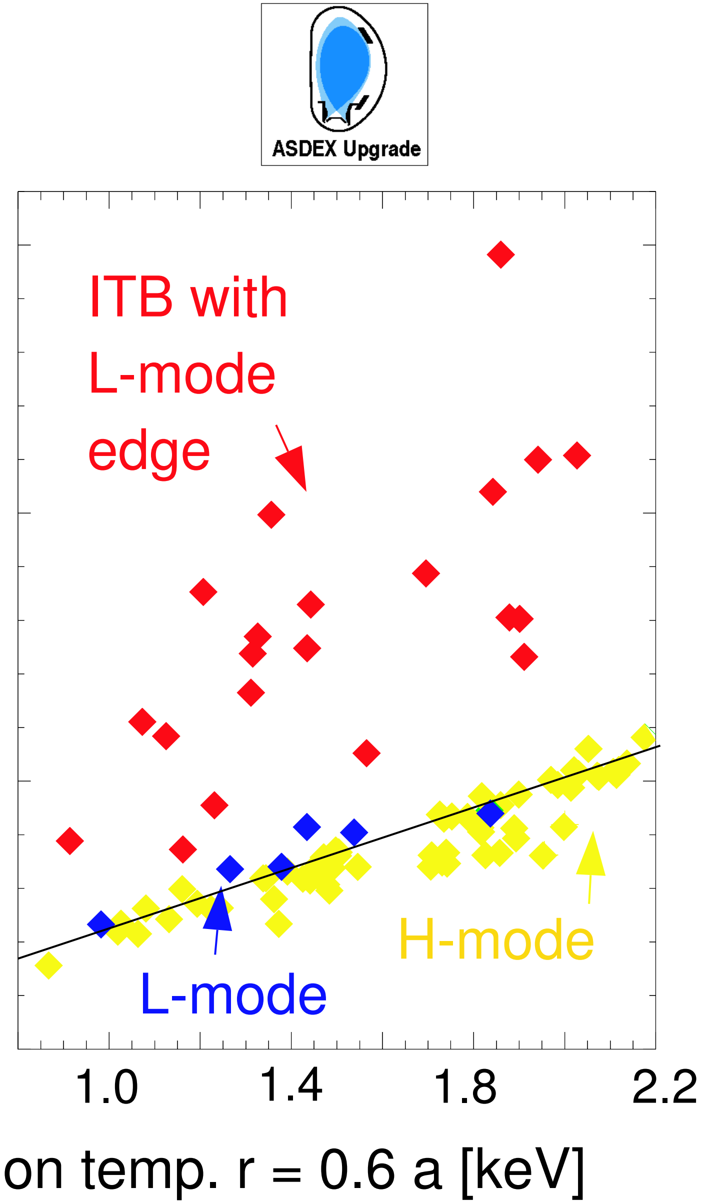
➢Pedestal energy increases linearly with power

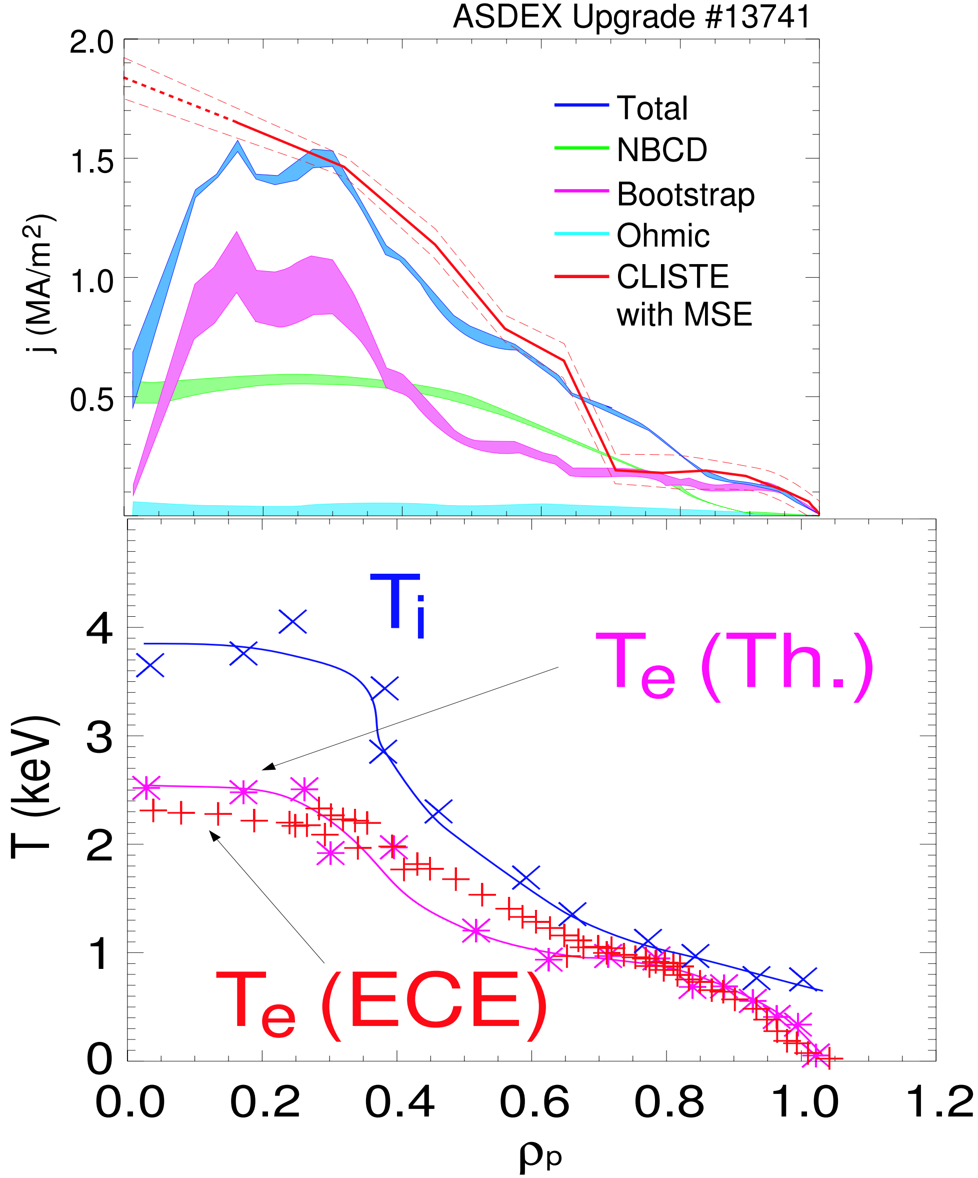
➢Core energy degrades with ~$P^{0.5}$ until the ITB is formed, then follows the pedestal energy

➢Core energy dominates performance ($W_{pedestal}$ / W_{dia}~15%)

C. Challis et al., EPS Conf. 2001

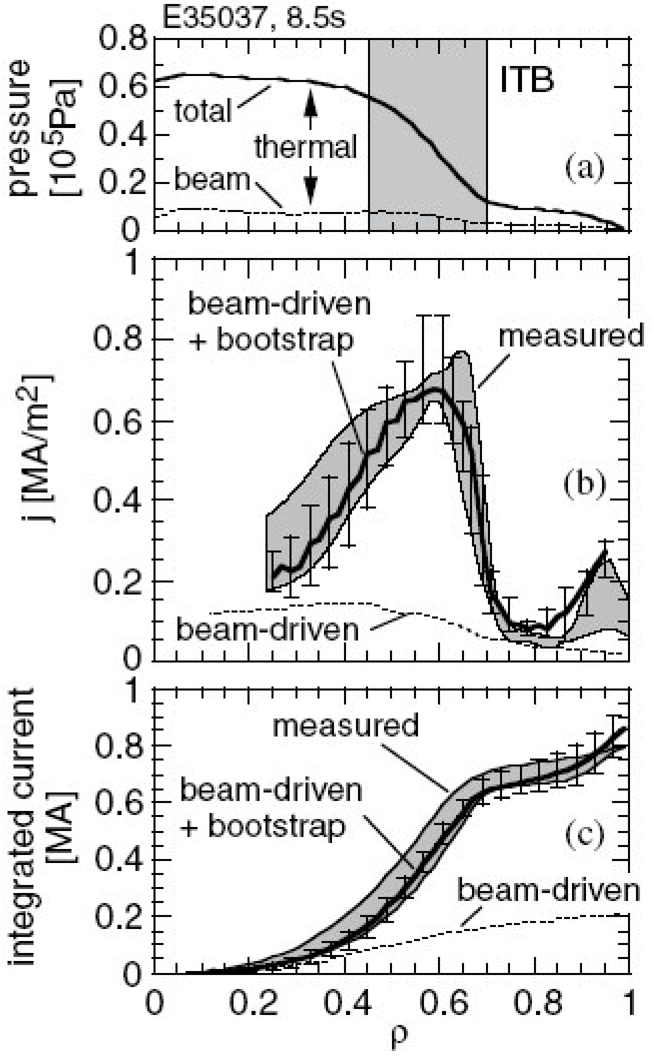
Large Pressure Gradients with ITBs

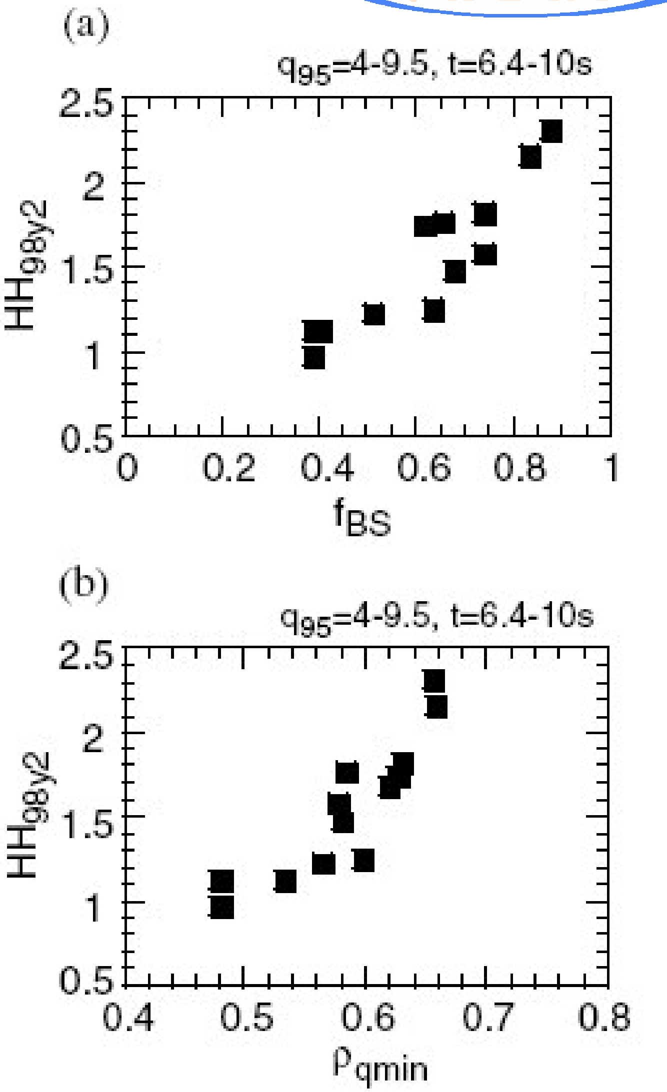




A. Peeters et al., NF 42 (2002) 1376

High Bootstrap Fractions with ITBs





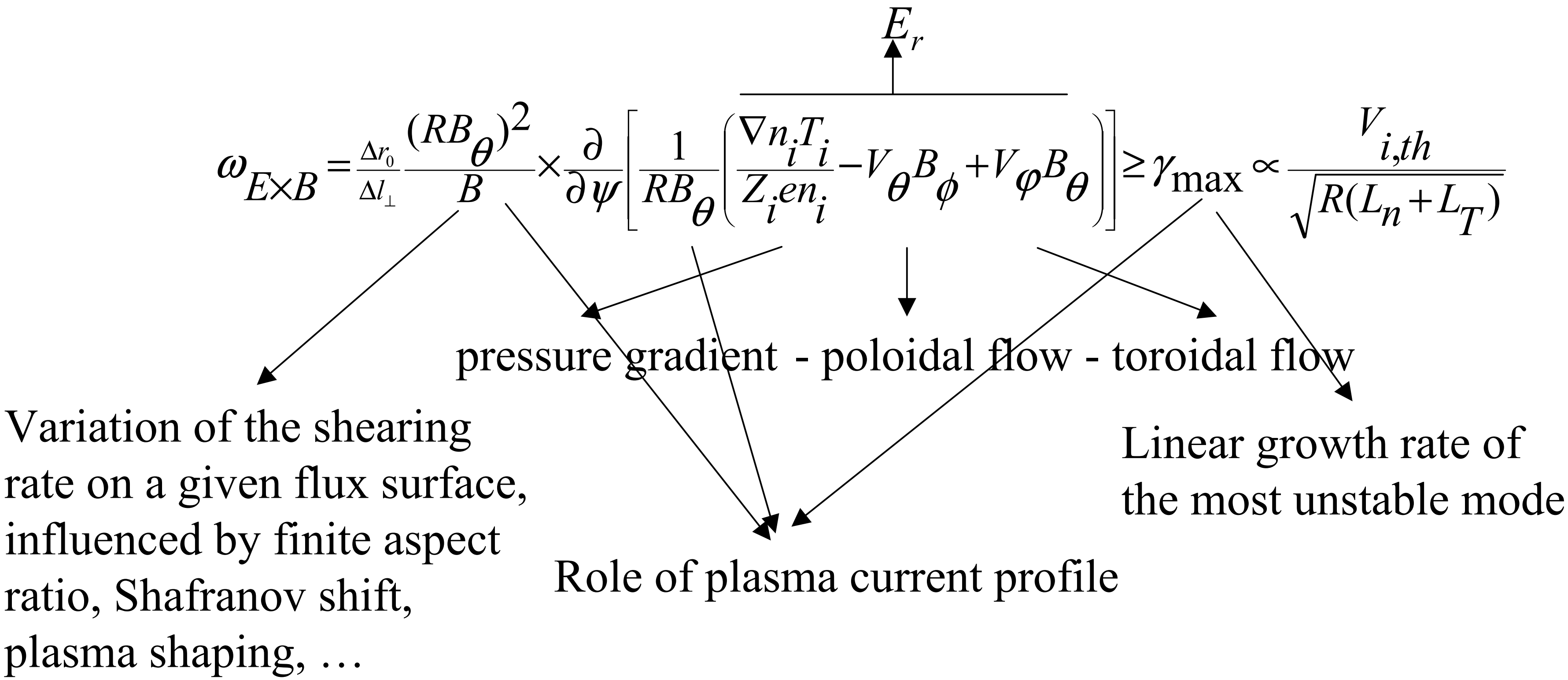
T. Fujita et al., NF 42 (2002) 180

Part A:
Physics Mechanisms which Trigger Internal Transport Barriers

The Role of Rotation Shear

The plasma poloidal rotation shear stabilises the drift-type plasma turbulence,

- either by reducing/suppressing the mode amplitude (predominantly ITGs & TEMs)
- or by altering the radial correlation lengths (breaking up turbulence eddies)



$$\omega_{E\times B}=\frac{\Delta r_0}{\Delta l_\perp}\frac{(RB_\theta)^2}{B}\times\frac{\partial}{\partial\psi}\left[\frac{1}{RB_\theta}\overbrace{\left(\frac{\nabla n_i T_i}{Z_i e n_i}-V_\theta B_\phi+V_\varphi B_\theta\right)}^{E_r}\right]\geq\gamma_{\max}\propto\frac{V_{i,th}}{\sqrt{R(L_n+L_T)}}$$

pressure gradient - poloidal flow - toroidal flow

Variation of the shearing rate on a given flux surface, influenced by finite aspect ratio, Shafranov shift, plasma shaping, …

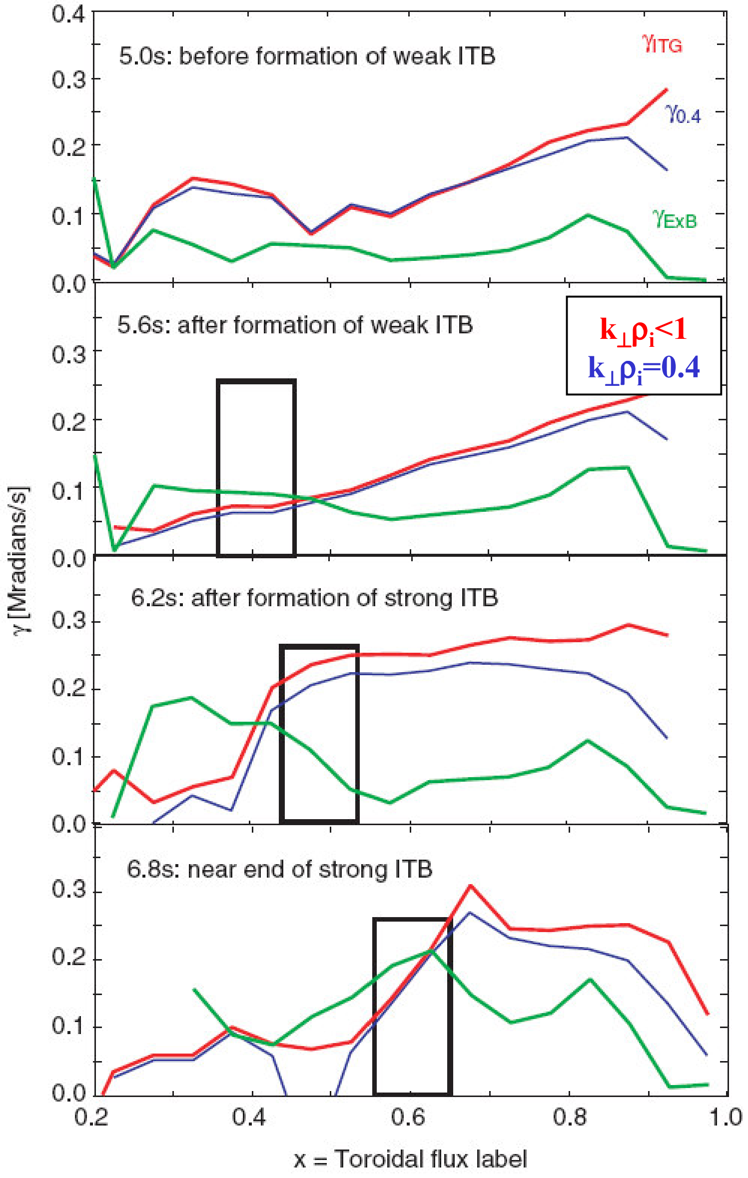
Role of plasma current profile

Linear growth rate of the most unstable mode

J. Connor et al., sub to NF

TS Hahm, KH Burrell, Phys. Plasmas 2 (1995)1648

The Role of Rotation Shear



JET pulse 51976

(Ip ~ 2.5MA, B=3.45T; q_{95} ~ 5, $H_{ITER89L-P}$. β_N = 7.8)

GS2 simulation with long wavelength modes

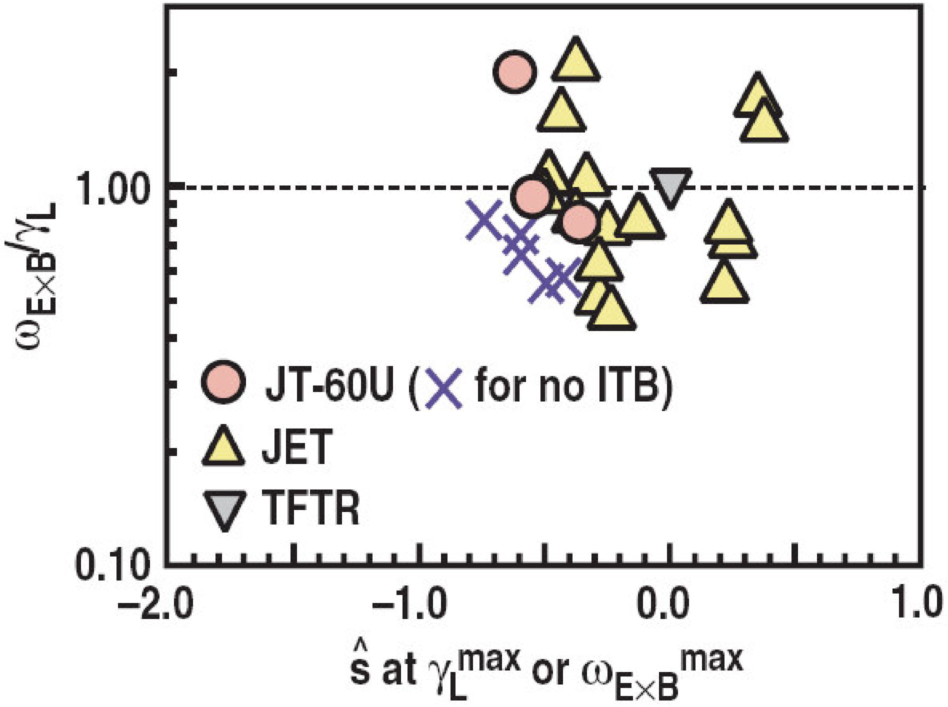
- A developed ion ITB clearly fulfills $\omega_{ExB}>\gamma_{ITG}$, mostly due to the pressure term in Er (self-amplification)

- Experimental uncertainties on ω_{ExB} and present turbulence models prevent from detailed conclusions about causality.

R. Budny et al., PPCF 44 (2002) 1215

The Role of Rotation Shear

The role confirmed on many tokamaks

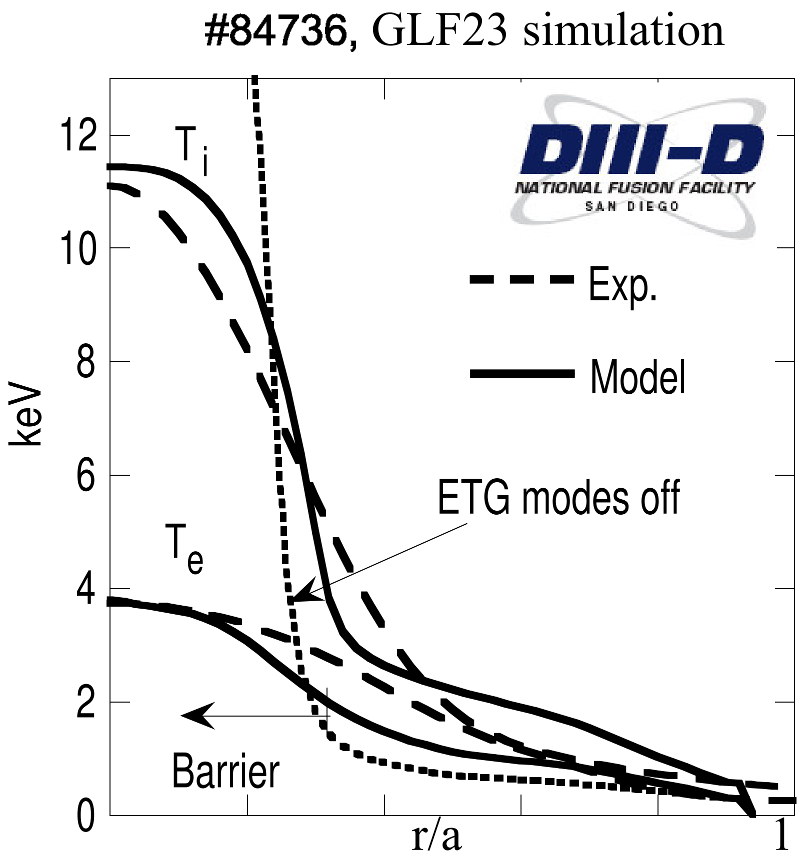


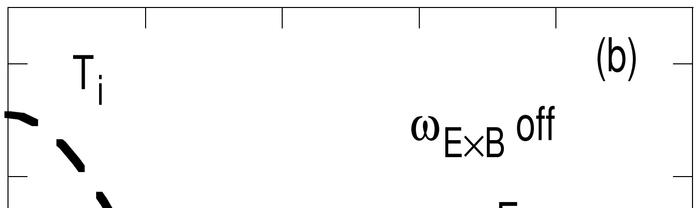
- International ITB database
- Ion ITBs with dominant ion heating
- Data taken at ITB onset

T. Fukuda et al., PPCF 44 (2002) B39

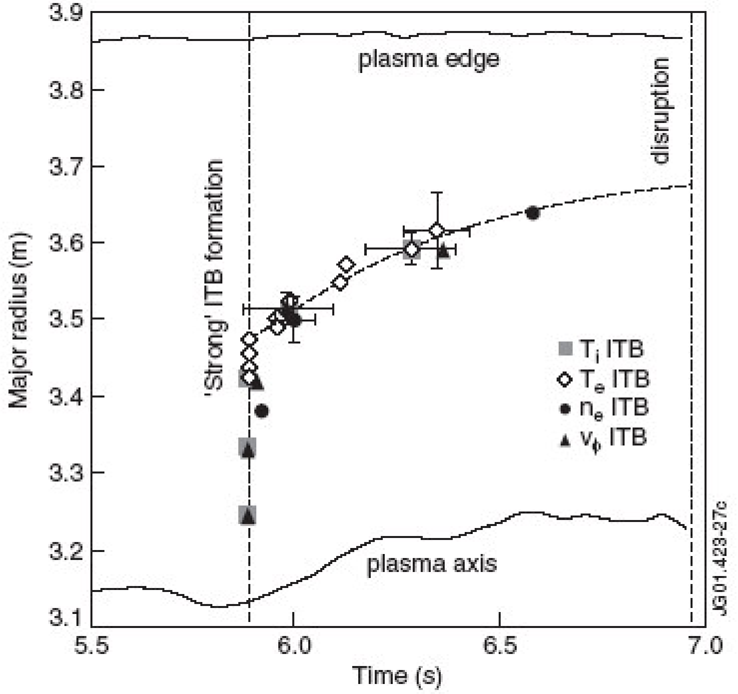
Ions, electrons, density, …

The various turbulence modes are not stabilized under similar conditions: the overall “background” confinement, collisionality, … conditions seem to play a role.


#84736, GLF23 simulation



EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET



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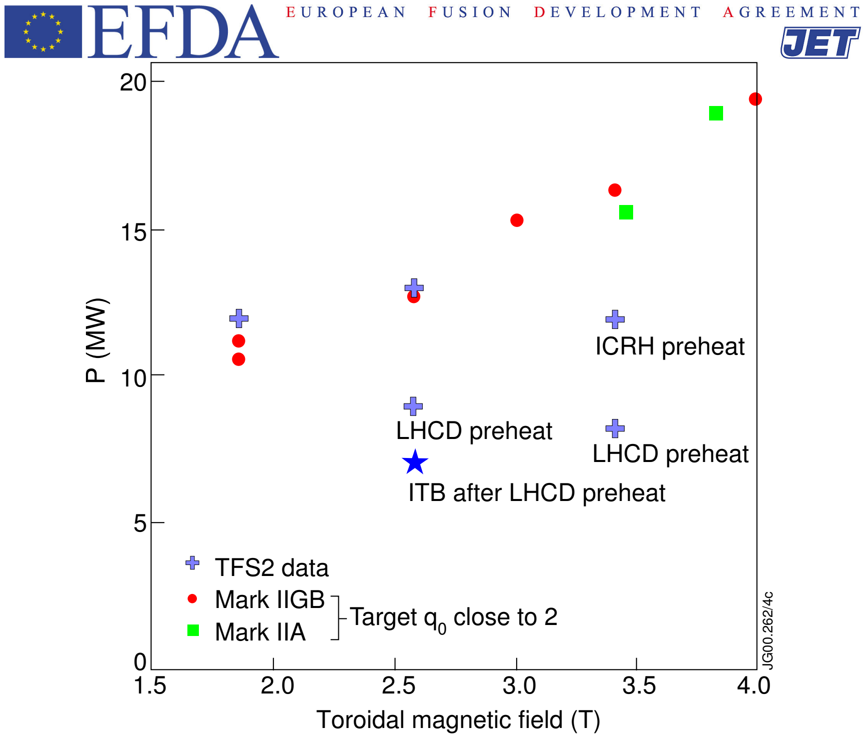
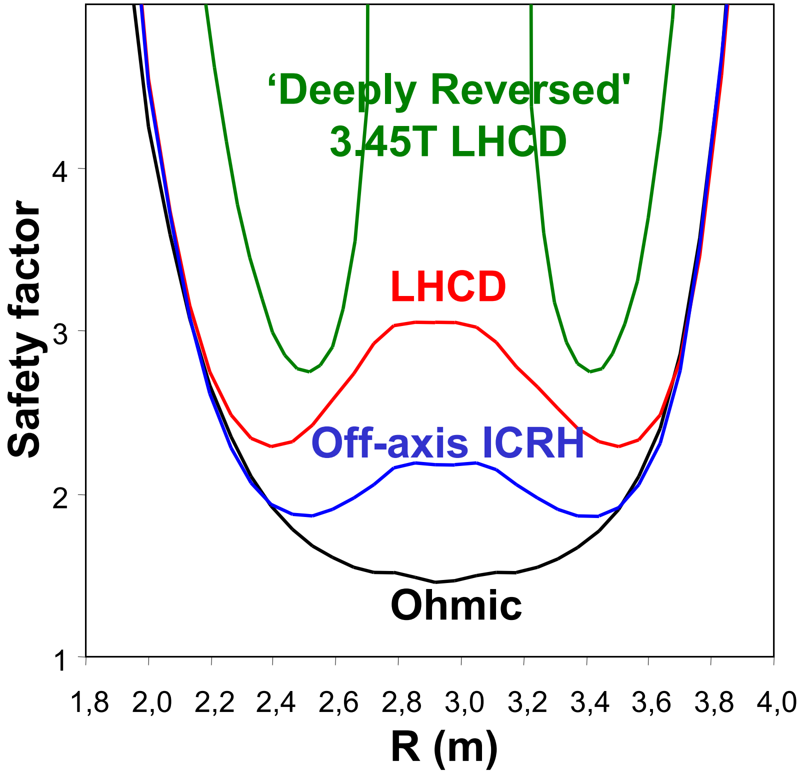
C. Challis et al., PPCF 2002

Influence of the Plasma Current Profile

The target q-profile influences the ion-ITB triggering power



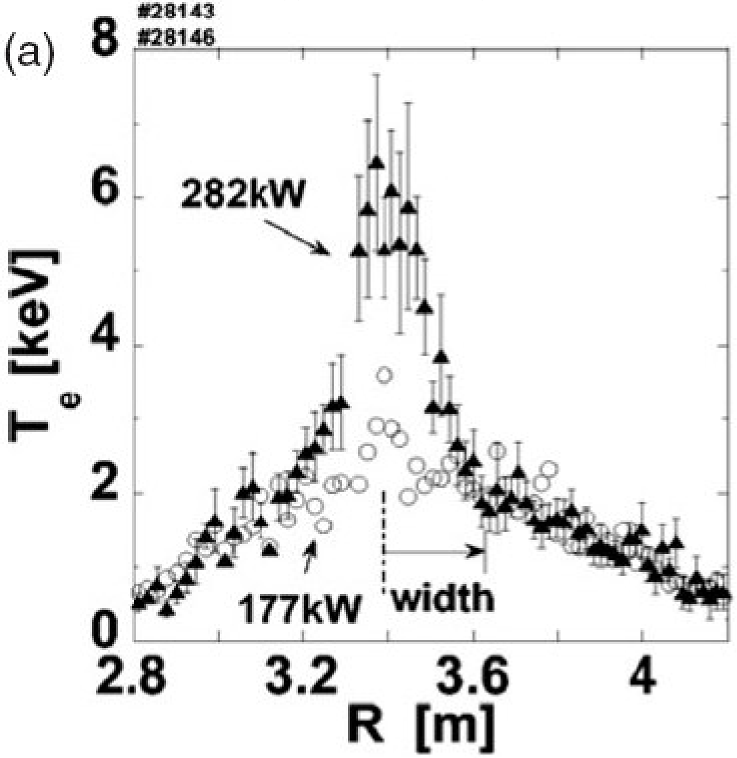


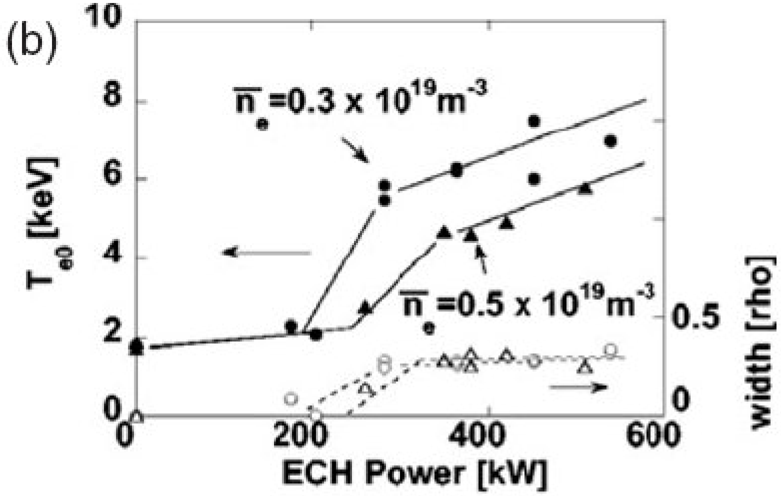
A. Bécoulet et al., EPS Conf. 2001

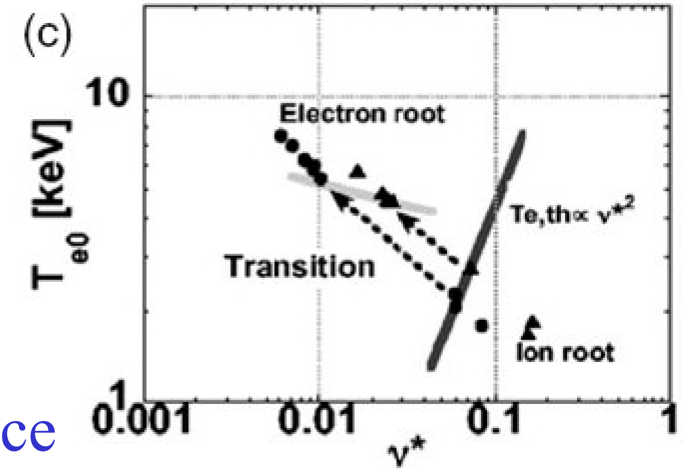
Electron ITBs in Helical Devices

The magnetic configuration is a key element in electron ITBs

4MW NBI + ECRH



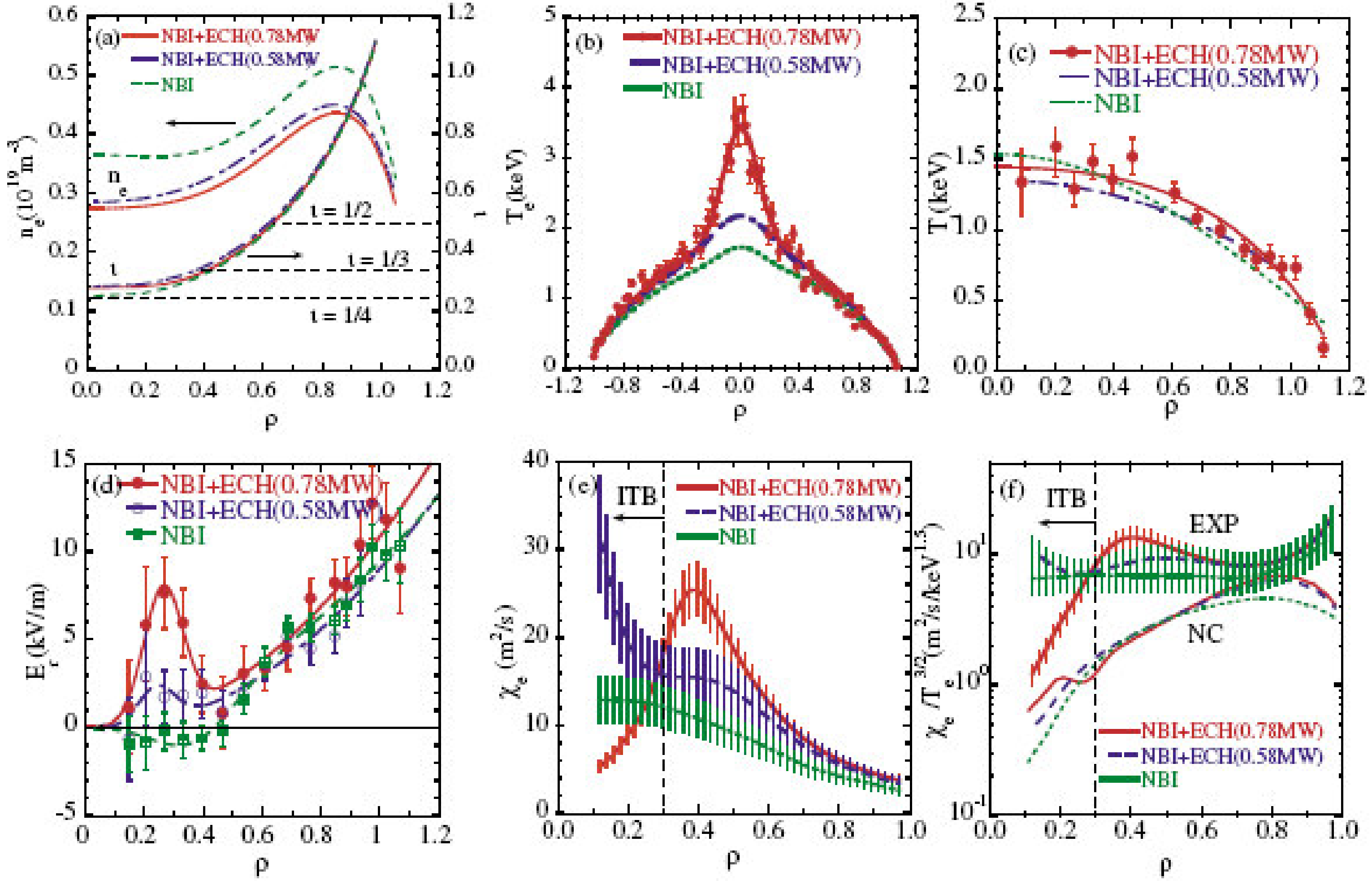




The width is linked to ι=0.5 surface

T. Shimozuma et al., PPCF 2003

Electron ITBs in Helical Devices



The width is linked to ι=1/3 surface

K. Ida et al., PRL 2003

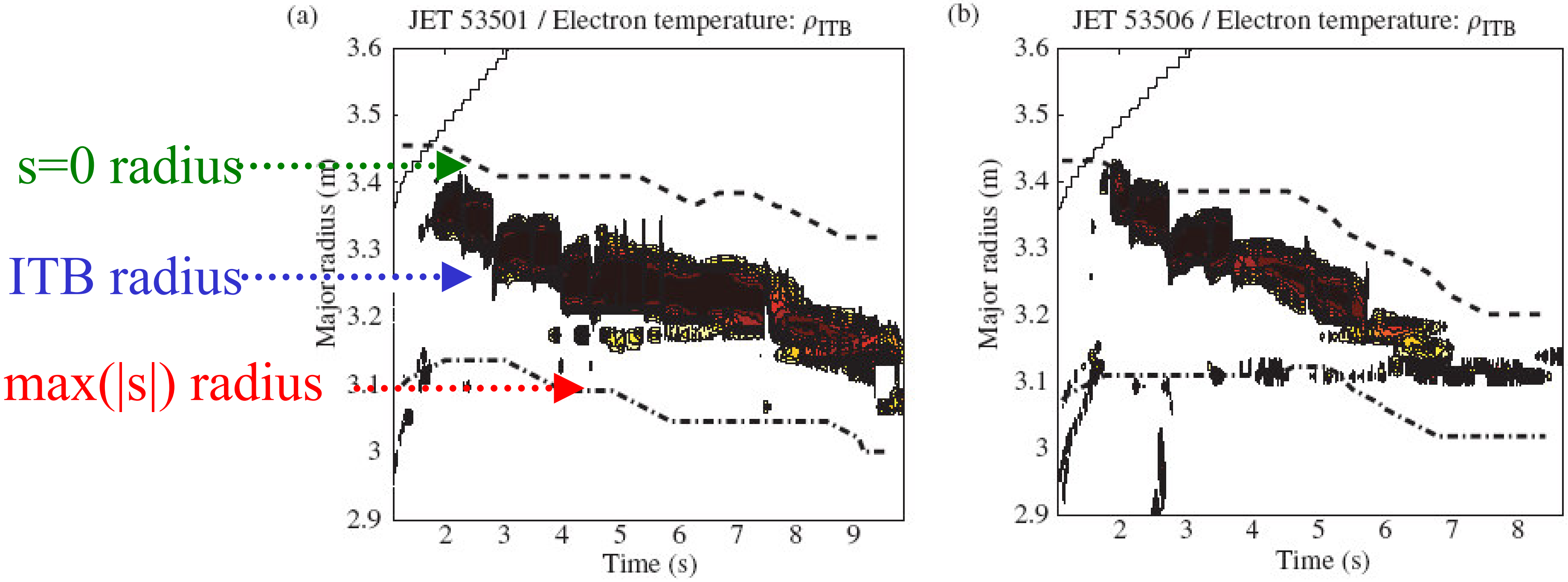
The « manifold role » of current profile

- B_θ directly influences ω_{ExB} (*lower magnetic shear -> lower shearing rate*)
- The magnetic shear modifies the turbulence behaviour,
  - *either by reducing or suppressing the growth rate of some instabilities*
  - *or by disconnecting toroidally linked vortices (low shear & rational-q surfaces)*
- a particular q-profile might
  - suppress the confinement reduction due to MHD instabilities (sawteeth, …)
  - locally enhance shear flows through MHD islands located close to rational-q surfaces.

Electron ITBs in Reversed Shear Plasmas

Electron ITBs observed in negative magnetic shear regions.

(reversal of the trapped electron curvature drift decreasing the TEM drive for instance)



s=0 radius

ITB radius

max(|s|) radius

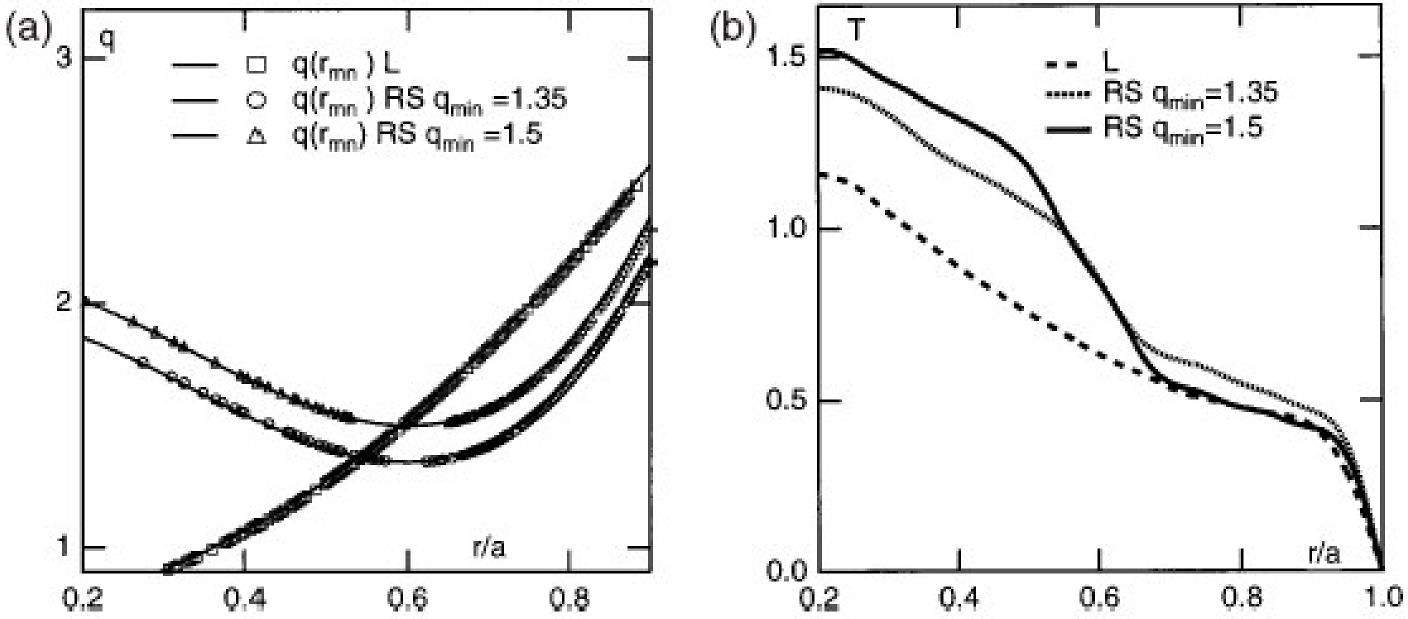
LHCD only

LHCD + ICRH

GMD. Hogeweij et al., PPCF 2002

Reversed shear and rational q-surfaces

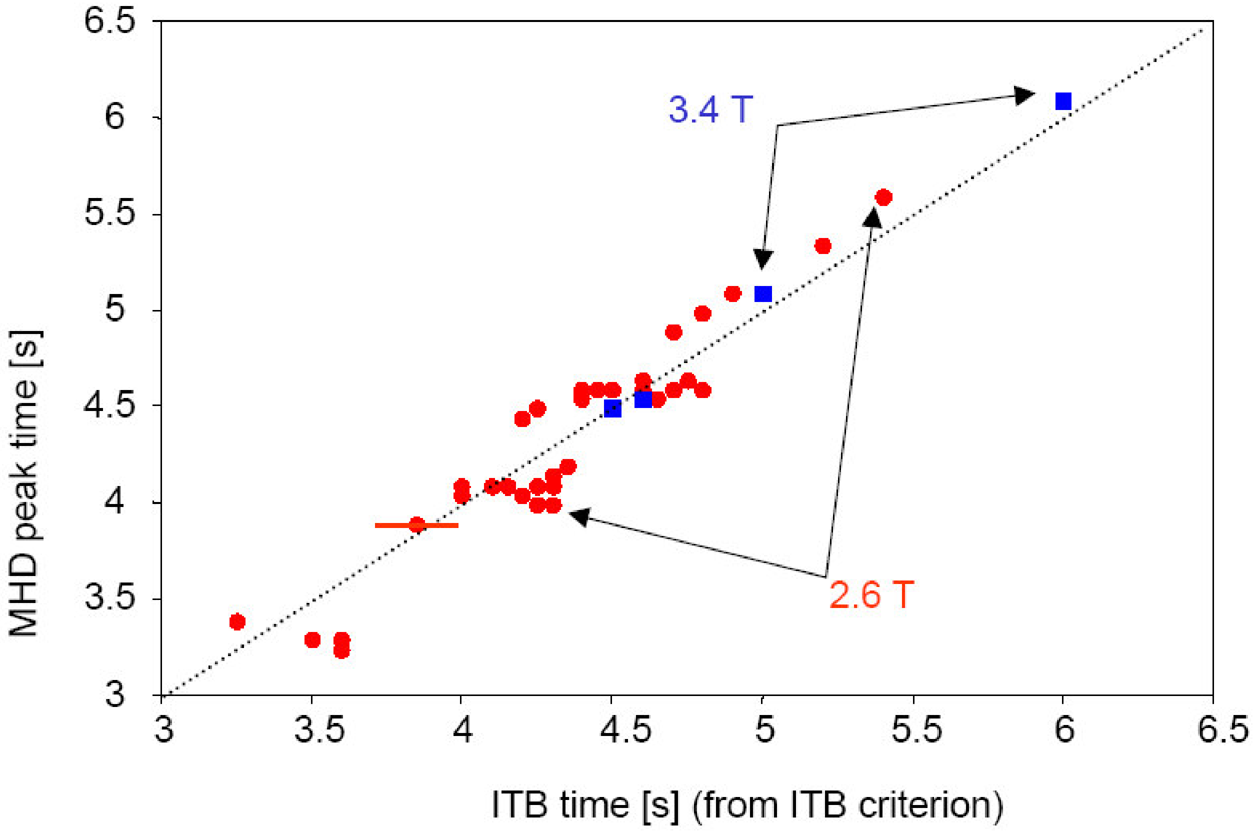
The rarefaction of rational-q surfaces in the vicinity of a low order rational q_{min} may cause a transport reduction by preventing turbulent cells to overlap.



X. Garbet et al., PPCF 2001

MHD may also play a direct role

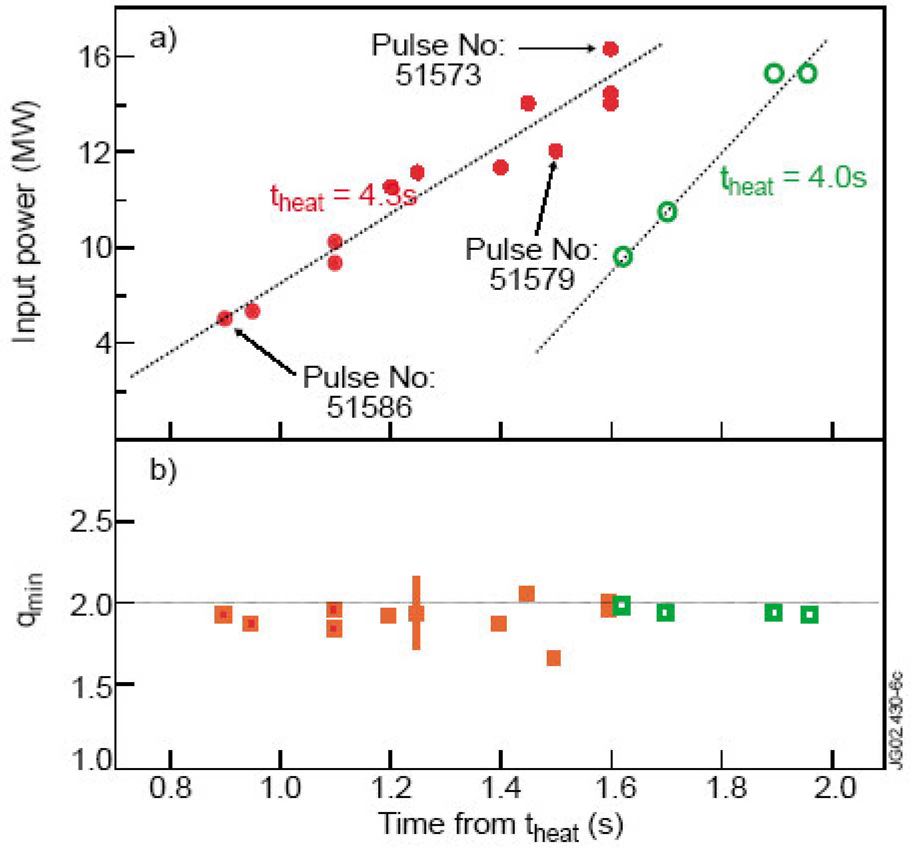
Correlation between edge MHD and ITB emergence
(monotonic q-profiles, ITBs linked with q=2 or q=3 radius)

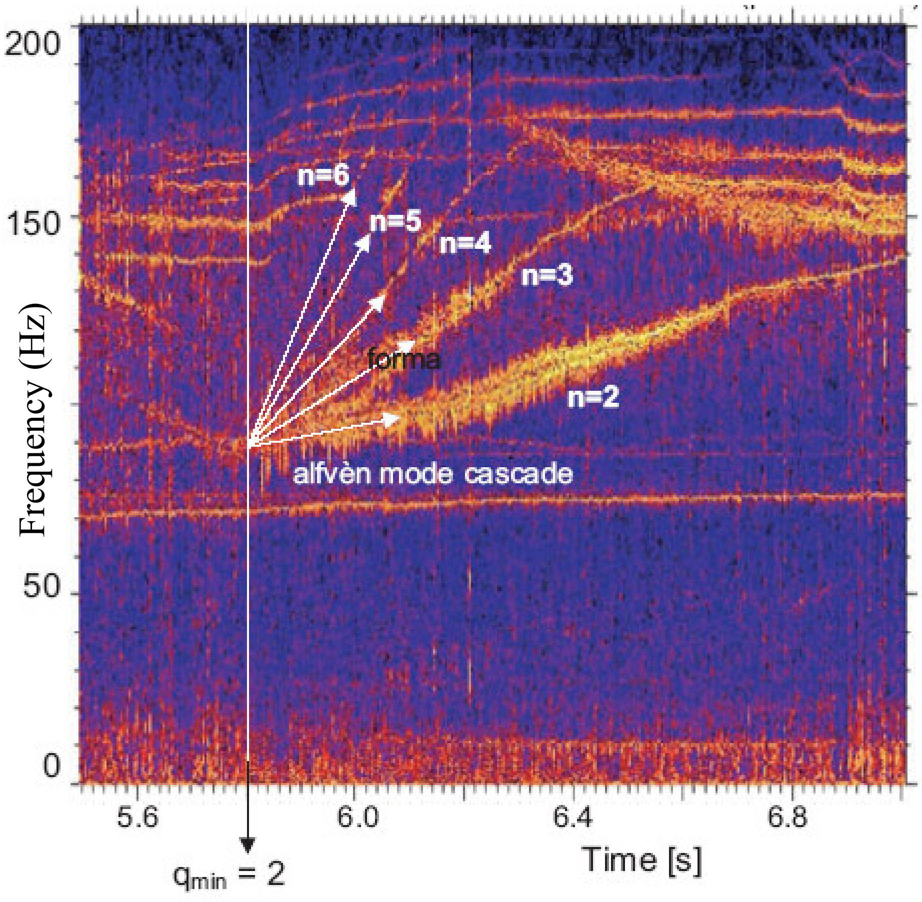


E. Joffrin et al., NF 2001

Reversed shear and rational q-surfaces

In RS plasmas, the ITB onset is linked to q-profile rather than to a threshold power ?



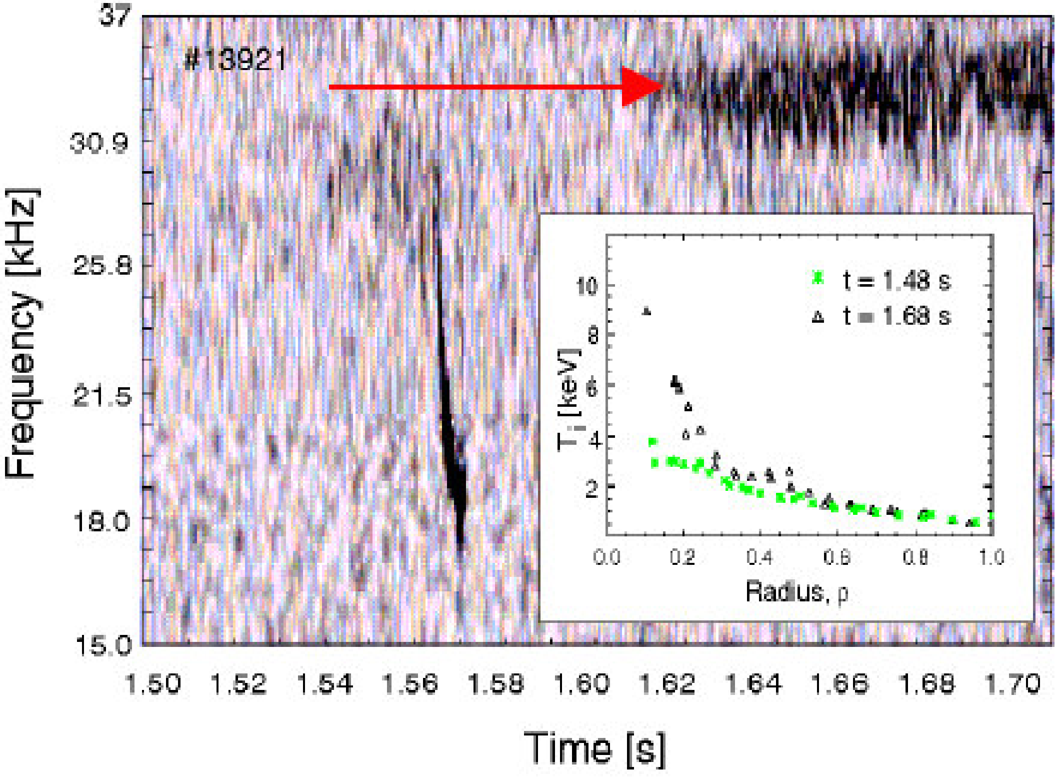


E. Joffrin et al., PPCF 2002

MHD may also play a direct role

MHD islands located close to rational-q surfaces locally enhance shear flows

Fishbone activity detected prior ITB formation

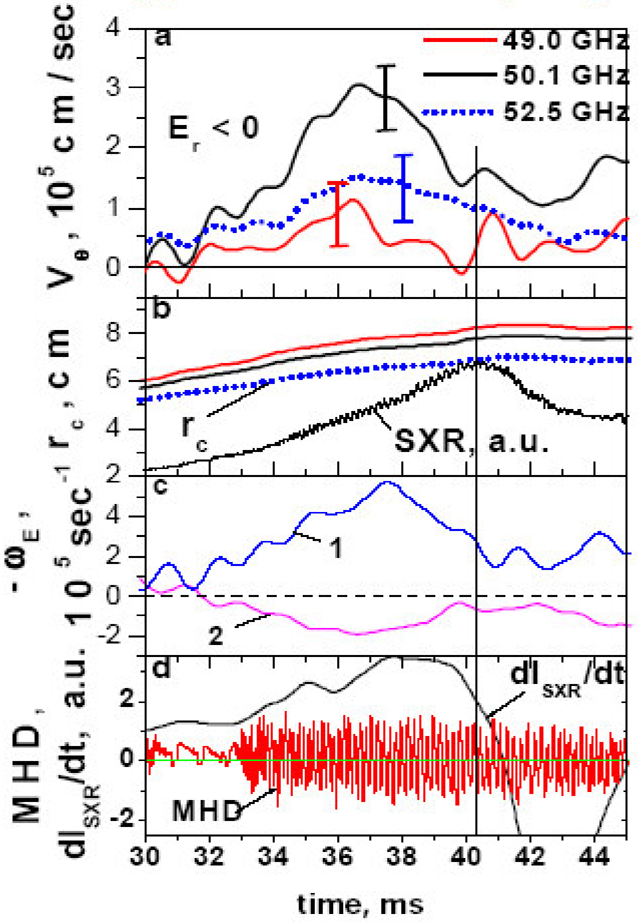


ASDEX Upgrade

E. Joffrin et al., IAEA 2002

MHD may also play a direct role

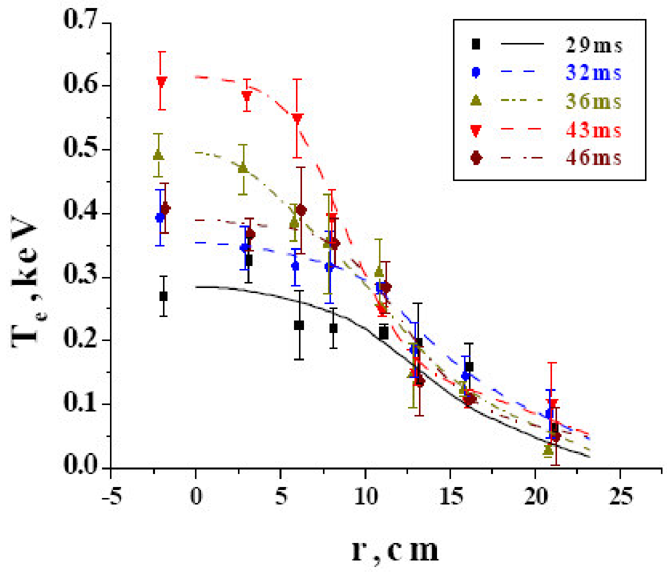
Results of Doppler Reflectometry Experiment



Evolution of poloidal velocities V_θ (a), cutoff radii r_c and $I_{SXR}(0)$ signal (b), shear of plasma fluctuation rotation rate ω_E (c), Mirnov probe signal (MHD) and $dI_{SXR}(0)/dt$ (d)

The Initial Phase of **Ohmic Discharge** in the TUMAN-3M

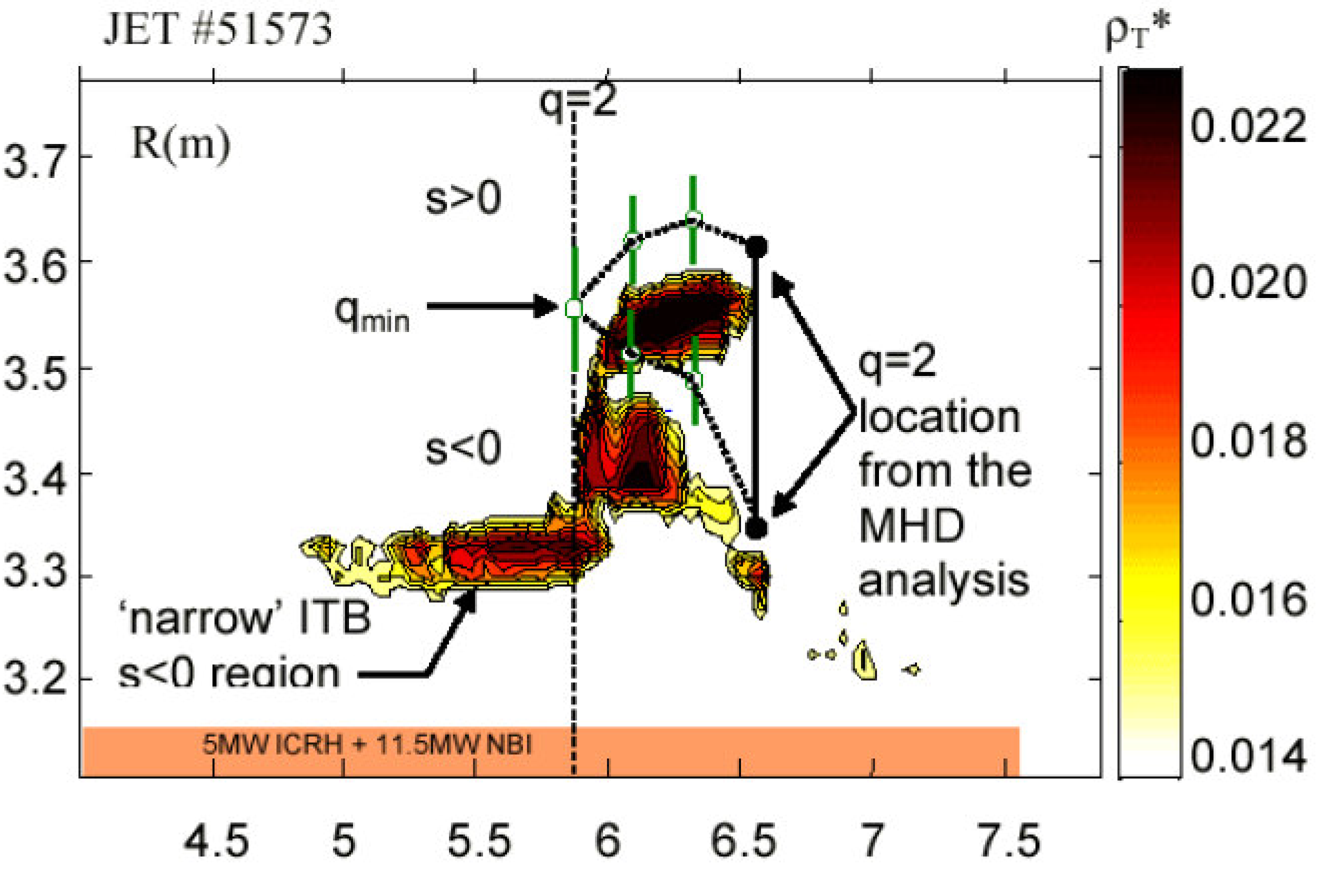
T_e profile evolution (Thomson scattering)



Temporal ITB formation was found in the core plasma during current ramp up phase

L.G. Askinazi et al., This Conf.

Complex situations then occur…



E. Joffrin et al., PPCF 2002

The role of Shafranov shift

- A large Shafranov shift also leads to a reduction of turbulence (compression of flux surfaces)
- A large Shafranov shift increases pressure gradients (on LFS) and hence E_r and ω_{ExB}
- strong negative magnetic shear favours large Shafranov shifts.

Turbulence is in fact sensitive to the local curvature of field lines (Low Field Side):

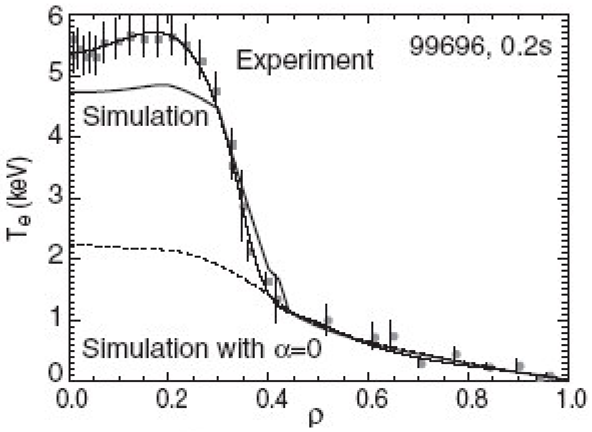
"actual shear"

=

"magnetic shear" + "velocity shear" + "Shafranov shift" + …

The role of Shafranov shift $\alpha = -q^2 R_0 \nabla\beta$

- The Shafranov shift can hardly play a role in the (usually low β) ITB triggering, but is certainly present in the development and sustainement phase
- The Shafranov shift effect probably competes with kinetic ballooning mode turbulence at high-β, making experimental identification of both effects difficult.



Off-axis ECRH

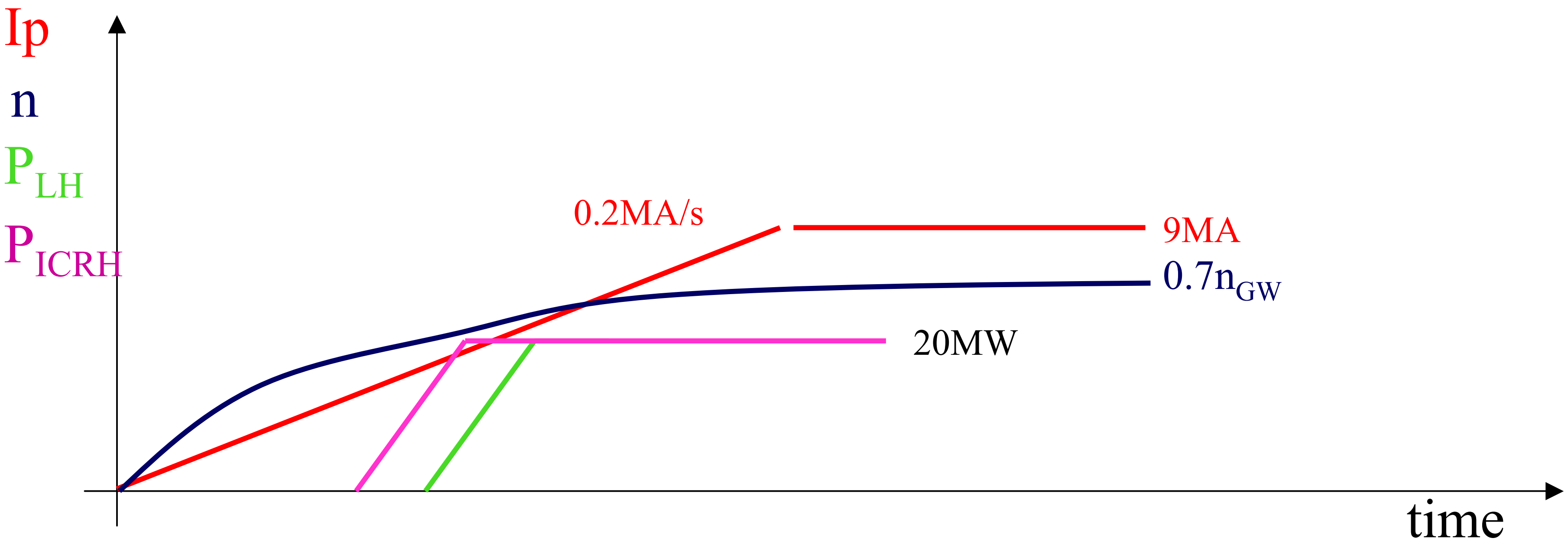
E. Doyle et al., NF 2002

Predictive modelling

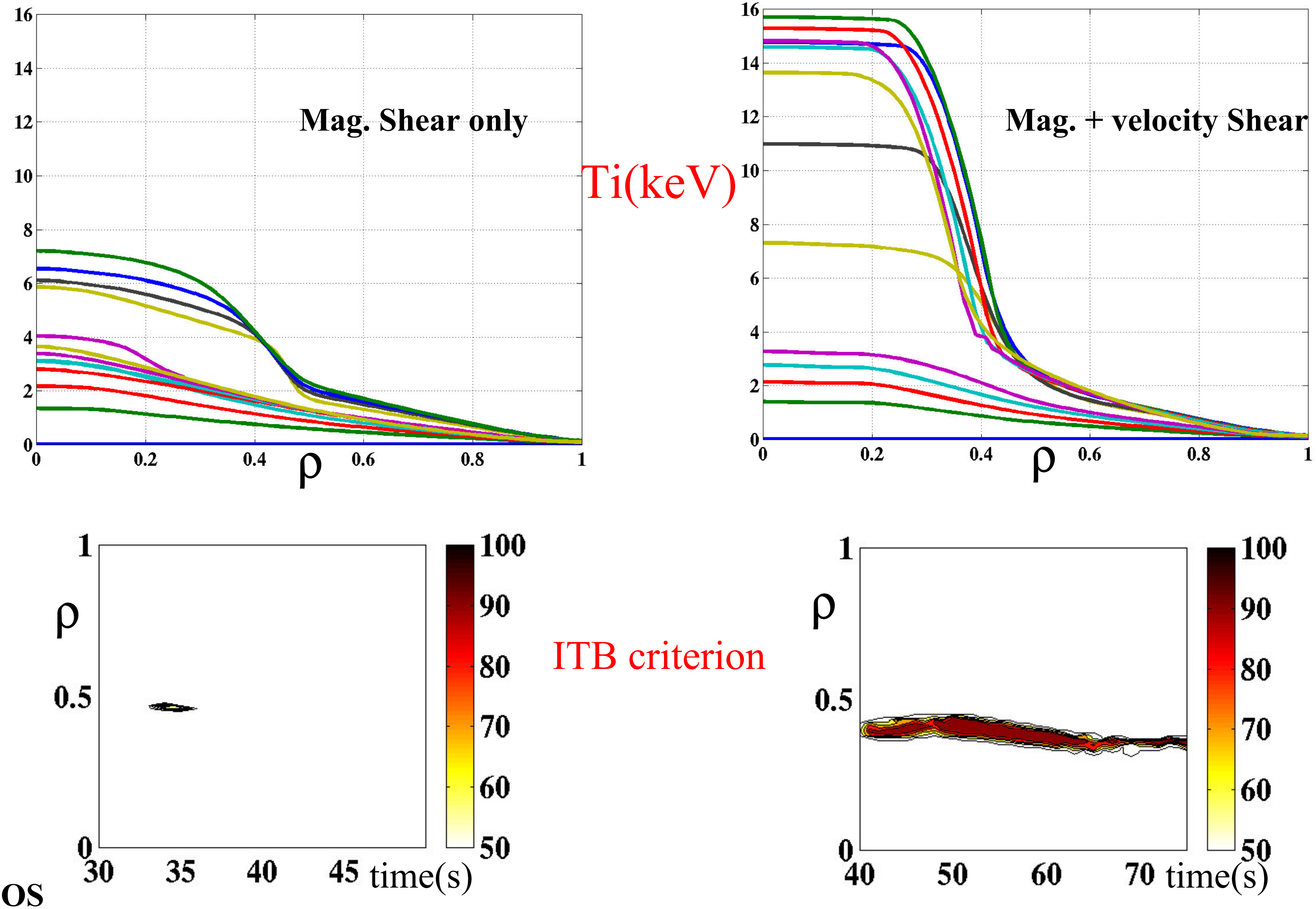
$$\chi = \chi_{Bohm}\, F(s_m, \omega_{ExB}/\gamma_{max}, \ldots) + \chi_{gBohm} + \chi_{neo}$$

$$F = 1/[1+\exp(\kappa(s_{crit} - s_m - \omega_{ExB}/\gamma_{max} - \ldots))]$$

A JET-like ramp-up phase in ITER, simulated by CRONOS



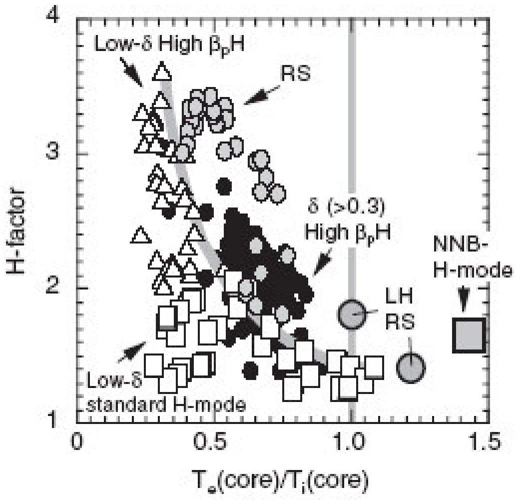
Predictive modelling for ITER



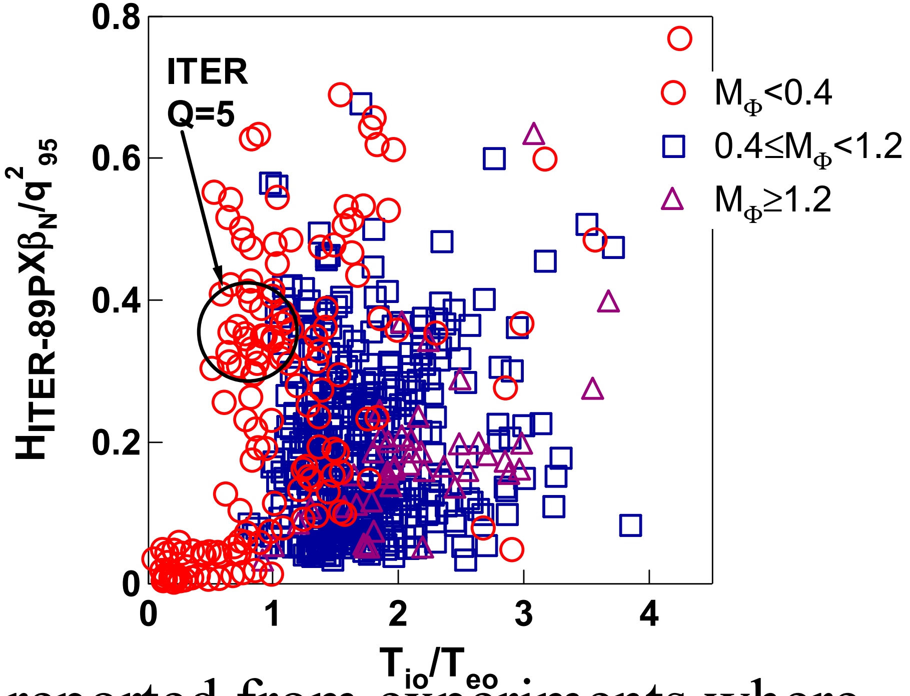
CRONOS

Role of Te/Ti

When Te/Ti increases, the growth rate of long wavelength turbulence (ITG) increases



Japan Atomic Energy Research Institute



But contradictory results are reported from experiments where electron heating is added to ion ITBs, mostly due to the possible compensation effects on e/i transport provided by the current profile modifications (direct CD, bootstrap) and/or Shafranov shift.

X. Litaudon et al., This Conf.

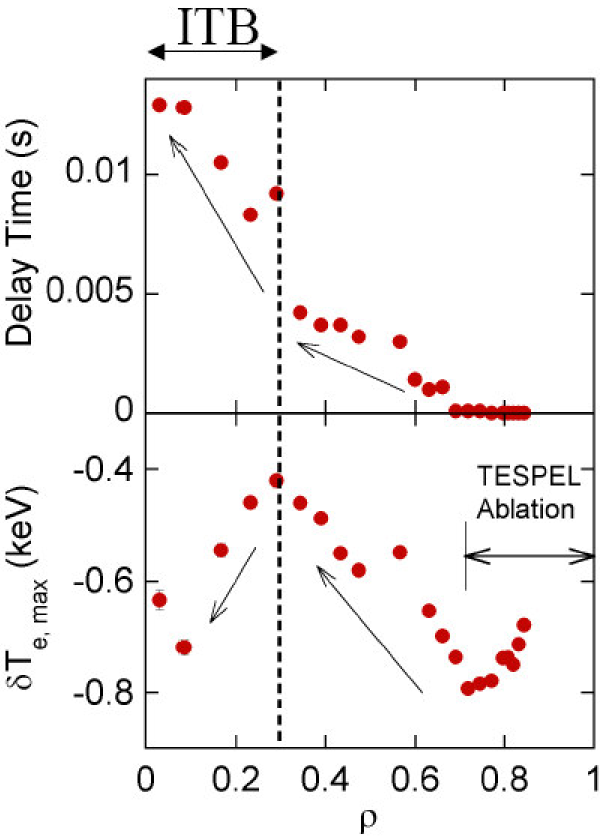
Probing transport in ITBs

Cold Pulse Experiments in Plasmas with ITB on LHD

The first attempt to apply the perturbative technique to ITB plasma in helical system is performed in LHD.

- ●Slowing down of cold pulse propagation velocity
- ●Enhancement of cold pulse peak

are observed inside the eITB in LHD.



S. Inagaki et al., This Conf.

The Role of Density Gradient

- ITGs are not directly associated with particle transport
- ITGs are not driven by density gradients
- ITGs are even partly stabilized by density gradients
- TEMs can also be driven by density gradients
- Interaction between ITGs and TEMs induces particle transport

⇒The density peaking plays a complex role on the turbulence behaviour.

⇒It does not seem to play the central role in the transition to ITB regimes.

R. Wolf, PPCF 45 (2003) R1

Discussion Part A

Do we agree on:

- The existence of a “$\omega_{ExB}>\gamma_{lin}^{max}$” criterion for long wavelength turbulence stabilisation, i.e. for ion heat transport improvement ?
- The very complex but crucial role played by the plasma current profile (and the V_ϑ term) on this criterion, in particular during the triggering phase?
- The dynamics of (pure) e-ITBs linked to the current profile evolution (power threshold?)
- The crucial role played by the pressure driven term and alpha stabilisation, after the triggering phase.

Open questions:

- What meaning for a simple power threshold criterion?
- What about particle transport barriers (Cmod)?

Part B:
Sustaining ITBs

MHD situation

The MHD instabilities in the advanced scenarios are either due to

-the large pressure gradients at the internal transport barrier

-the shape of the q-profile required to obtain an internal barrier

MHD related to ***pressure profile*** :

♦ global pressure driven kink

modes due to large peaking factor of pressure profile: $\beta_{N,max} \sim \langle p \rangle / p_0$

♦ Resistive-wall mode

unstable when $\beta_{N,max}$ exceeds ideal β limit without conducting wall but below the β limit with an ideally conducting wall

♦ Neo-classical tearing modes

in positive shear region, require a seed island to become unstable. Stable in negative shear region.

G. Huysmans

MHD situation

Instabilities related to the ***q-profile***:

◆ double tearing modes

with two nearby rational surfaces

◆ external kink modes

due low-li, large edge current from current ramp (possibly coupled to internal pressure driven modes)

◆ infernal modes

driven by large ∇p in low shear region

◆ resistive interchange modes

driven by large ∇p in large negative shear

The possible MHD instabilities pose strong restrictions on the pressure and q-profiles in steady state advanced scenarios

- ∇p not too large

- no low order rational q surface (1, 1.5 and 2)

- negative central shear not too large and not too small

NEED FOR

→ PRESSURE PROFILE CONTROL

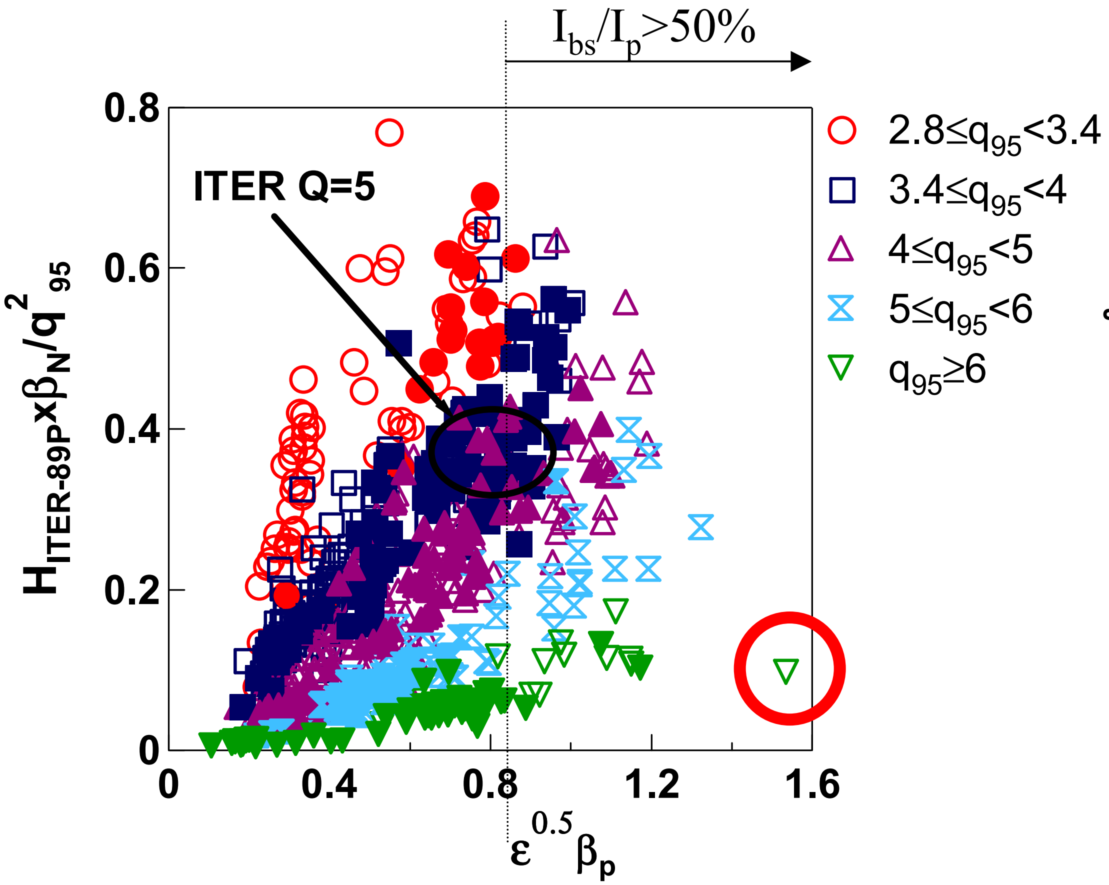
→ CURRENT PROFILE CONTROL

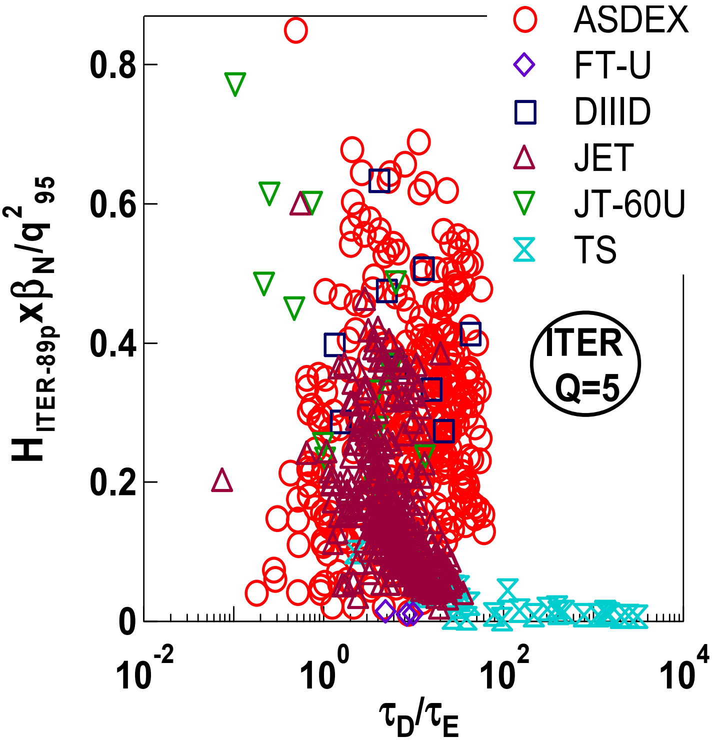
G. Huysmans

Performance level: where are we ?

Advanced Tokamak regimes seem to reach the performance required by ITER,

BUT …

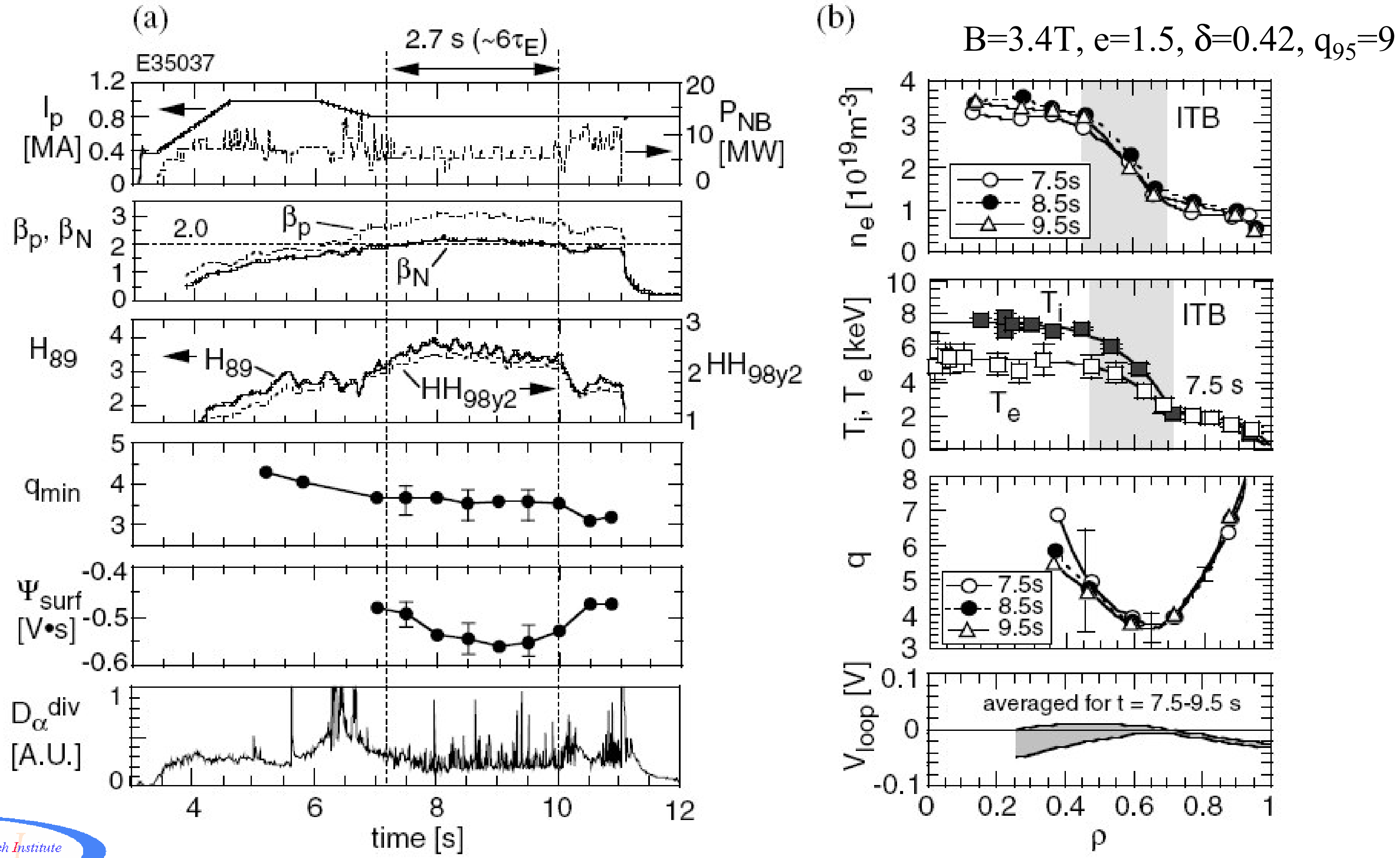




X. Litaudon et al., This Conf.

High Bootstrap fraction discharges

Sustaining ITBs, and thus performance, in steady-state requires a full control of the plasma current profile



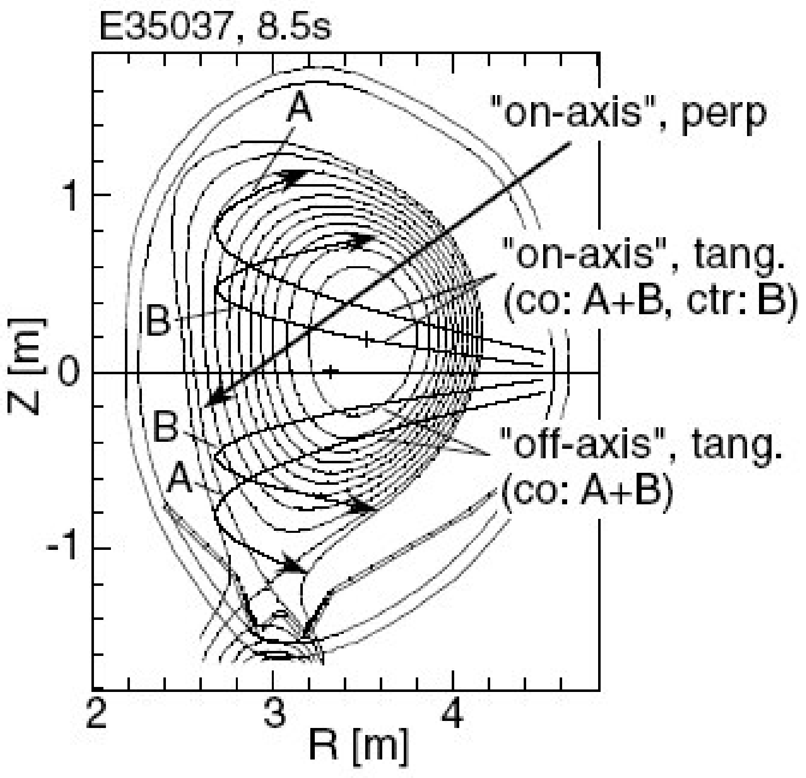
T. Fujita et al., NF 42 (2002) 180

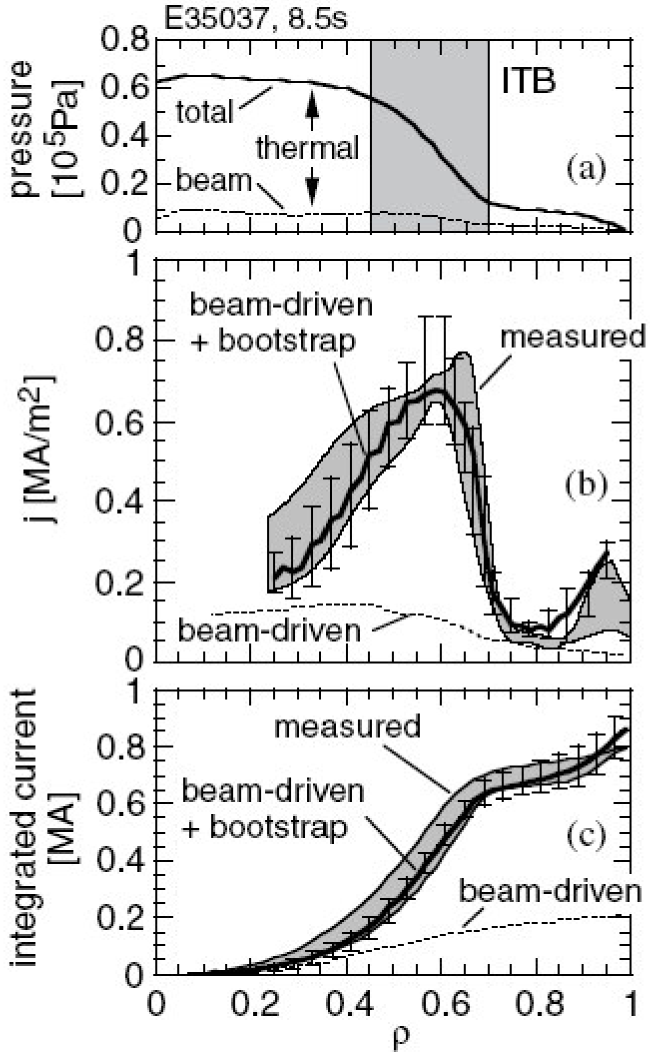
Japan Atomic Energy Research Institute

High Bootstrap fraction discharges

NBCD fraction: ~25 %

Bootstrap current fraction: 78-84%

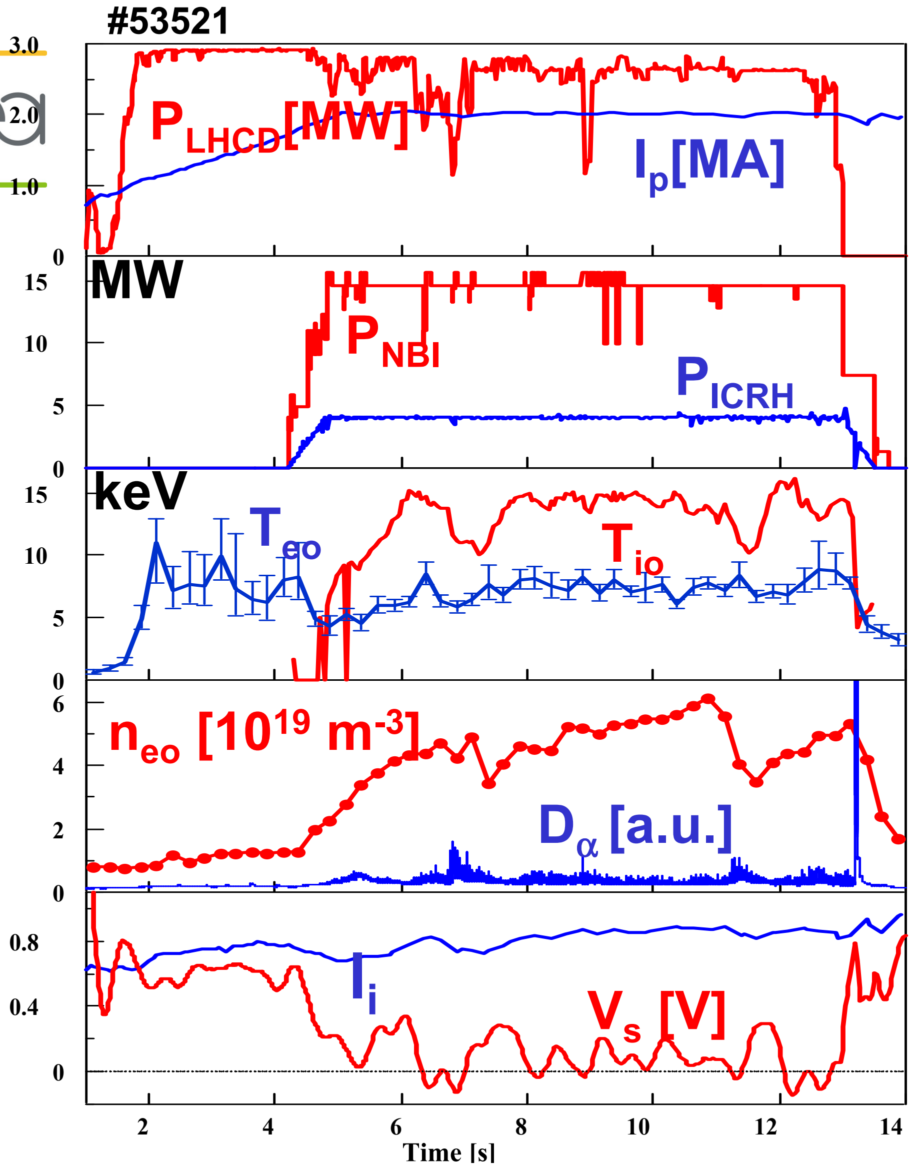




Japan Atomic Energy Research Institute
JAERI

T. Fujita et al., NF 42 (2002) 180

Fully non inductive discharges

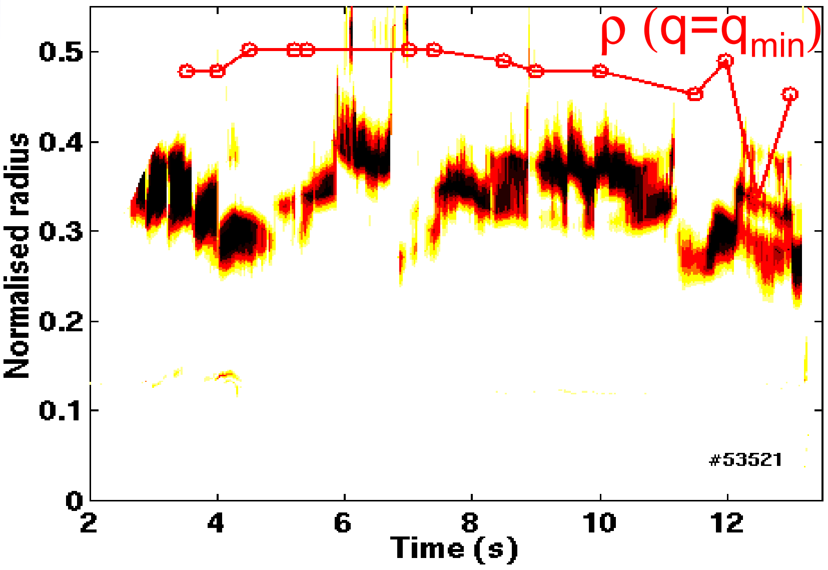


➢ LHCD power sustained all along the high power phase (CD_4 puff)

➢ e-ITB sustained for 11s ($36\tau_E$)

➢ Ti/Ne/Vtor-ITB sustained for 8s ($27\tau_E$)

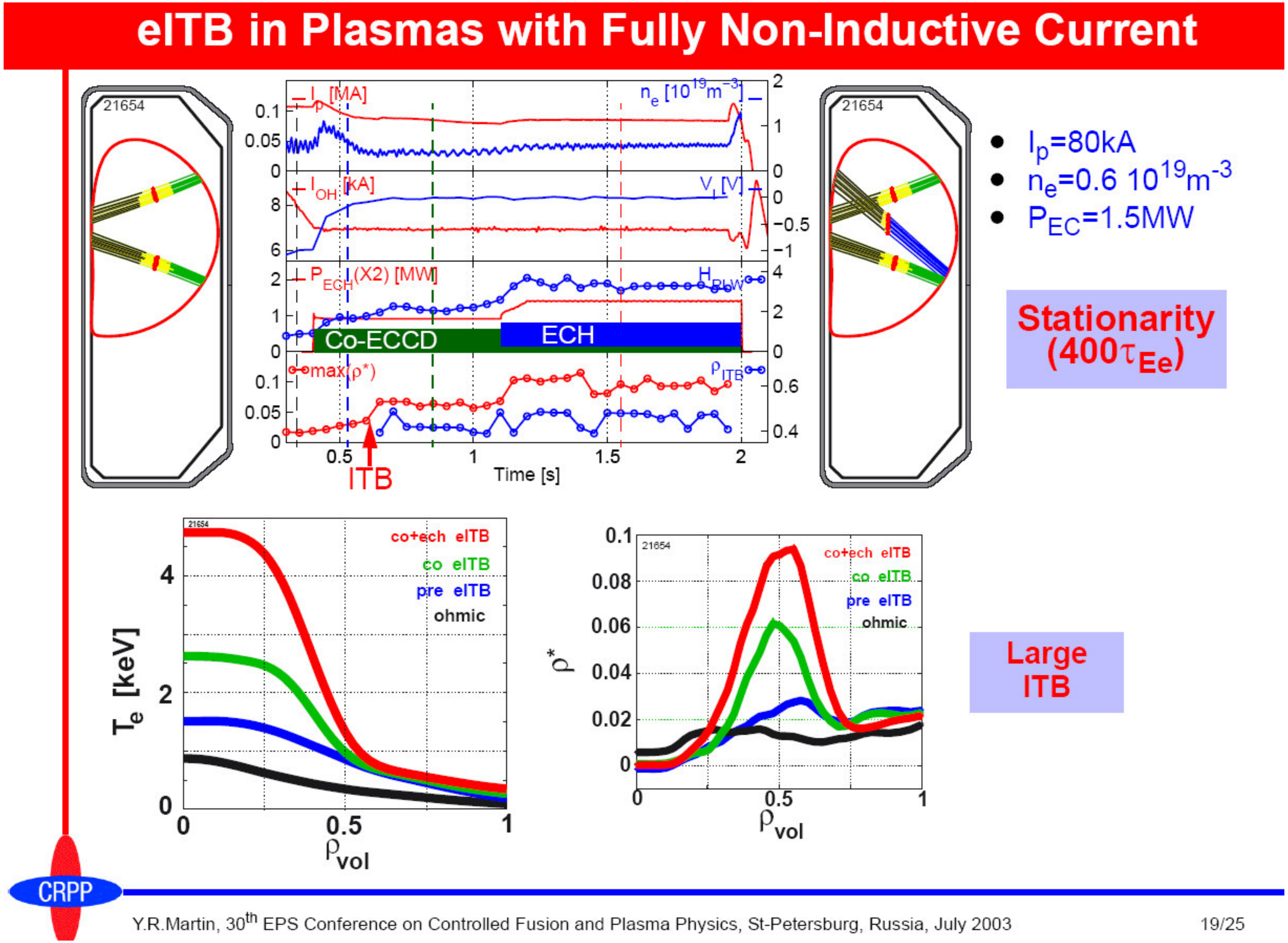
➢~ 80% non inductive current



➢ITB time history strongly linked to the current profile.

X. Litaudon et al., EPS 2001

Fully non inductive high Bootstrap



eITB in Plasmas with Fully Non-Inductive Current

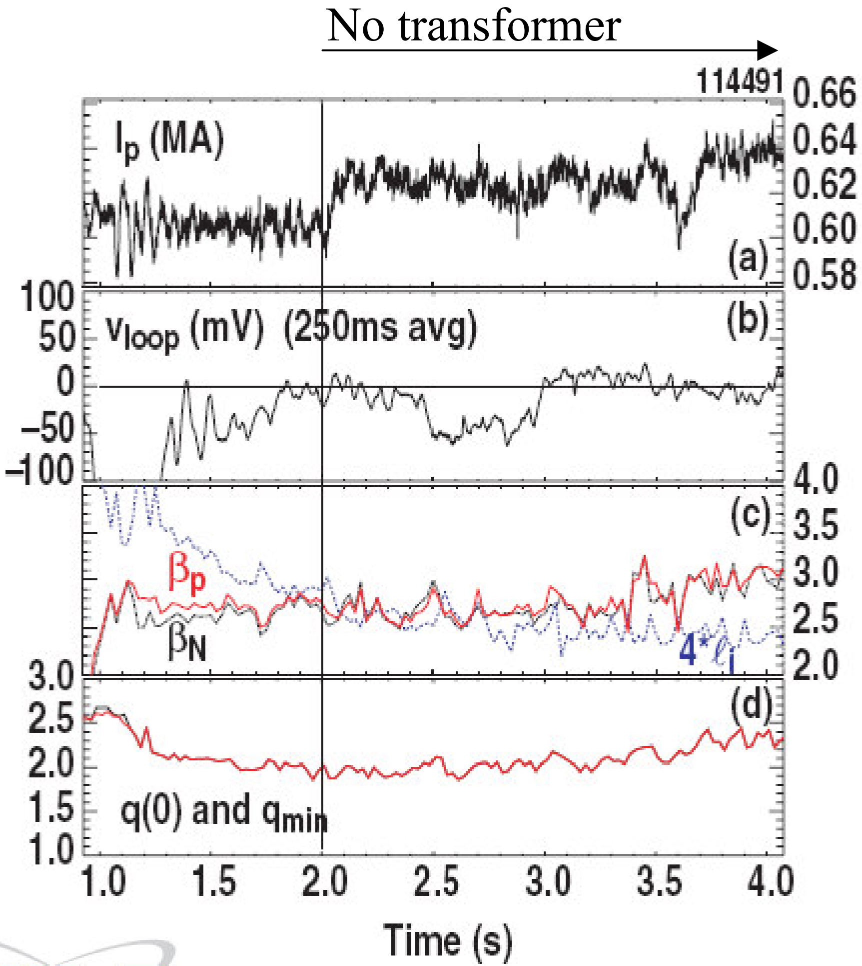
- I_p=80kA
- n_e=0.6 $10^{19}m^{-3}$
- P_{EC}=1.5MW

Stationarity ($400\tau_{Ee}$)

Large ITB

Y.R.Martin, 30th EPS Conference on Controlled Fusion and Plasma Physics, St-Petersburg, Russia, July 2003 19/25

Fully non inductive high Bootstrap



$\beta_N \sim \beta_p \sim 2.8$

65-80% bootstrap
25-30% NBCD
5-10% ECCD

P. Politzer et al., EPS Conf. 2003

Discussion Part B

Do we agree on:

- The role to be played by an ITB in providing a large bootstrap fraction discharge
- The central role played by the plasma current profile in the stationarity conditions of ITBs
- A satisfactory understanding of the MHD limits, though more experimental confirmation is desirable, and real time control to be further developed.

Open questions:

- current profile alignment
- detailed time sequence to reach such regimes in next step devices (consistency with alpha particle pressure)
- impurity control (heat vs density ITBs)
- integration with edge aspects (cf topic A)