On the control of plasma transport

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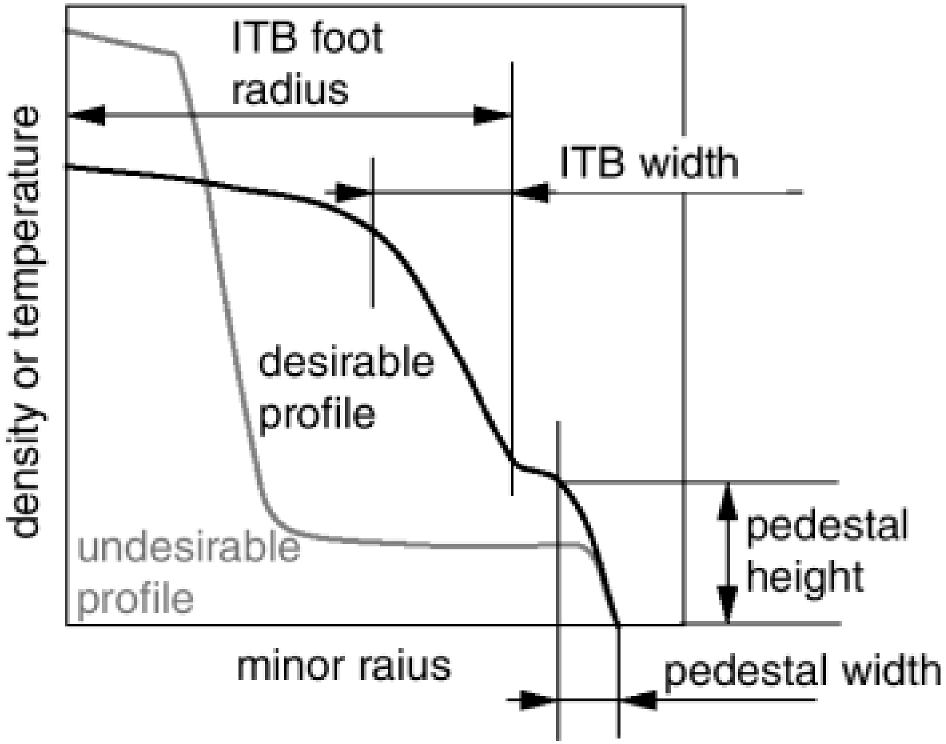
Transport control:
Internal and edge barriers



•**Spatial structure of ITB**: trigger, reactor relevant conditions ($T_e \approx T_i$).

•**Spatial structure of ETB**: trigger, scaling on pedestal height and width

•**Compatibility and linkage between ITB and ETB**: Softening or eliminating the ELM activities.

Transport barriers :

an important issue in magnetic fusion plasmas (tokamaks / stellarators / RFPs)

Topics

- **Internal transport barriers in tokamaks and stellarators:**
  - **Role of magnetic topology**
- **Transport barriers as phase transitions:**
  - **Physics of spontaneous sheared flow development**
  - **First and second order phase transition**
- **Momentum transport**
  - **Momentum re-distribution and edge physics**
- **Experimental techniques:**
  - **2- D visualization techniques**
  - **Velocity field measurements**

- **Internal transport barriers in tokamaks and stellarators:**
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Internal transport barriers in tokamaks and stellarators

Tokamaks:

- **Turbulent transport mechanisms:**
- **Turbulence scales (K_θ cm^{-1})**
- **Transport channels**
- **Stabilization mechanisms**

ITG	TEM	ETG

1	10	100

Ion	Electron

ExB shear	magnetic shear / Shafranov shift

Stellarators:

Electron ITB: neoclassical (electron / ion roots) and ExB stabilization mechanisms

Trigger mechanisms: **magnetic topology / …..**

Turbulence measurements and code predictions in tokamaks

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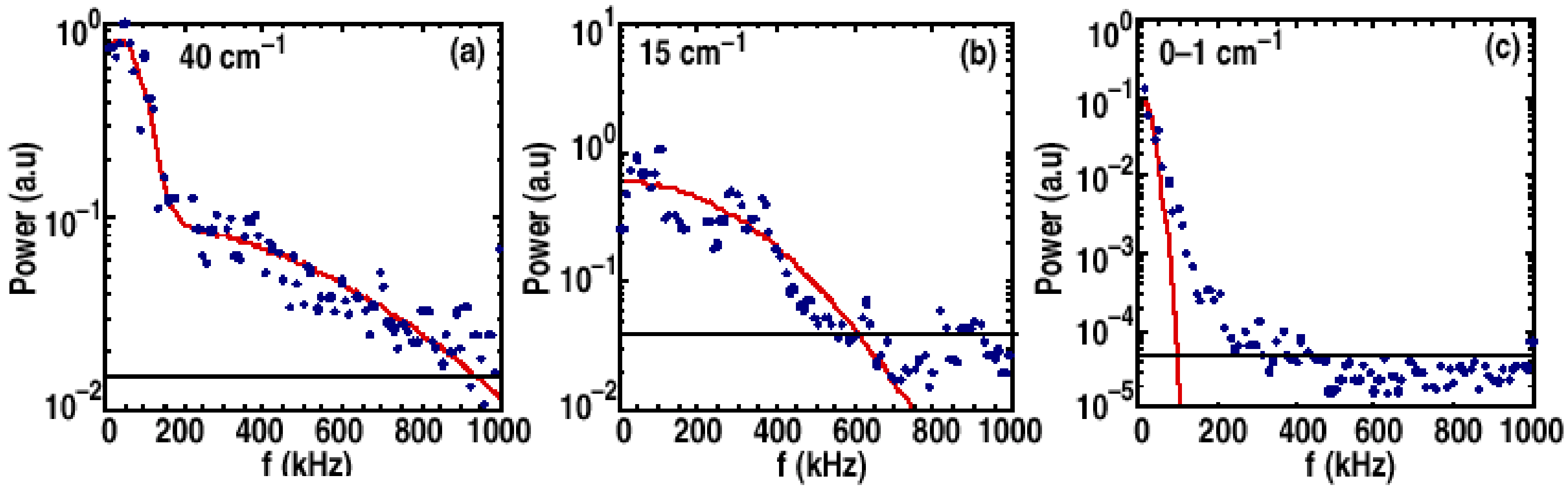

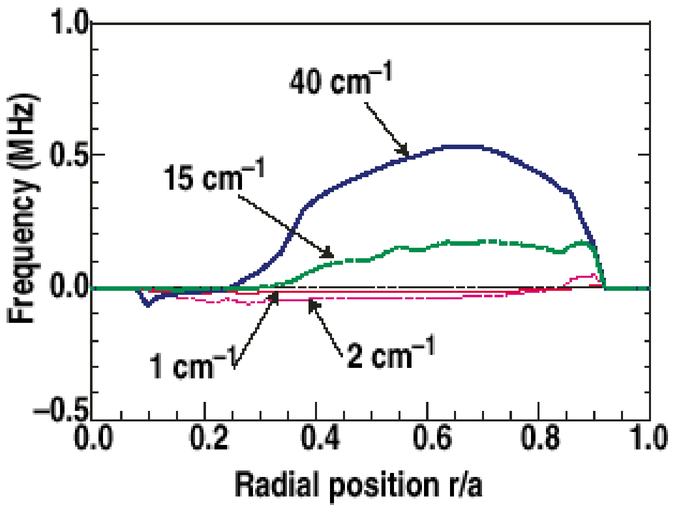

- Broadband wavenumber measurements show significant activity over a wavenumber range (0 - 40 cm^{-1}) relevant to ITG, TEM and ET.
- Qualitative agreement with gyrokinetic code calculations.

D-III-D

T. Rhodes et al., IAEA - 2004.

Triggering of ITB in tokamaks: role of rationals

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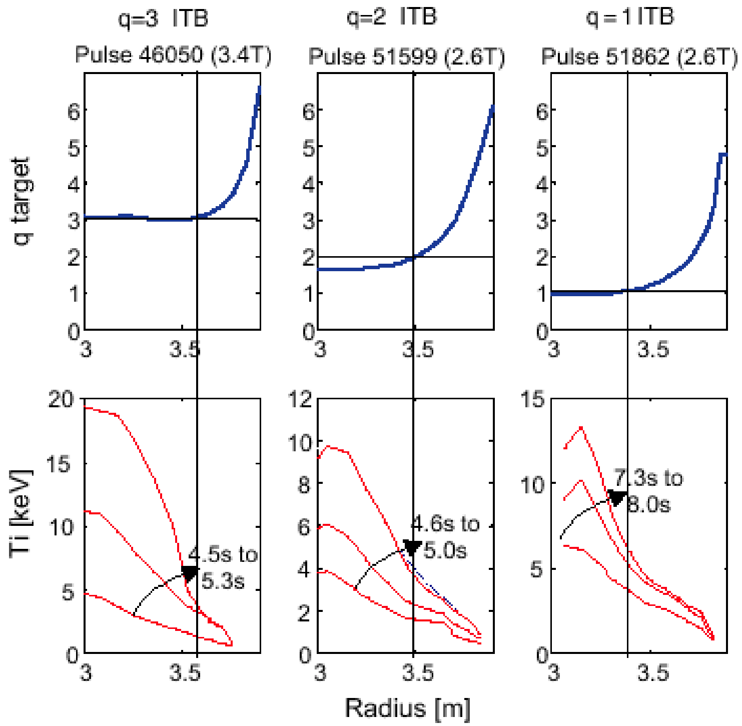
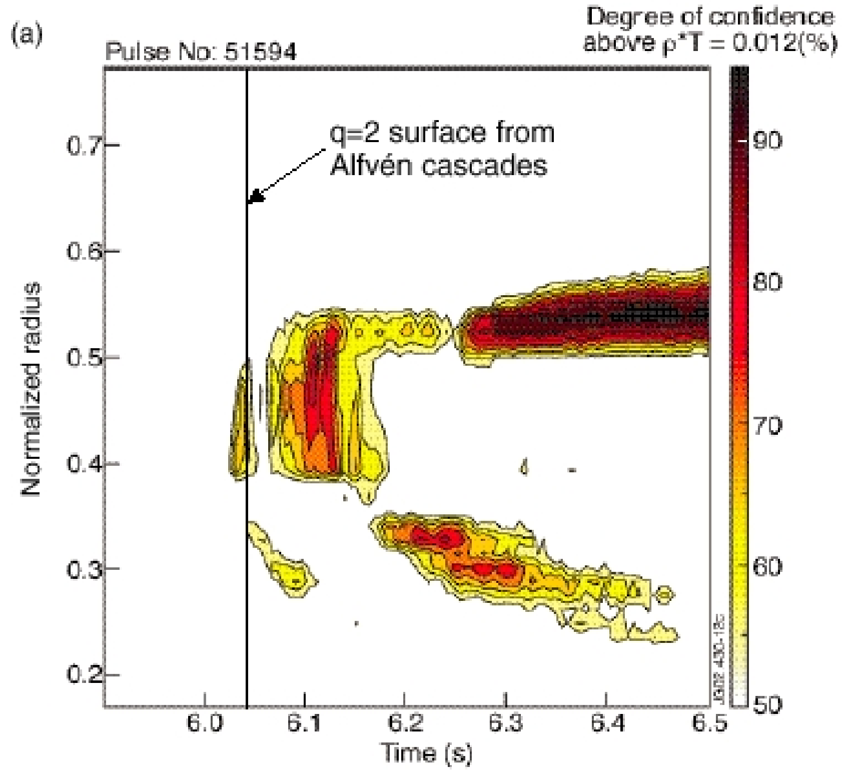




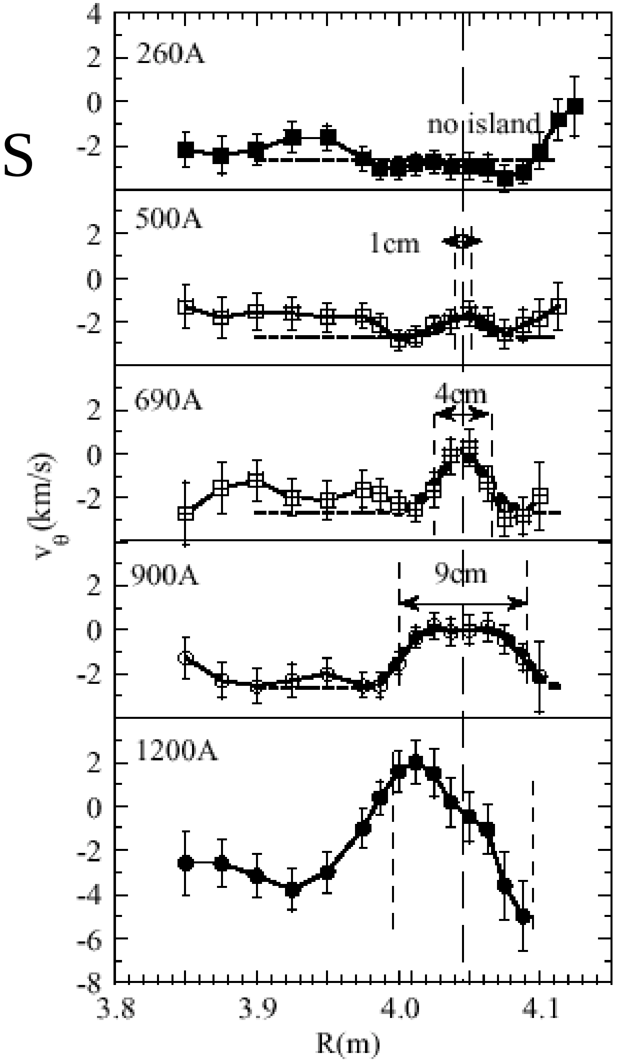
Joffrin et al., Nuclear Fusion 43 (2003) 1167

Low order rational q surfaces play a key role in the ITB formation with both reversed and low positive magnetic shear in tokamak devices :

JT-60 (Koide et al., 1994 PRL), RTP, JET,….

Triggering of ITB in stellarator: role of rationals

CHS



- **Evidence of ExB sheared flows linked to rationals in TJ-II stellarators.**

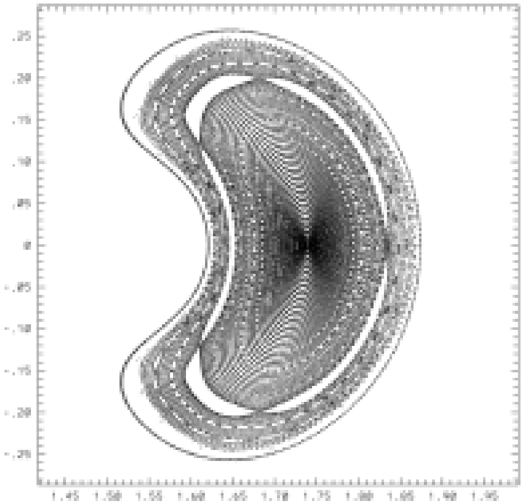
C. Hidalgo et al., PPCF (2000)

Estrada et al., PPCF 2004

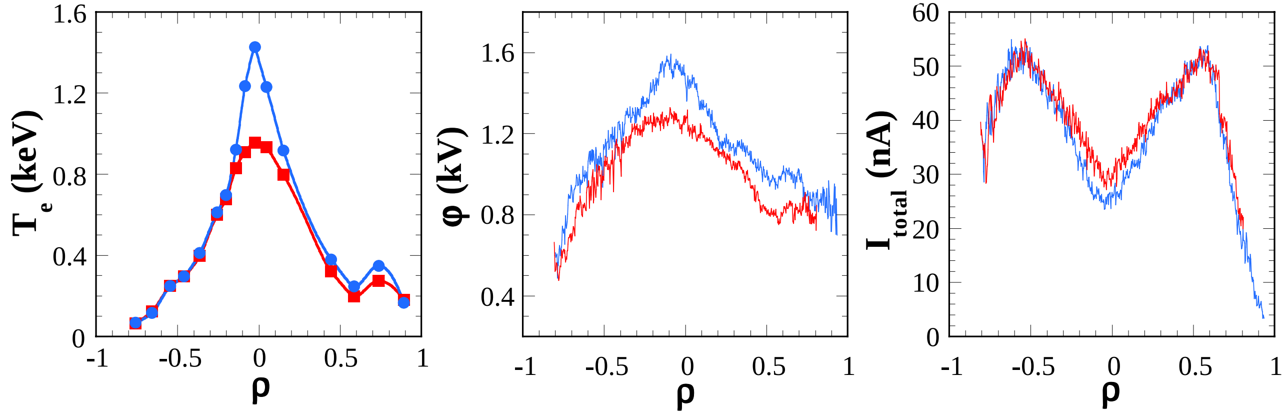
- **Close link between flow shear and island structure.**

Ida et al., PRL 88 (2002) 015002 / NF 2004

Triggering of ITB in stellarator: role of rationals



before & during e-ITB



Great flexibility of stellarator devices in magnetic configuration (TJ-II)

- **The rational 3/2 has to be positioned inside the plasma for the e-ITB to appear.**
- **Still the question remains: is the presence of rational surfaces in the plasma essential to e-ITB formation or does it simply modify the power threshold?**

T. Estrada et al., Plasma Physic and Controlled Fusion (2004)

Why do rational trigger ITBs?

Due to the triggering of ExB sheared flows in the proximity of rationals

Hidalgo 2000 / Pedrosa 2000/ Carreras 2001/ Ida 2002 /Shaing 2003/ Estrada 2004:

•kinetic effect.

•Viscosity

•Neoclassical effects

•Turbulence driven flows

Due to a rarefactation of resonant surfaces in the proximity of low order rationals which is expected to decrease turbulent transport.

Romanelli 1993 / L. Cardozo 1997/Brakel 2002 / Garbet 2001

Is this interpretation consistent with the universal features of turbulence observed in Tokamaks / Stellarators (i.e. shear and shearless devices)?

Comparative studies in tokamaks and stellarators will help to clarify the leading mechanism

- **Internal transport barriers in tokamaks and stellarators:**
  - **Role of magnetic topology**
- **Transport barriers as phase transitions:**
  - **Physics of spontaneous sheared flow development and density limit**
  - **First and second order phase transition**
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Transport barrier physics: a phase transition phenomena ?

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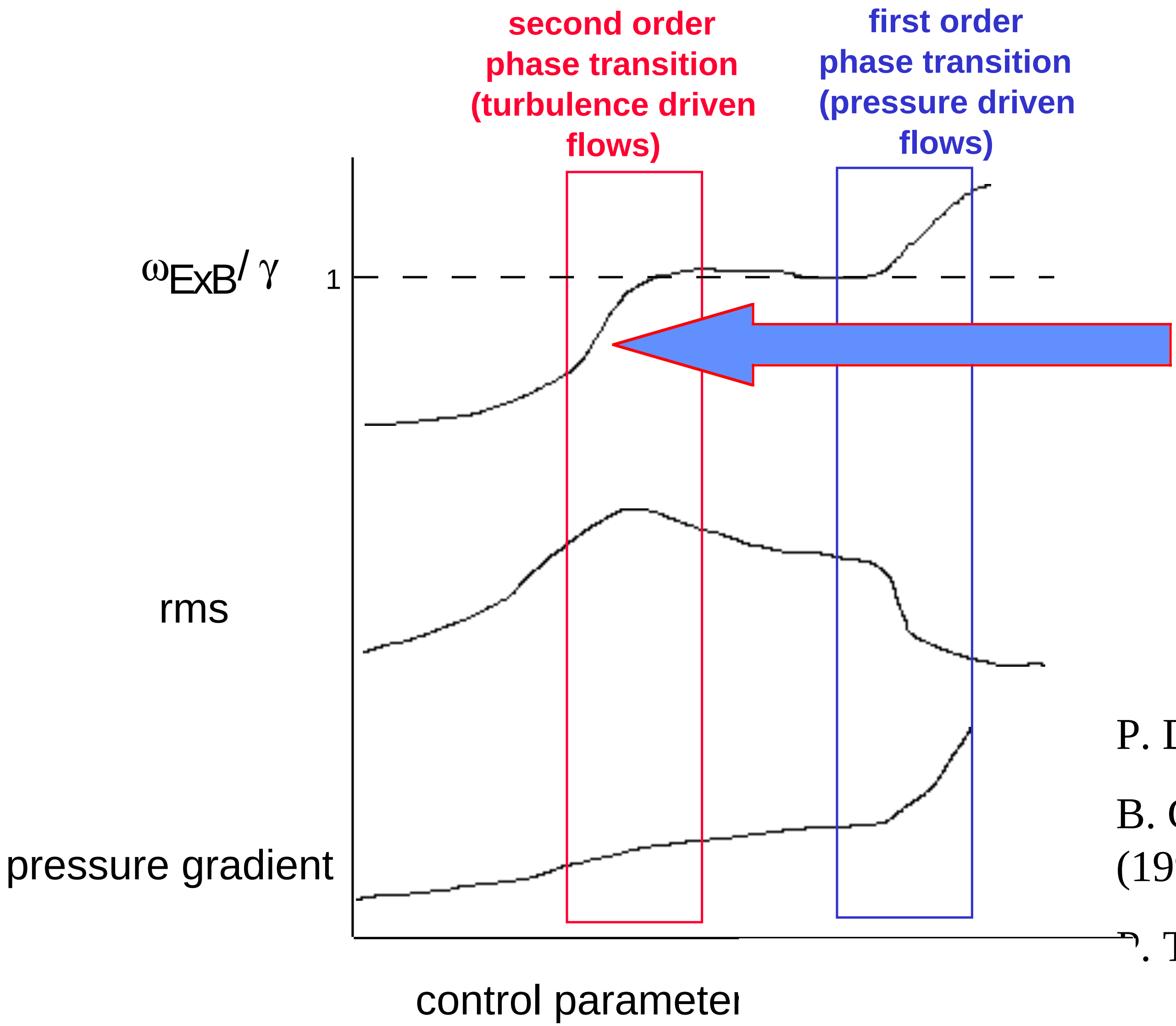

- The order parameter (the sheared poloidal flow) is expected to increase when the turbulent energy is large enough to overcome the flow damping.

- No hysteresis

P. Diamond et al., PRL (1994)

B. Carreras et al., Phys. Plasmas (1995)

P. Terry Rev. Mod. Phys. 2000

Transport barriers and operational limits: a phase transition phenomena* ?

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- Physics of ExB sheared flow development
- Density limit physics

Second order phase transition phenomena?

Critical exponents
Tails in correlation length

*"The research worker, in his efforts to express the fundamental laws of Nature, should strive mainly for matematical beauty "

P. Dirac.

Role of gradients and fluctuations in sheared flow development

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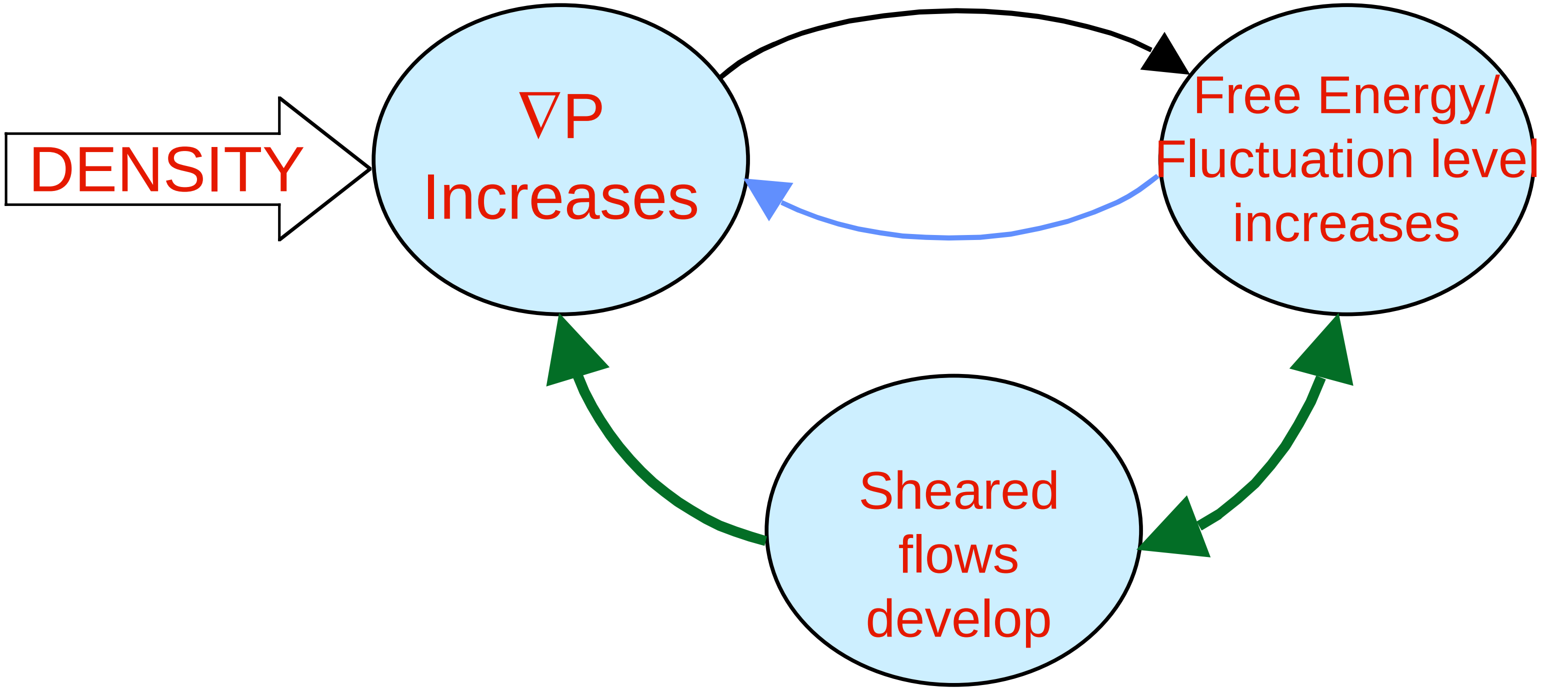
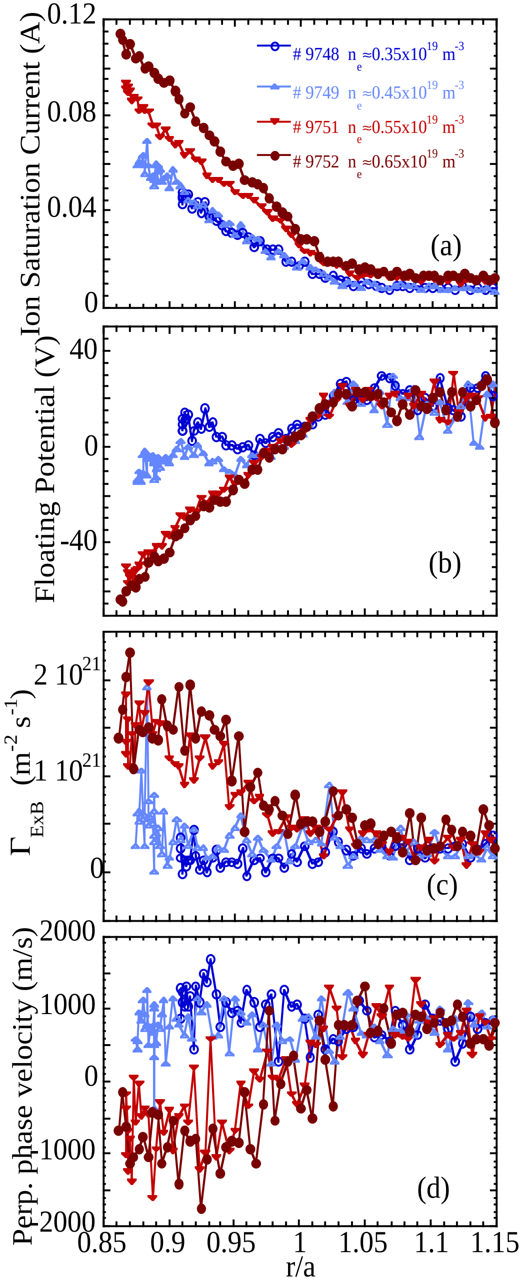


Link between onset of sheared flow development and threshold plasma density



•The development of the naturally occurring velocity shear layer requires a minimum plasma density (or gradient) in TJ-II stellarator.

•There is a coupling between the onset of sheared flow development and an increase in the level of plasma edge turbulence in TJ-II.

•Sheared flows and fluctuations keep themselves near marginal stability.

C. Hidalgo et al., Phys. Rev. E (2004);

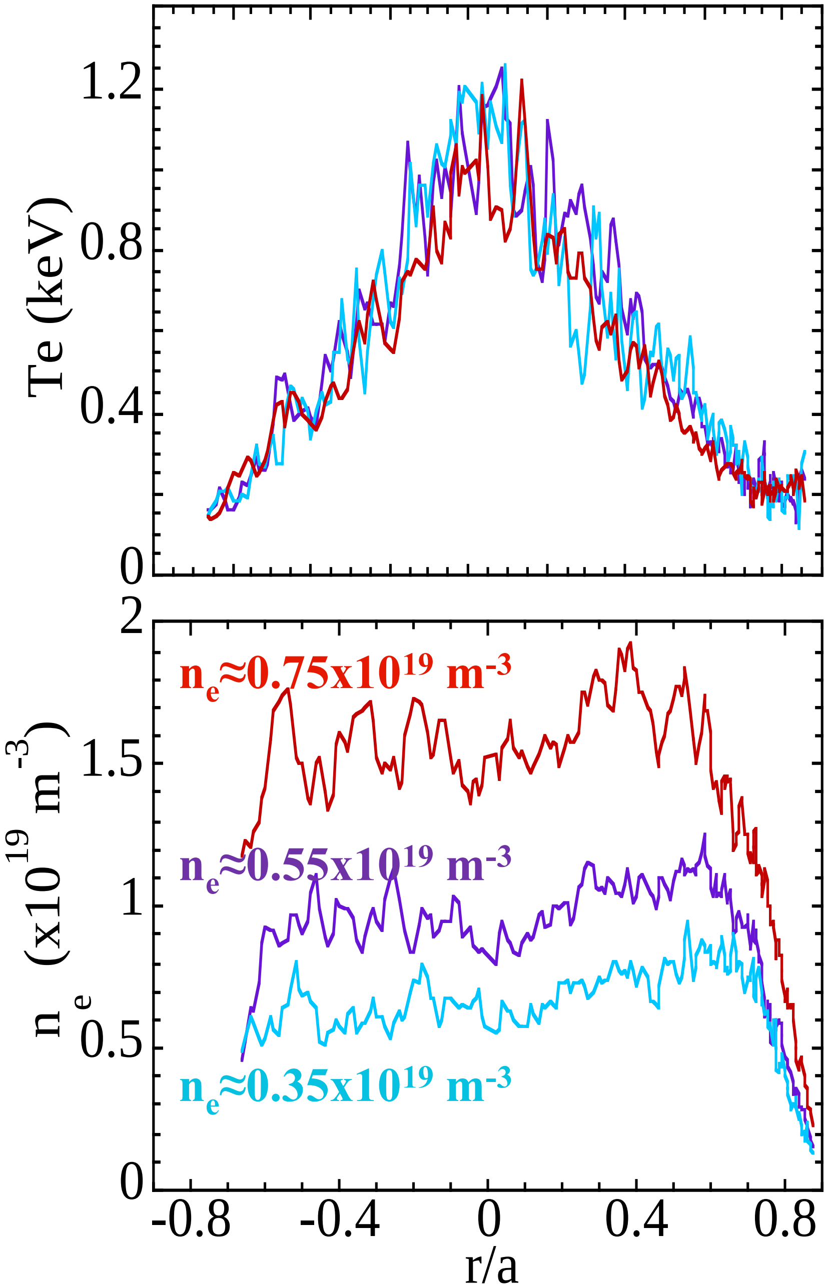
M.A. Pedrosa et al., PPCF (2004)

•This mechanism can explain spontaneous improved confinement in TJ-II

F. Tabarés et al., JNM (2003);

I. García - Cortés et al., PPCF (2002).

Global confinement and sheared flows



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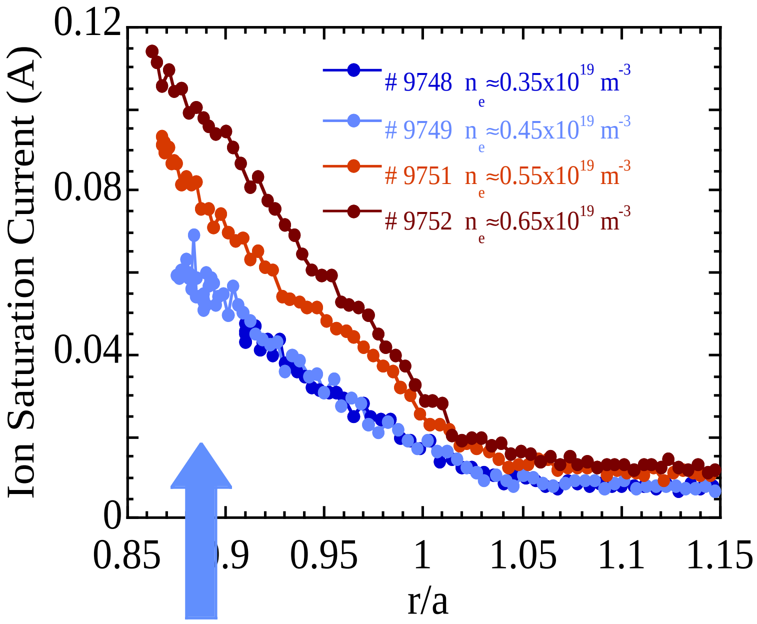
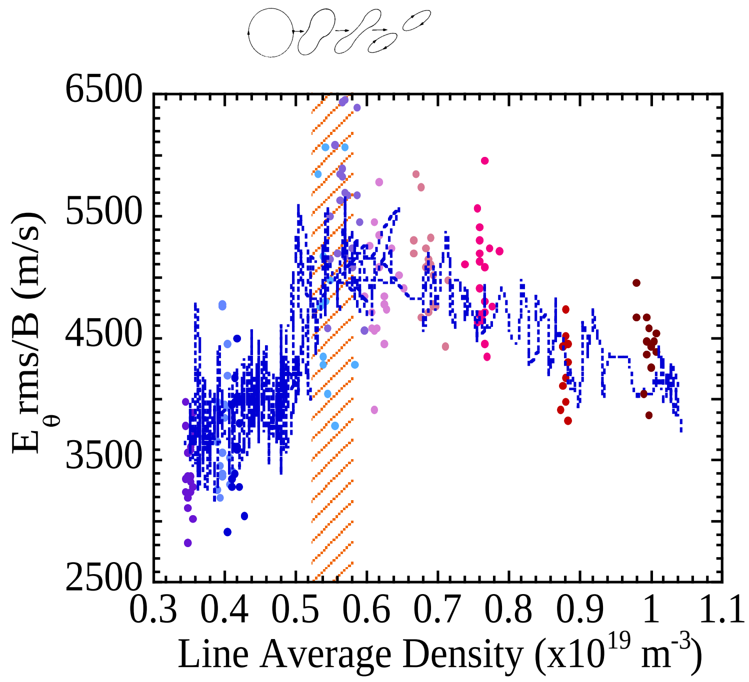
- **Global pressure profiles are modified during the development of edge sheared flows.**

- **The existence of edge sheared flows in TJ-II could be a key element to understand global confinement dependence on plasma density.**

Onset of ExB sheared flows and turbulence





Maximum level of turbulent kinetic energy at the onset of ExB sheared flow development.

Once ExB sheared flows are developed, the level of turbulence decreases.

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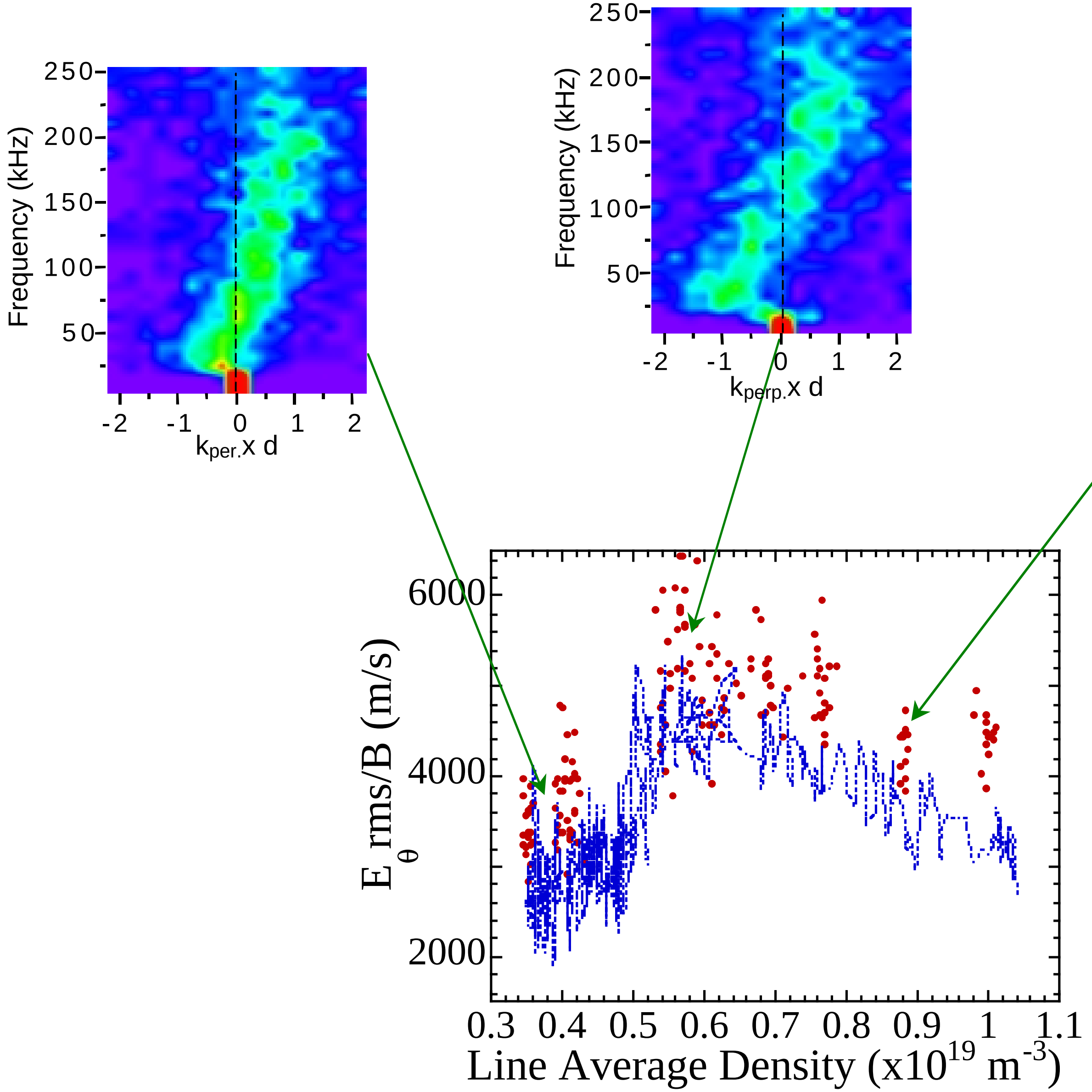
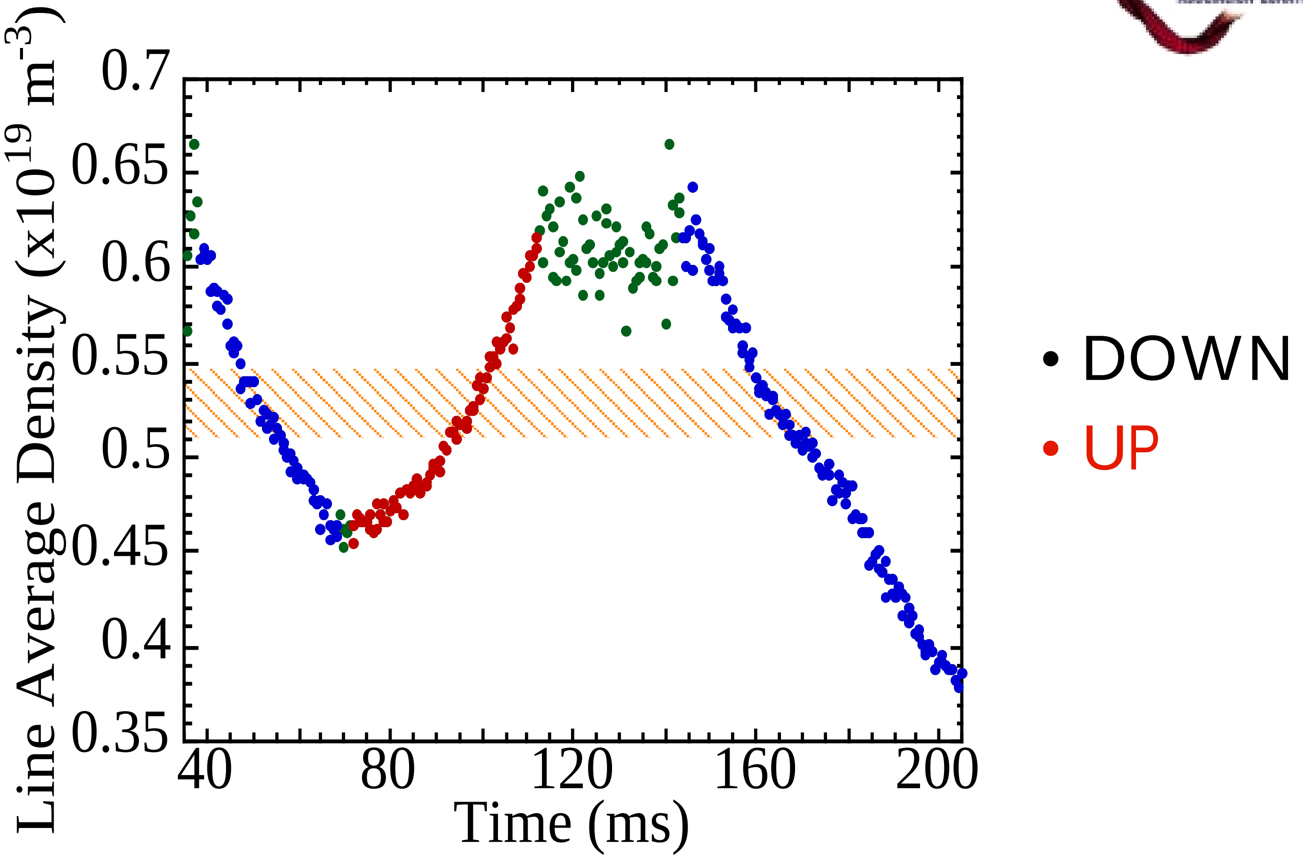
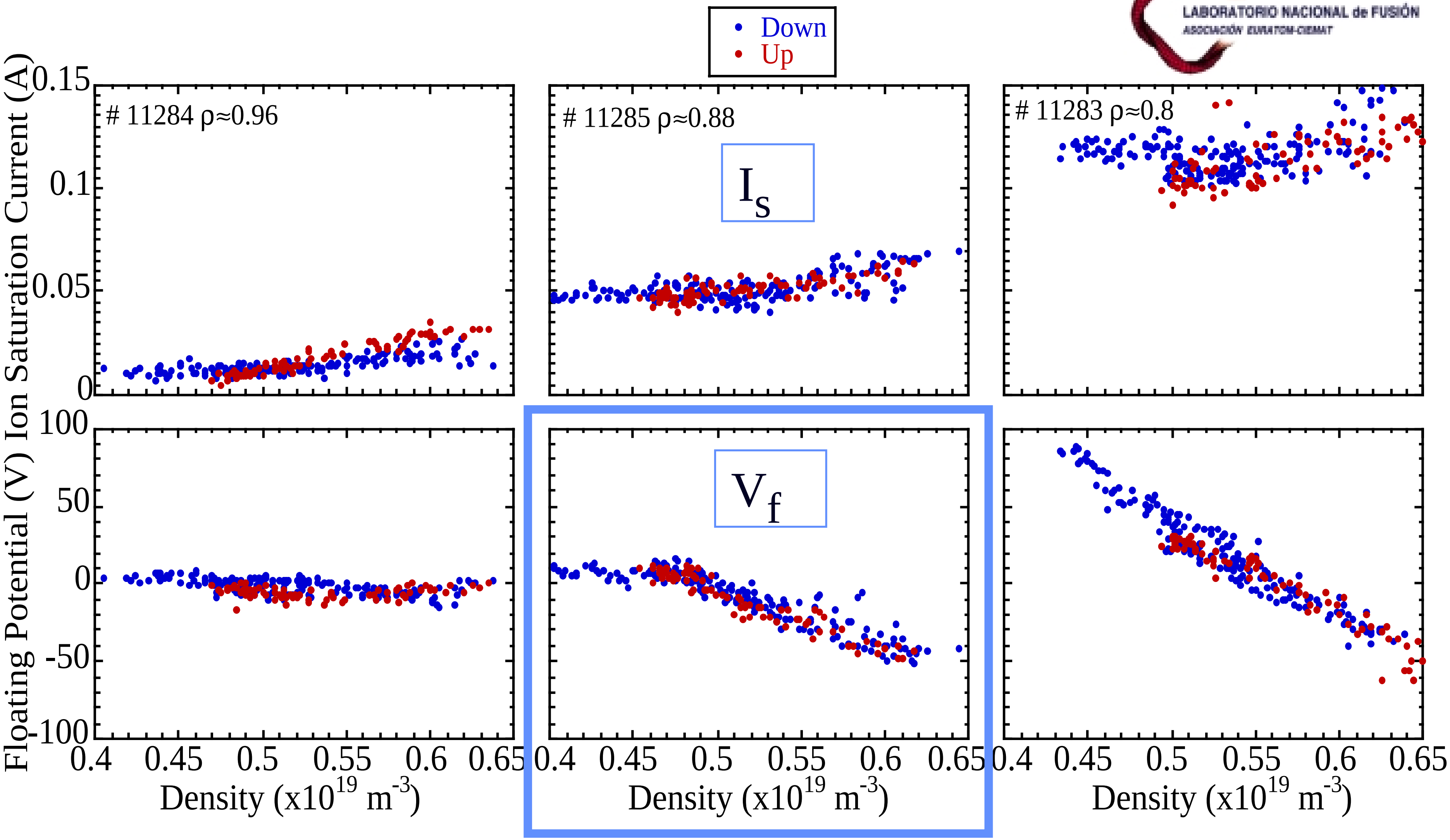


Evidence of hysteresis during ExB shear development?



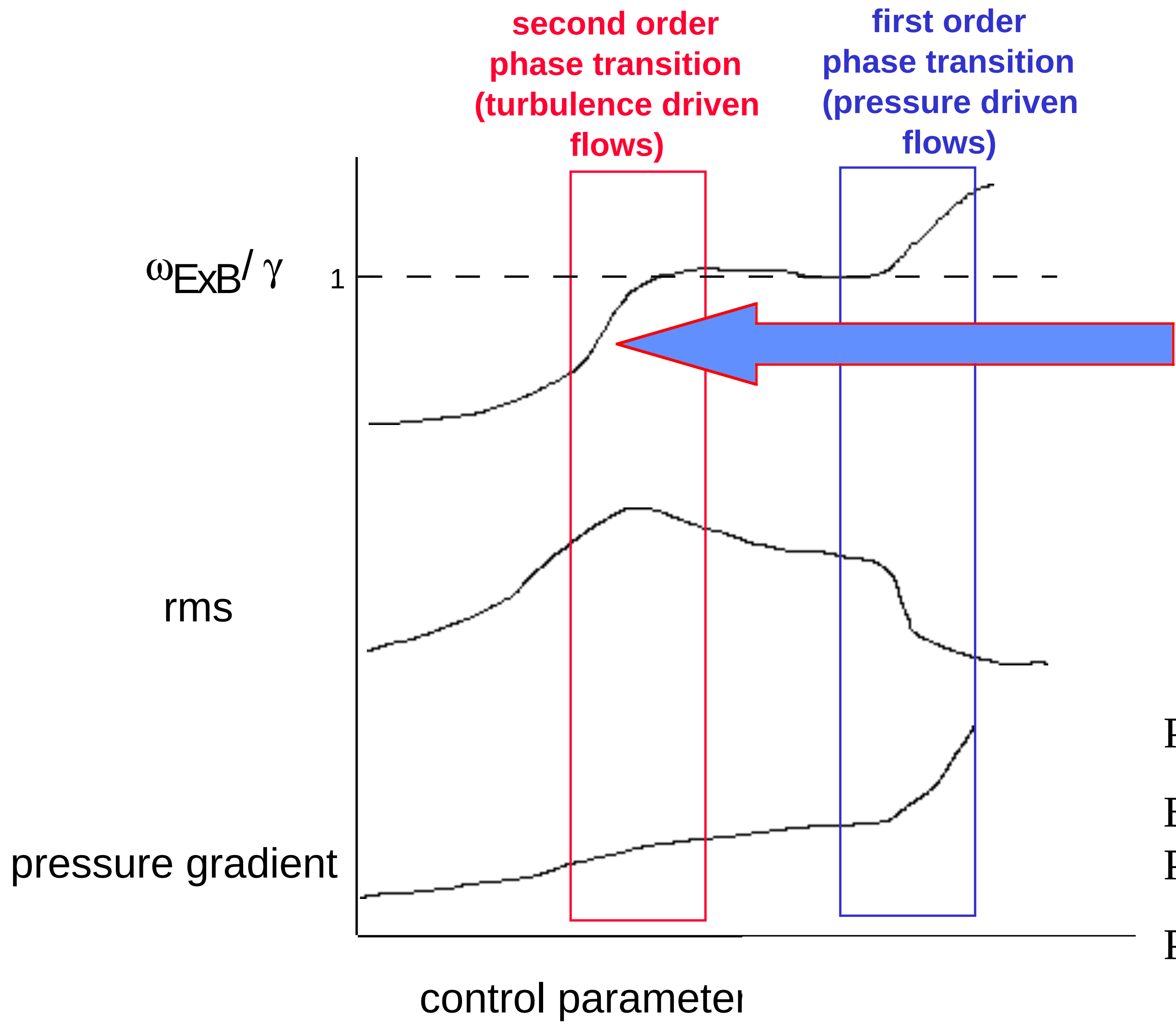
Density modulation near the critical value

Density modulation near the critical value



The transition is continuous and without evidence of hysteresis

Sheared flow development in TJ-II: second order phase transition ?



- The order parameter (the sheared poloidal flow) is expected to increase when the turbulent energy is large enough to overcome the flow damping.

- No hysteresis

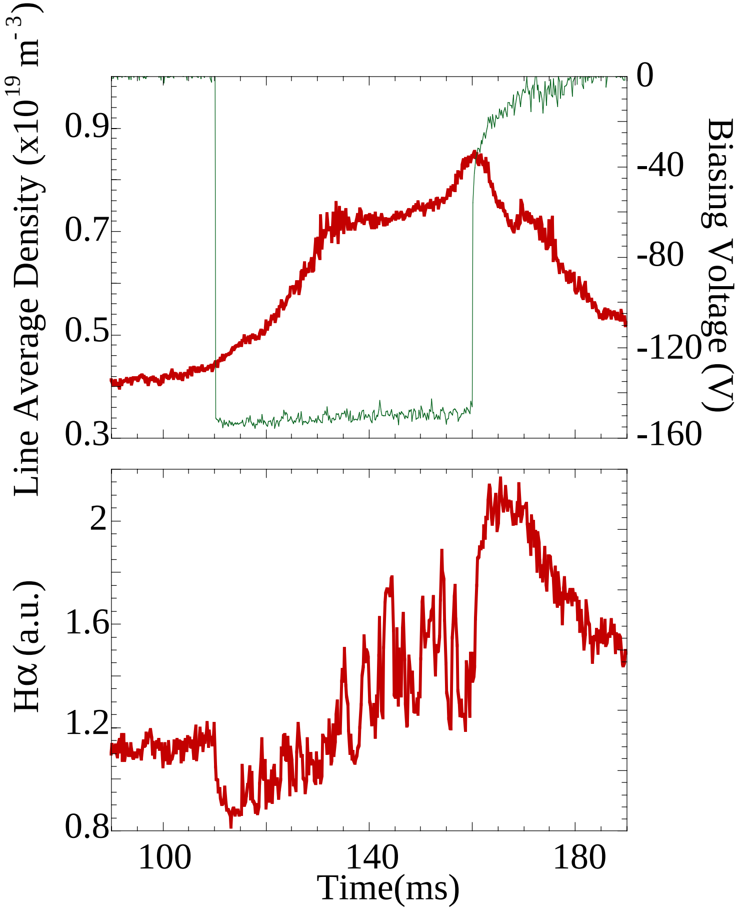
P. Diamond et al., PRL (1994)

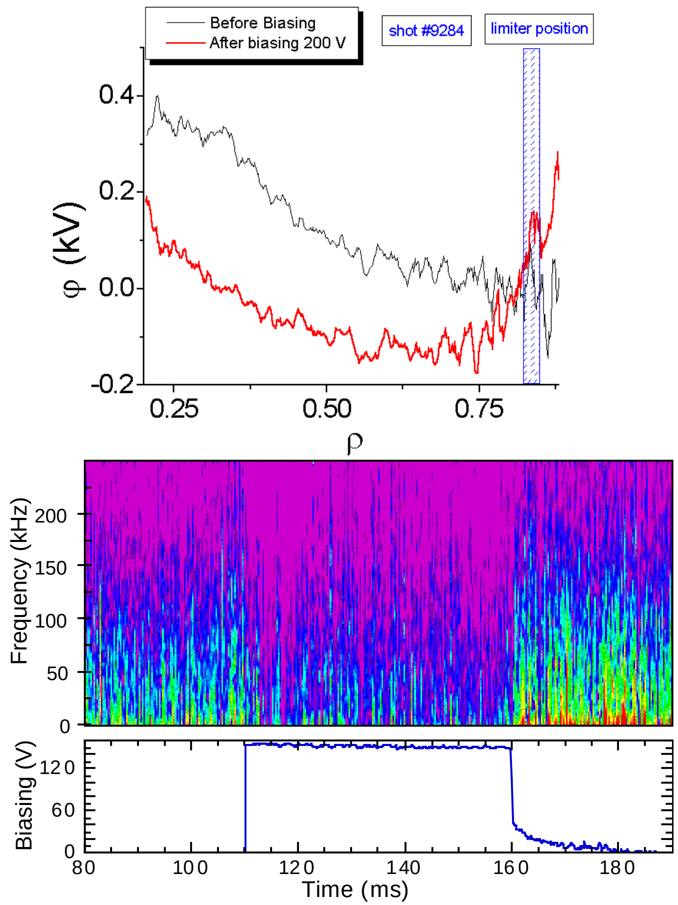
B. Carreras et al., Phys. Plasmas (1995)

P. Terry Rev. Mod. Phys. 2000

Are spontaneous sheared flows and fluctuations ornanized themselves near marginal stability?

Biasing induced improved confinement studies

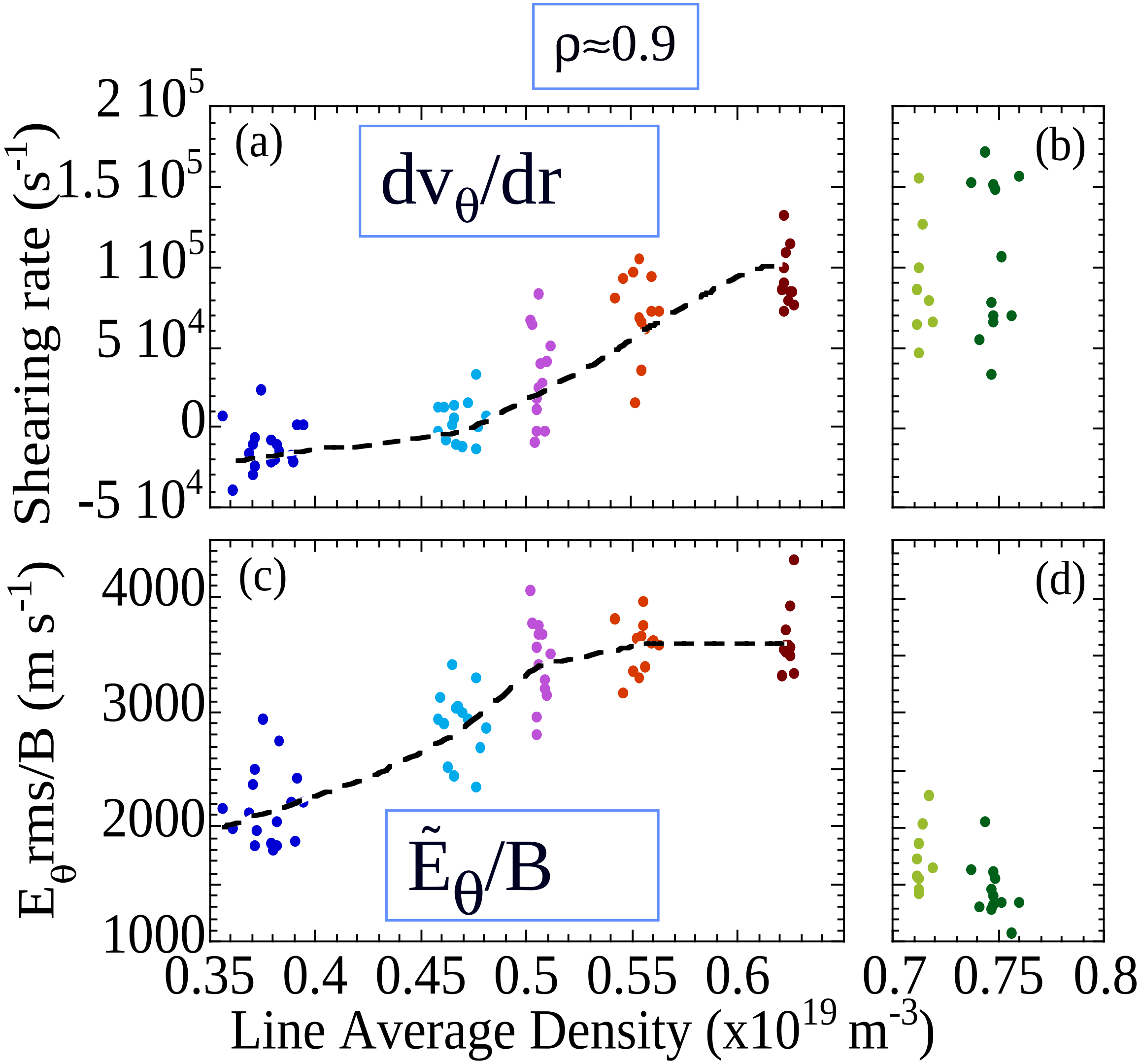




- **Modification of edge radial electric fields by limiter biasing.**
- **Improvement in particle confinement time and reduction of turbulence**
- **No significant impurity influx.**
- **Bursty behaviour in H_α**

C. Hidalgo et al. PPCF- 2004

Sponteneous and biasing inducced sheared flows



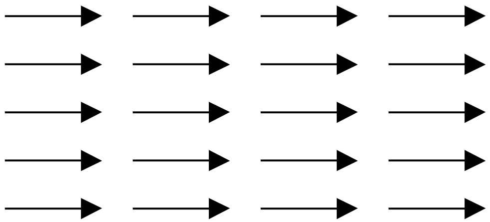
Shearing rates of spontaneously developed sheared flows and those measured in biasing regimes are comparable.

Results suggest that spontaneous sheared flows and fluctuations organized themselves to be near marginal stability.

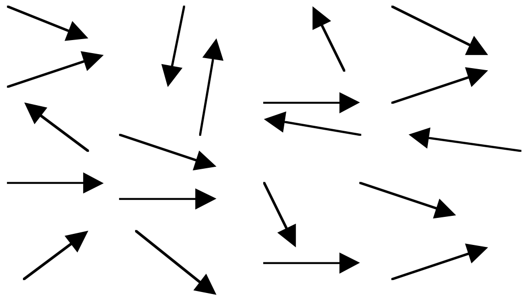
Transport barrier: a phase transition phenomenon? (critical exponent)

Phase transition and critical exponents

Ferromagnetic



Paramagnetic



Control parameter (temperature) $(T-T_c)$

Order parameter (magnetisation) (M)

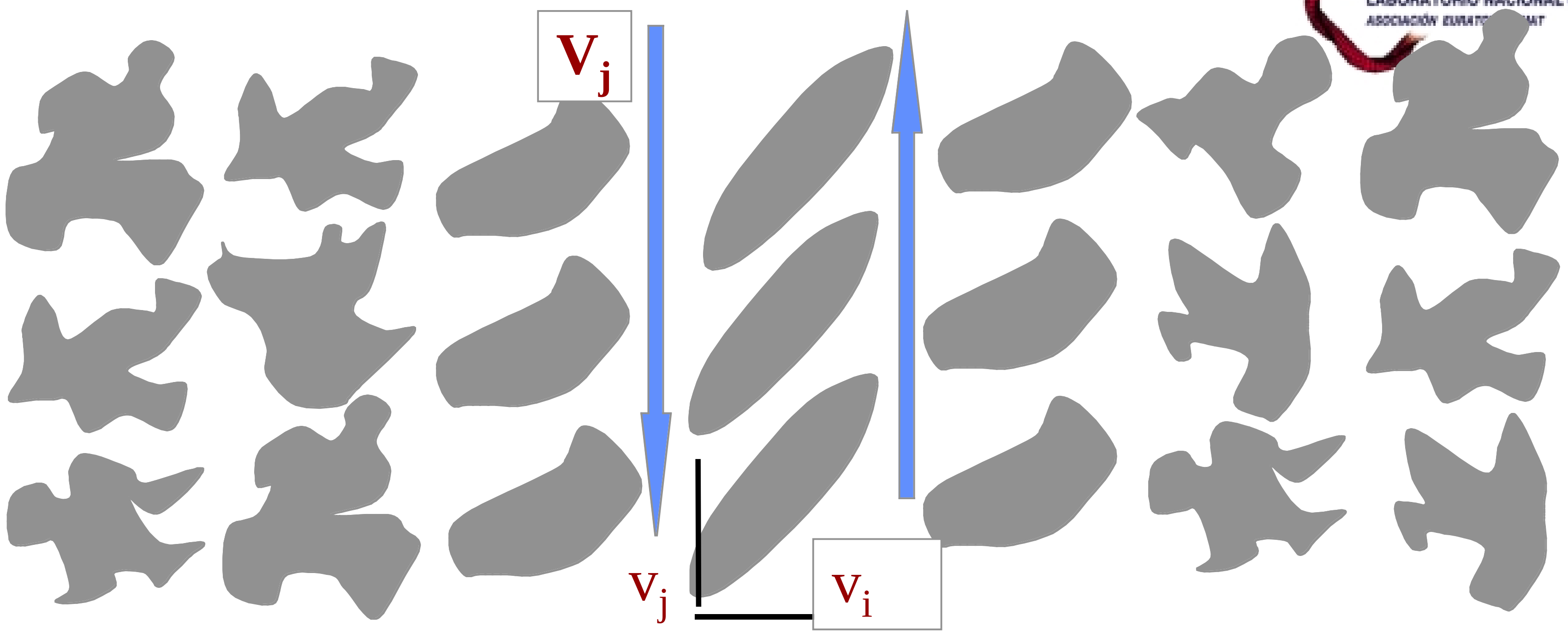
$$M \propto (T-T_c)^{\alpha}$$

The critical exponent (α) is in the range of 0.3 - 0.5 in many systems (fluids, magnetism)

What is the critical exponent during the development of a transport barrier*?

An open question for theorists and experimentalists in plasma physics

Second order transition: **Anisotropy and tails in correlation length ?**



•DC flows can be coupled with the degree of turbulent anysotropy (<$v_i v_j$>, momentum transport) .

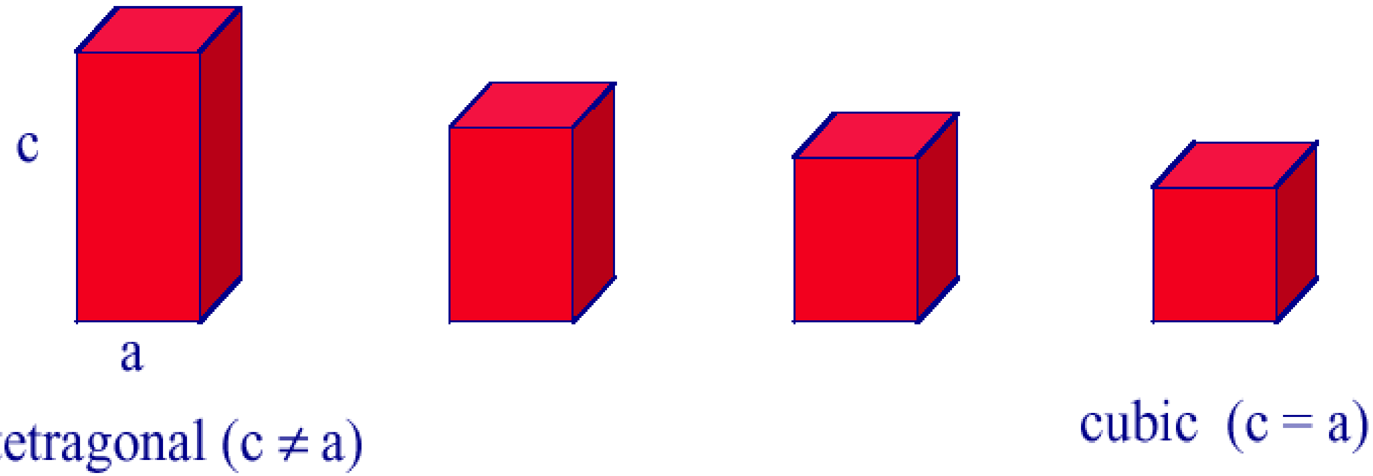
•The degree of anysotropy can be modified in a continuous manner (a key ingredient of second order phase transitions).

• In the proximity of bifurcation point the correlation length diverges (reflecting the ability to undergo a change in the whole system).

Symmetry and transition in solids and plasmas

Second order phase transition and symmetry (in solid state physics)

(Landau)

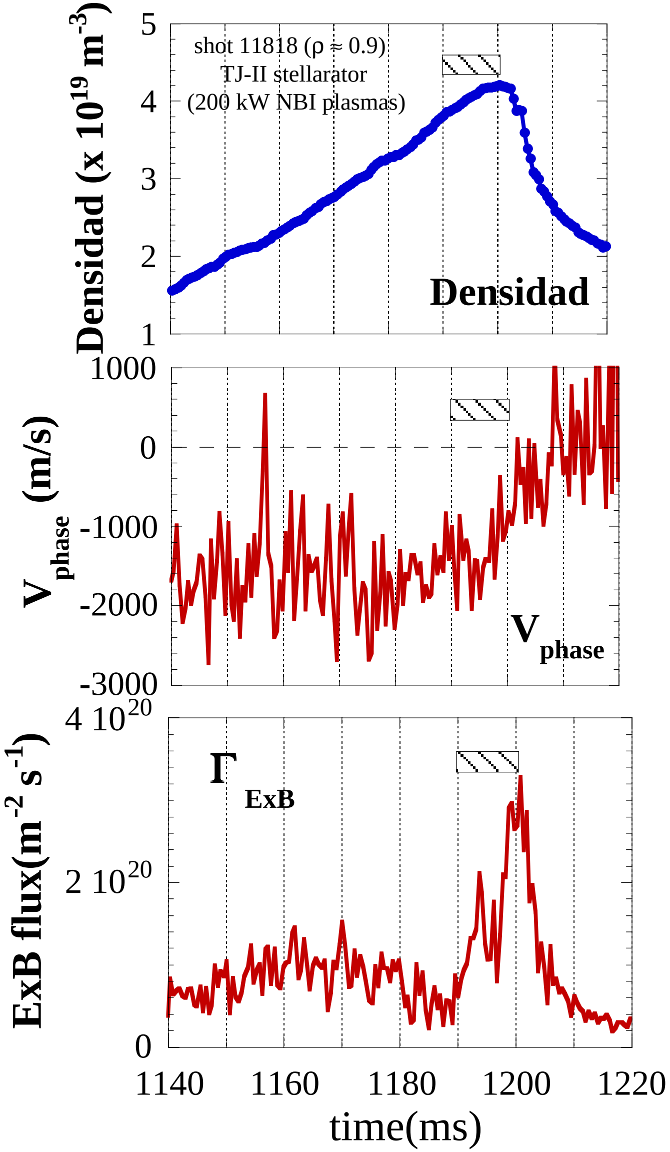


Anysotropy and phase transition:

Equilibrium system/solid state physics): c/a

Non-equilibrium system/ plasma physics) : <vi vj>

Transport barrier and density limits: phase transition physics?



TJ-II M.A. Pedrosa et al. (2004)

ExB generation, turbulence and flows (TJ-II)

1. ***Threshold gradient and level of fluctuations***
2. ***ExB generation (marginal stability with fluctyuations)***
3. ***<u>Second phase order (down - up) transition ?</u>***

C. Hidalgo Phys. Rev E (2004) in press

M.A. Pedrosa PPCF (2004)

Density limit in tokamaks and stellarators (TJ-II):

- ***Radiation inducced cooling***
- ***Disappearance of edge ExB sheared flows (?).***
- ***<u>Second phase order (up - down) transition?</u>***

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Anomalous momentum transport in tokamak plasmas

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- Anomalous core momentum transport has been observed in many tokamaks (Alcator C-mod, JET, Tore-Supra).

- Following the H-mode transition toroidal momentum (anomalous) is observed to propagate in from the plasma edge, although there is no external source (Alcator C-mod:Lee et al., Phys. Rev. Lett. 14_November_2003).

- This redistribution is clearly linked with an edge physics phenomenon (Rice et al., Nuclear Fusion, September 2004 / IAEA - 224)

- In fusion reactor there will probably not be strong external momentum source provided by NBI. It is consequently relevant to investigate other mechanisms that can give rise to plasma rotation.

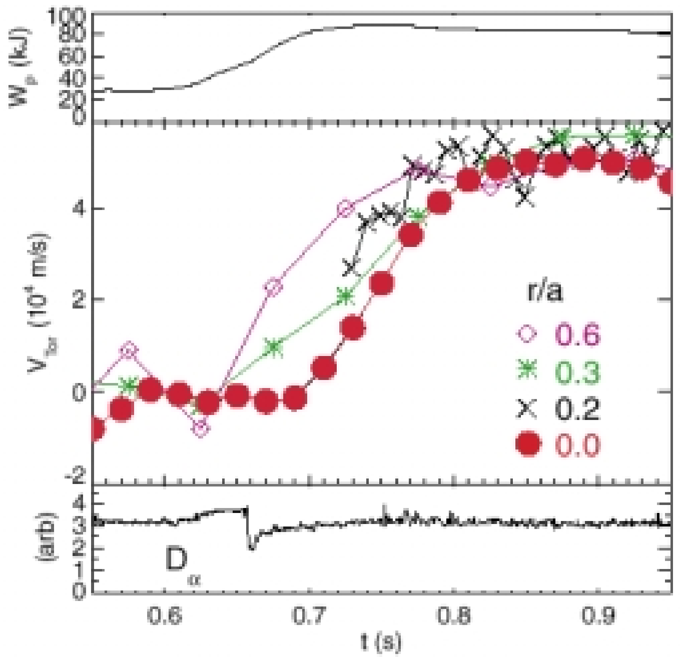

FIG. 1 (color). The plasma stored energy, impurity toroidal rotation velocity at three radii (red dots, green asterisks, and purple diamonds for $r/a = 0.0$, 0.3, and 0.6, respectively), magnetic perturbation rotation (×) at the sawtooth inversion radius ($r/a \sim 0.2$), and the edge D_{α} brightness for an ICRF heated EDA H-mode discharge.

Why anomalous toroidal rotation?

Momentum redistribution: transients and magnetic topology (Alcator / 2004)

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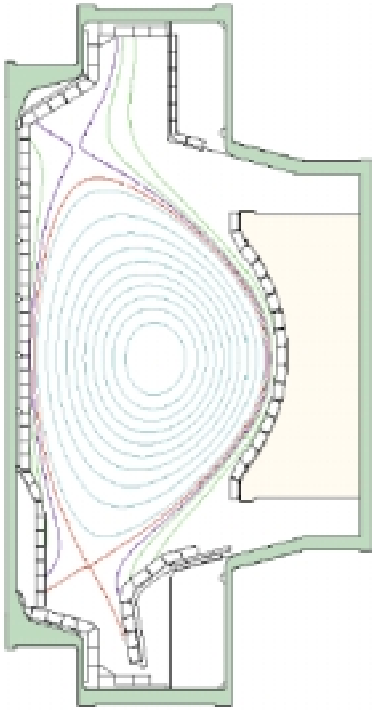
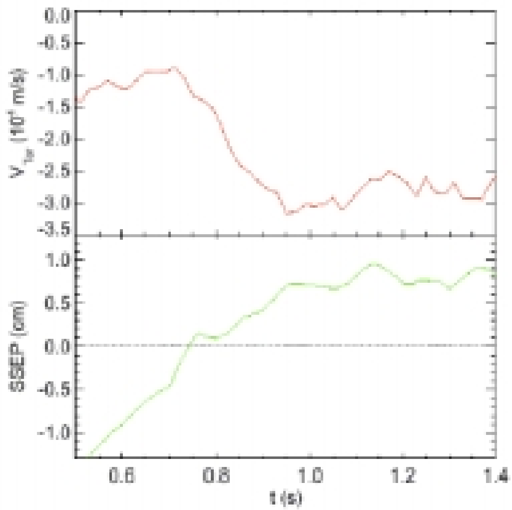


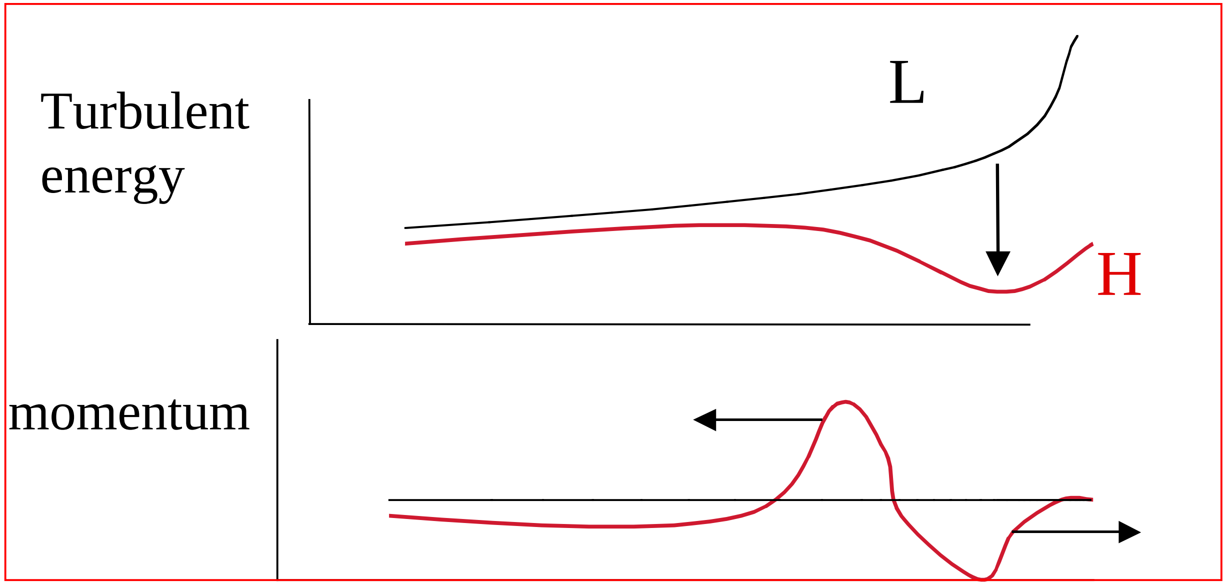


- **Recent experiments in Alcator-Cmod have been reported a core / edge momentum redistribution during L-H transition.**
- **This redistribution is clearly linked with an edge physics phenomenon**

(Rice et al., Nuclear Fusion, TTF Workshop September 2004 / IAEA - 224)

Why anomalous momentum transport at the L-H transition? …

a possible interpretation



Internal force =

$d < v_i v_j > / dr \neq 0$

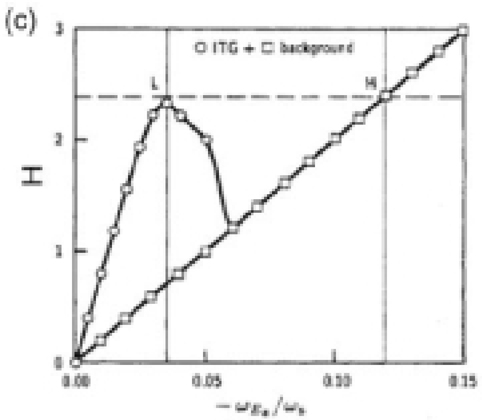
Momentum re-distribution

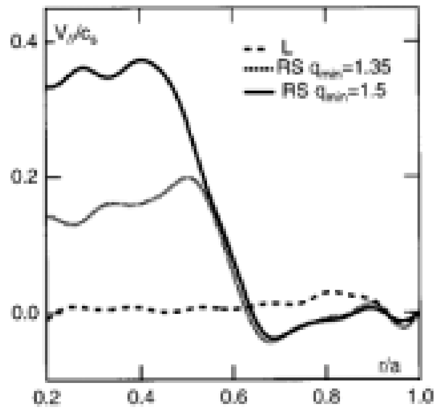
Momentum transport

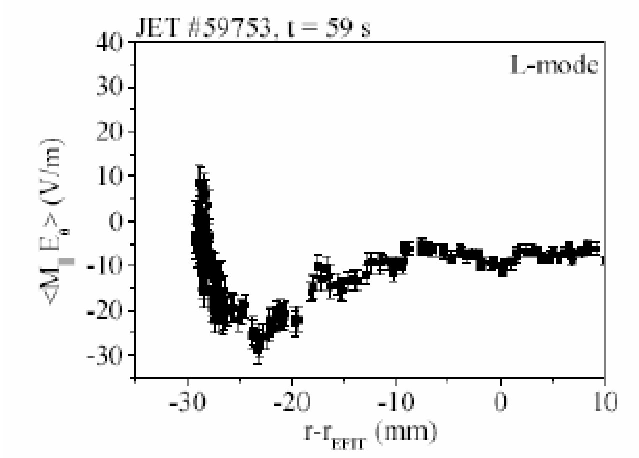
- **Turbulence:**
  - **Eddy viscosity**
  - **Turbulent momentum redistribution**

The importance of

$$< \tilde{v}_r \tilde{v}_{parallel} > \qquad < \tilde{v}_r v_\theta >$$







The existence of a maximum in the turbulent viscosity of ITG modes can play a role in the bifurcation theory of the H-mode.

Staebler et al., NF 1993

Simulations show toroidal rotation generated by turbulence. This rotation changes sign at the position of magnetic shear reversal.

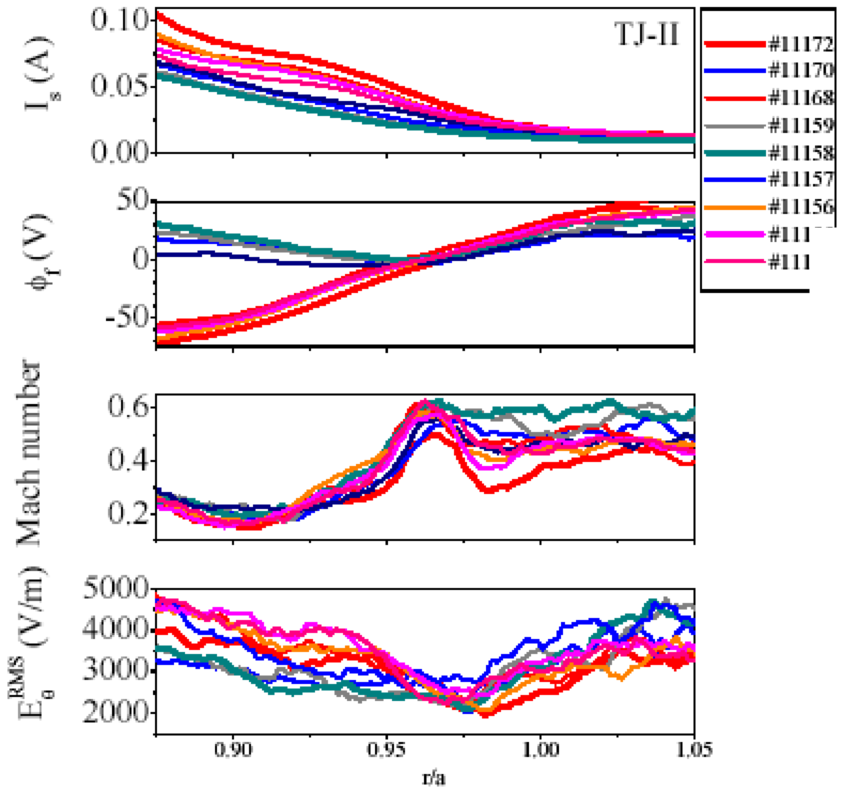
Garbet PoP 2001, Coppi NF 2002

Measurements of $<v_r v_{parallel}>$ show significant gradients in the proximity of the LCFS.

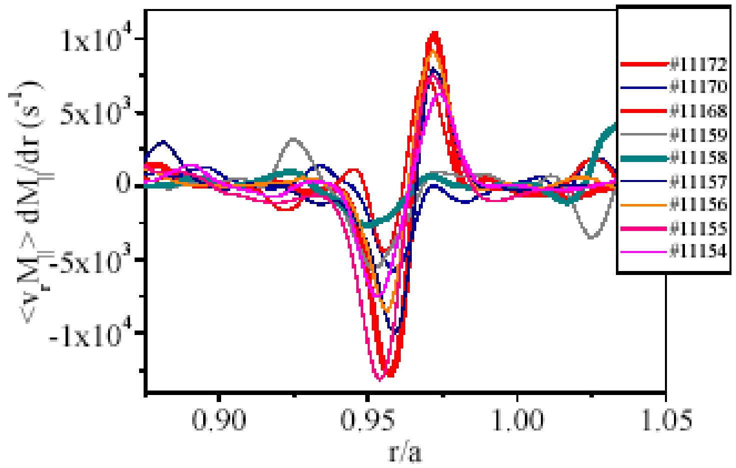
C. Hidalgo et al., EPS-2004

V.Antoni et al., IAEA- 2004

Momentum re-distribution via turbulence in fusion plasmas: energy transfer



$$P = < \tilde{v}_r \tilde{M}_{||} > \frac{\partial M_{||}}{\partial r}$$



Experiments carried out in the plasma boundary of TJ-II stellarator have shown the existence of significant gradients in the crosscorrelation between parallel and perpendicular flowsnear the LCFS.
B. Gonçalves et al., IAEA-2004

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Development of new diagnostics: A trigger of new physics

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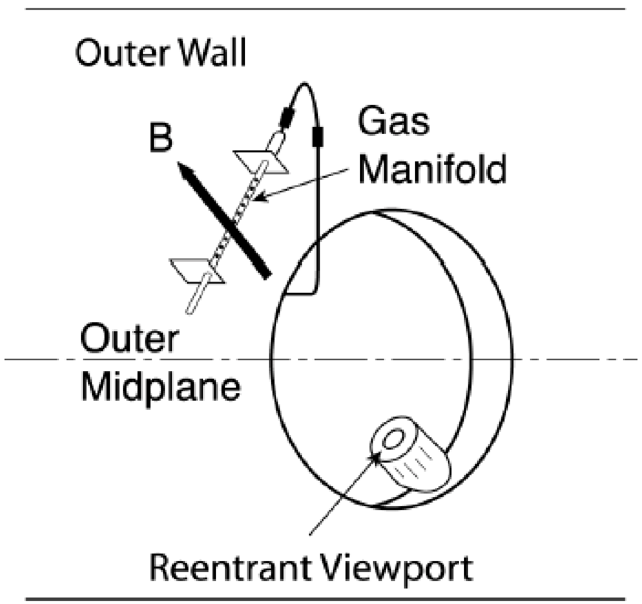
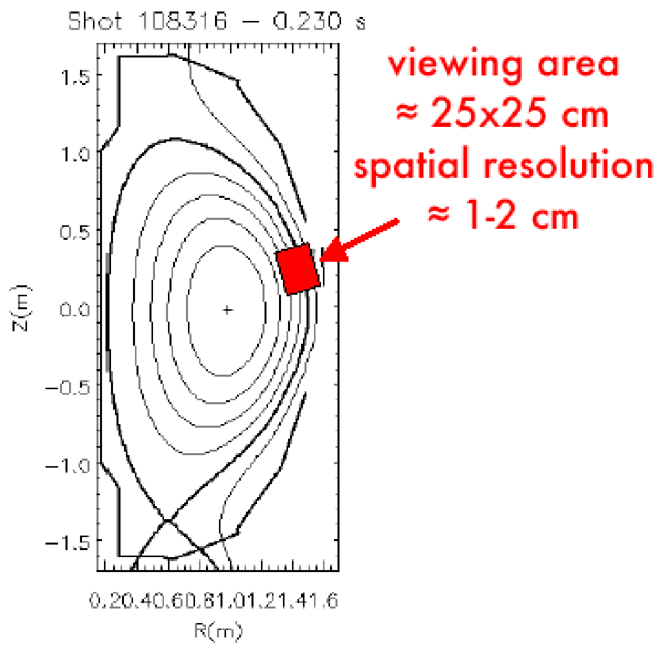
Is it possible to to visualize the 2-D structure of electric fields / velocity fields?

- **Multi-point measurements in the core (HIBP) and edge region (probes)**
- **2-D visualization tecniques (S. Zweben et al., Nuclear Fusion (2004)**

2-D visualization techniques

- Looks at D_α or HeI light from gas puff $I \propto n_o n_e f(n_e, T_e)$
- View ≈ along B field line to see 2-D structure ⊥ B
- Image coupled to camera with 800 x 1000 fiber bundle

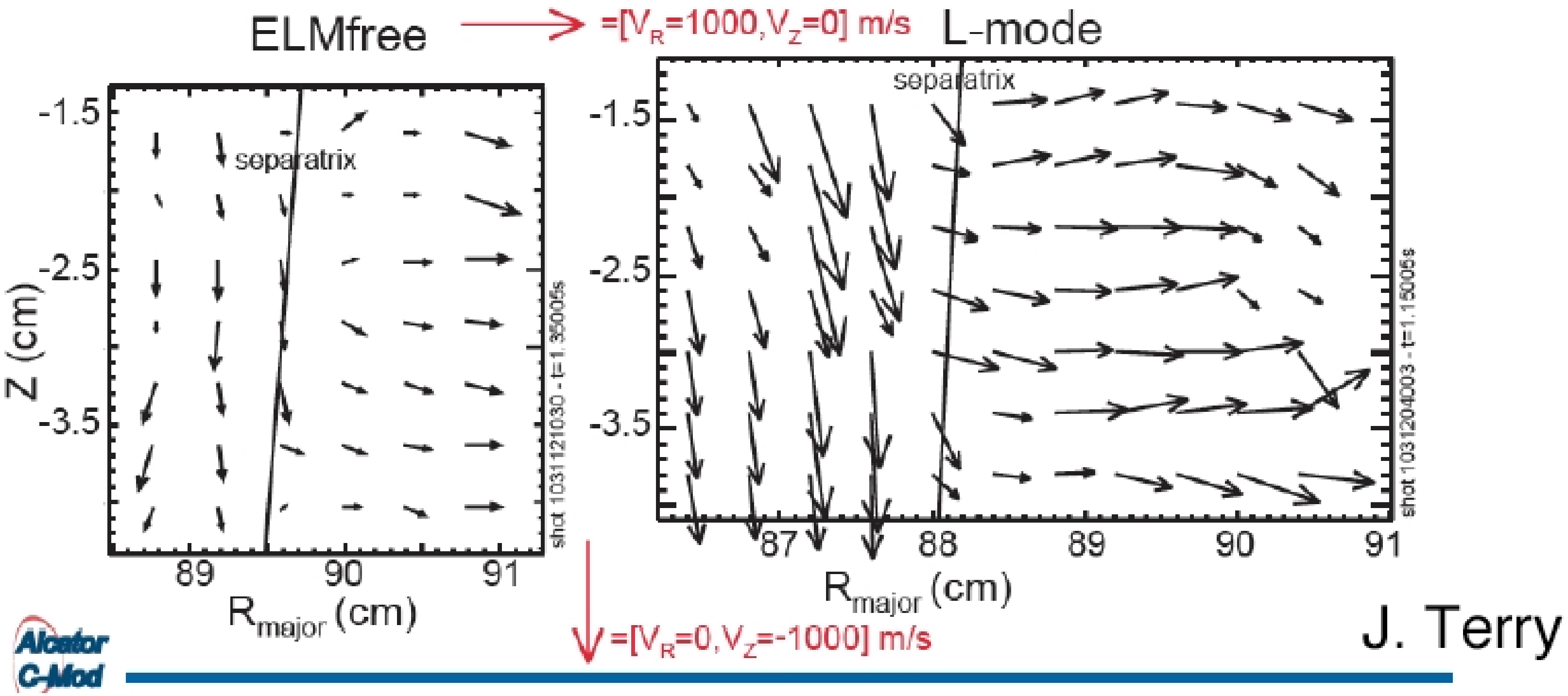




Experiments in

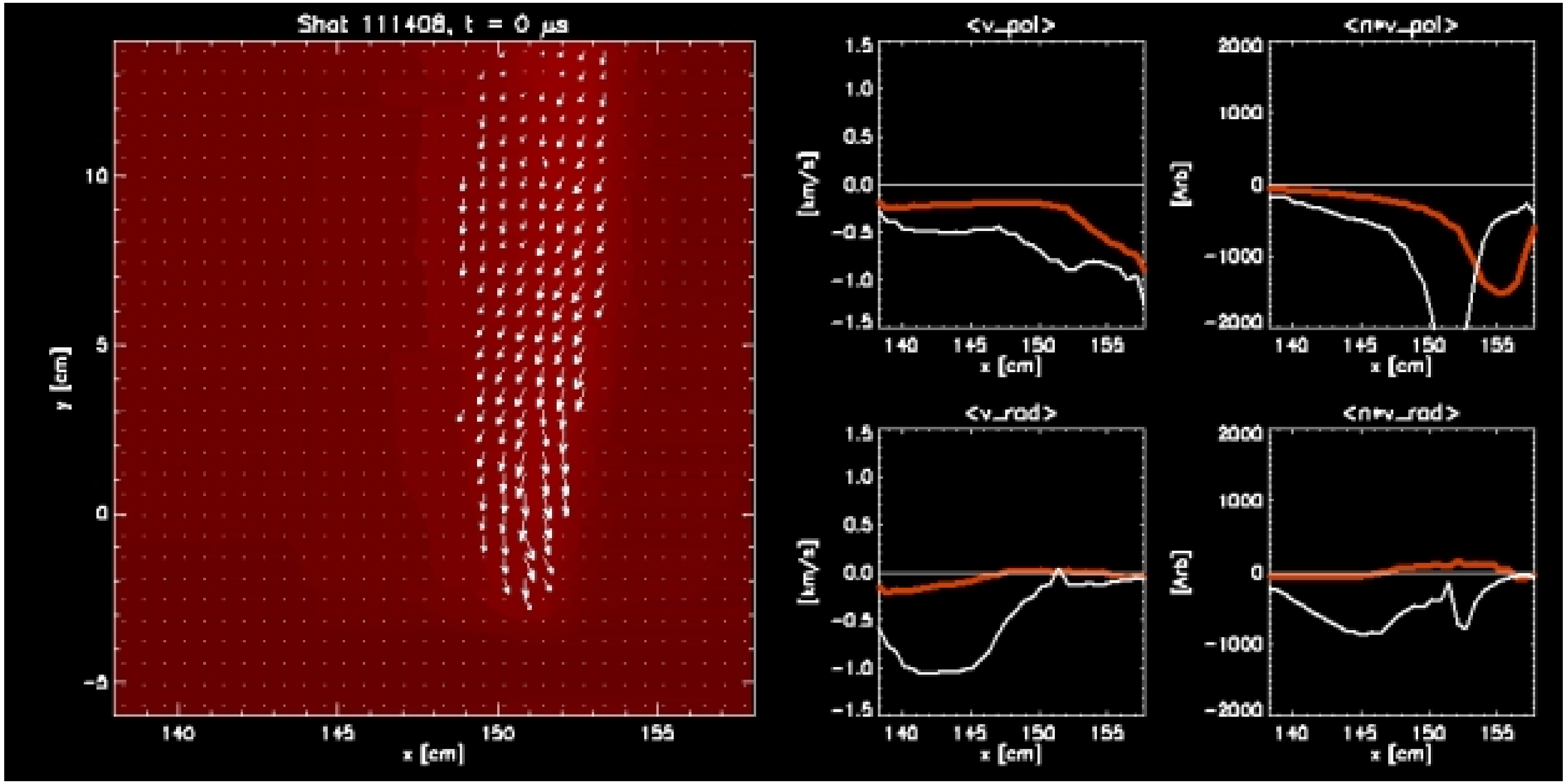
- **NXTS and Alcator Cmod (S. Zweben et al., Nuclear Fusion; J. Terry et al., Phys. Plasmas 2003)**
- **TJ-II stellarator (Ciemat / IPP / PPPL / MIT)**

First 2-D visualization of velocity fields



JNM-2004

Velocity analysis in NSTX



Munsat et al., 2004

Final conclusion

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- **Increasing understanding of transport control is emerging in fusion devices (tokamaks and stellarators), but also plenty of open questions which remain unexplained.**

- **Improved interaction in the plasma physics community (e.g. tokamak / stellarator /RFPs and non-fusion plasmas) provides a complementary view of bifurcation phenomena in non-equilibrium systems.**

- **New approaches (e.g. concept of phase transition, 2-D diagnostics) should be further developed.**