Outline

- Introduction
- Experimental set-up
- Sheared flows development in TJ-II
  - Spontaneously developed edge shear layer
  - Effect of externally induced electric fields
  - Relaxation time scales measurements for electric fields
- Model coupling shear flow and turbulence
  - Comparison with experimental results
- Summary and conclusions

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Introduction

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- ✓ Plasma confinement is limited by the presence of turbulence and shear flows are crucial elements in edge turbulence dynamics: ExB shear stabilization mechanisms are an important element for the improvement of plasma confinement in fusion devices. Clarifying the driving/damping mechanisms of sheared flow is a key issue for the development of fusion.
- ✓ The universality of the sheared flows characteristics points to a unique and common ingredient to explain the driving/damping mechanisms in the plasma boundary region of fusion devices. The role of neoclassical mechanisms to explain poloidal flows has been recently questioned. Turbulence is a candidate to explain experimental findings.
- ✓ Techniques for generation and control shear flow in the plasma are crucial to understanding and providing the plasma confinement needed in fusion devices. TJ-II is a good laboratory to characterize the dynamics of sheared flow development in fusion plasmas.
- ✓ The result of the present experiments can help to understand and quantify the importance of anomalous versus neoclassical mechanisms on the damping physics of radial electric fields and flows in fusion plasmas.

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Experimental set up

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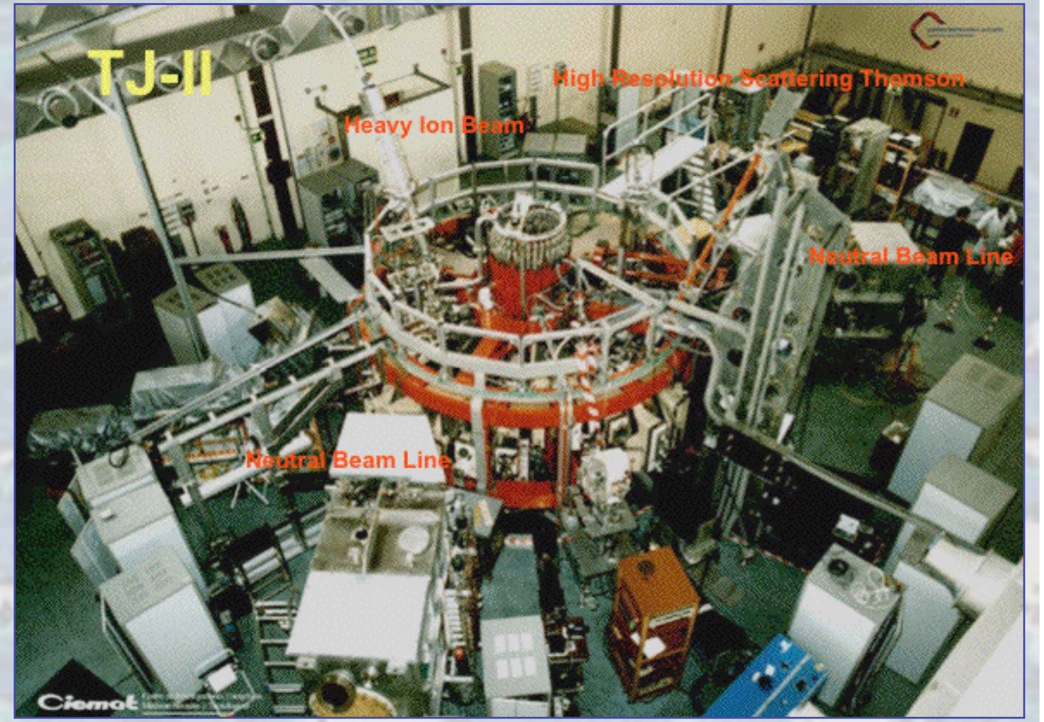


TJ-II Stellarator

$\langle R \rangle = 1.5$ m $\langle a \rangle \leq 0.22$ m

$B_T \leq 1.2$ T

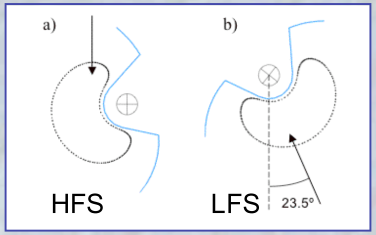
$\langle n_e \rangle \approx (0.35 - 1) \times 10^{19}$ m^{-3}

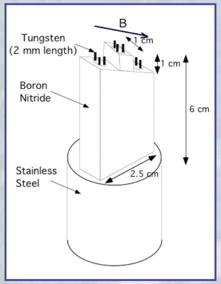
$P_{ECRH} \leq 400$ kW $f_{ECRH} = 53.2$ GHz

Langmuir/Mach Probes
180º toroidally apart

$I_s \propto nT_e^{1/2}$

$V_f \approx V_p - \alpha T_e$



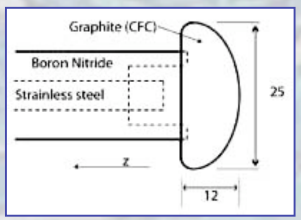


Electrode

2 cm inside the LCFS

V= 160 - 400 V

$I \approx 20 - 50$ A

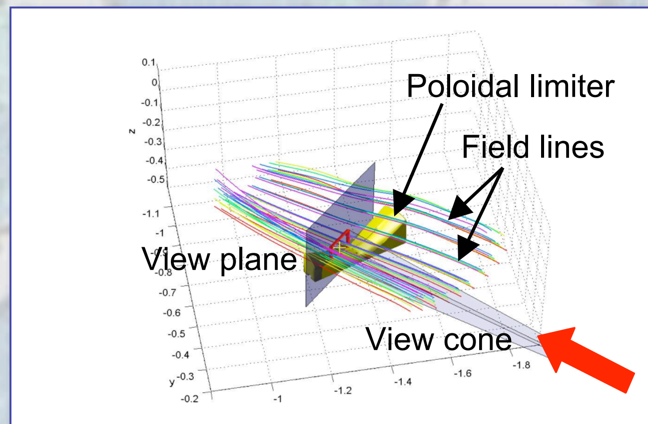


Fast Camera

CCD sensor (PSI-5)

Hα filter

250.000 frames/s



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Spontaneously developed edge shear layer in TJ-II

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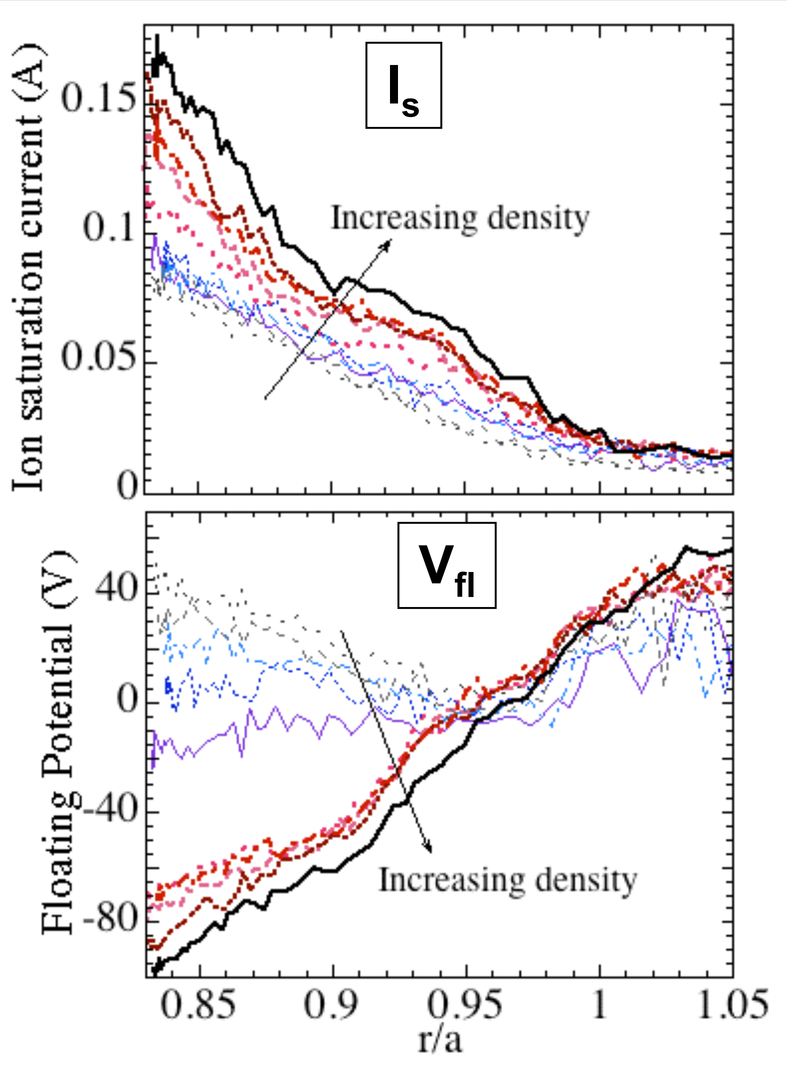
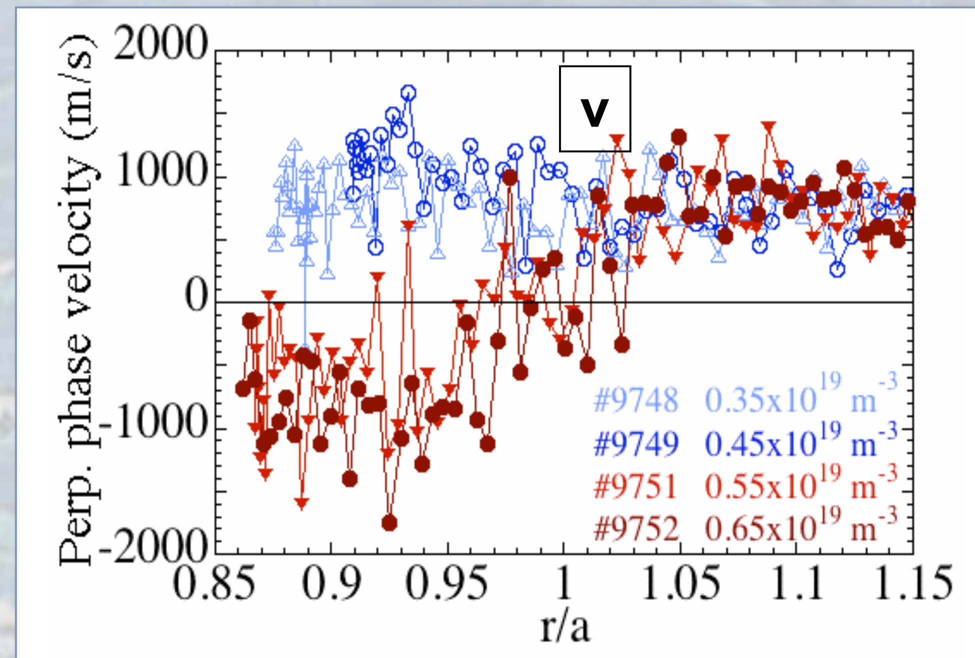
- **The existence of sheared flows in TJ-II requires a minimum plasma density (or gradient) that depends on the plasma configuration.**





C. Hidalgo, M.A. Pedrosa et al., Phys. Rev. E **70** (2004) 067402
M.A. Pedrosa, et al., Plasma Phys. Control. Fusion, **47** (2005) 777

Spontaneously developed shear layer in two toroidal positions

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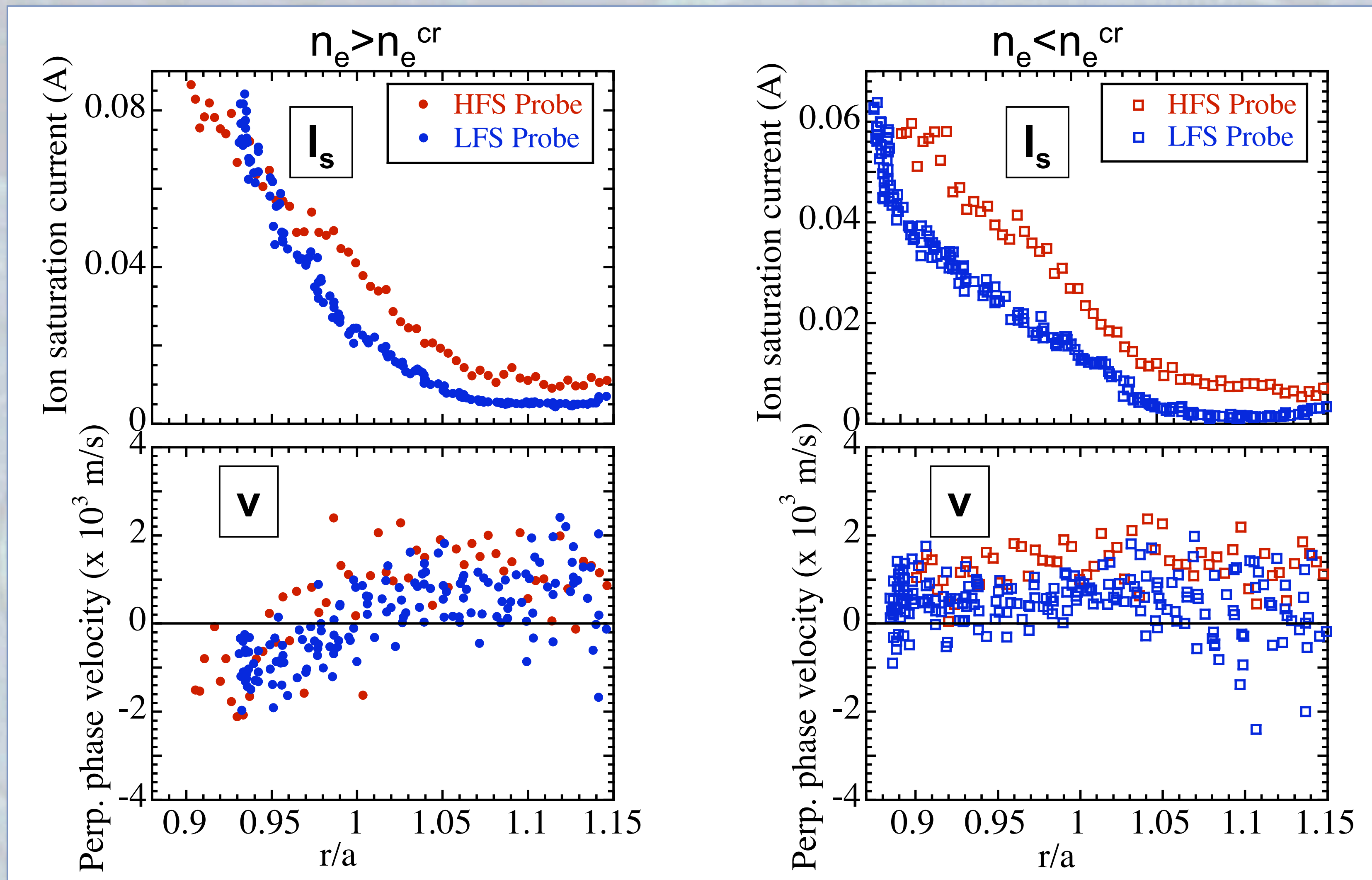
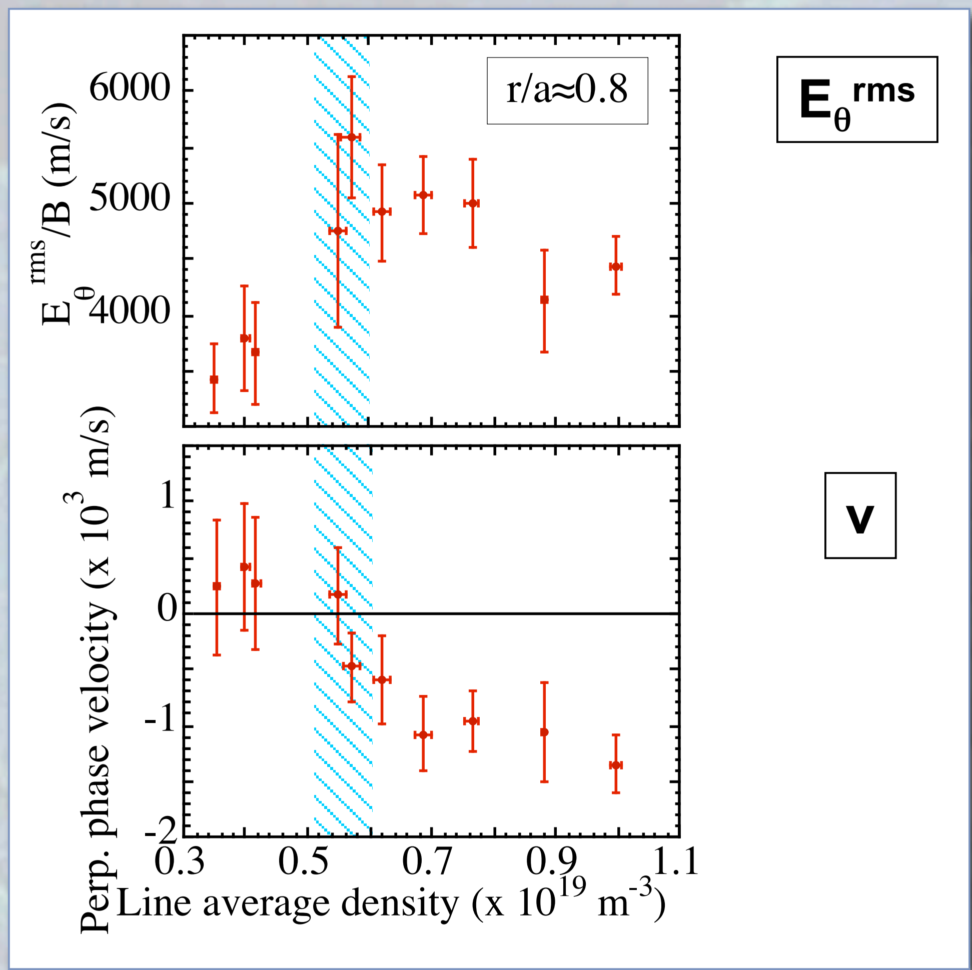
- Radial profiles have been simultaneously obtained in two toroidal positions approximately 180º apart for different plasma conditions.



Spontaneously developed shear layer in two toroidal positions

- **Sheared flows and fluctuations appear to be organized near marginal stability.**
- **The universality of this property is easily understood assuming that edge sheared flows are controlled by turbulence.**



C. Hidalgo, et al., Plasma Phys. Control. Fusion **46** (2004) 287

Spontaneously developed shear layer in two toroidal positions

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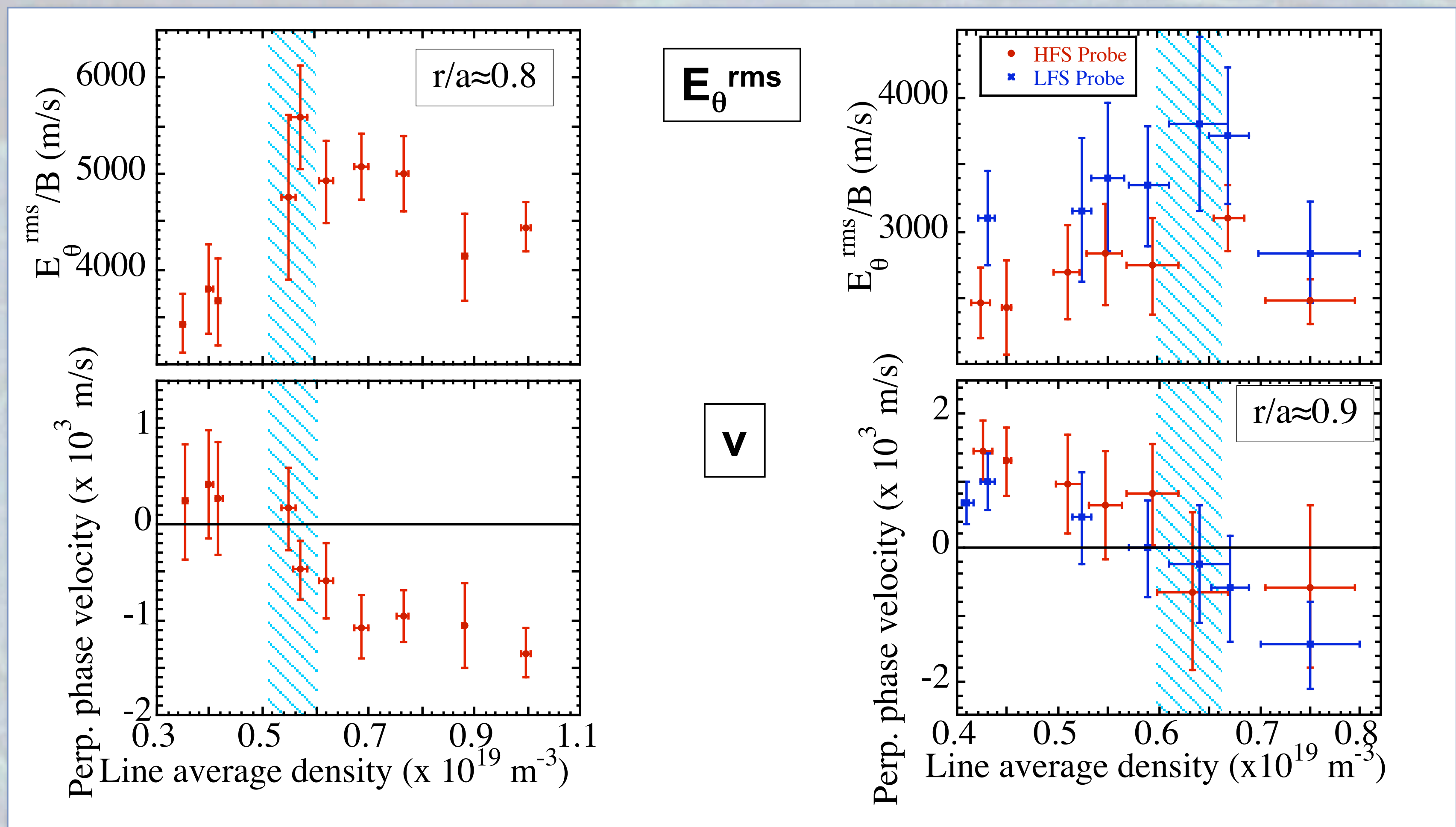
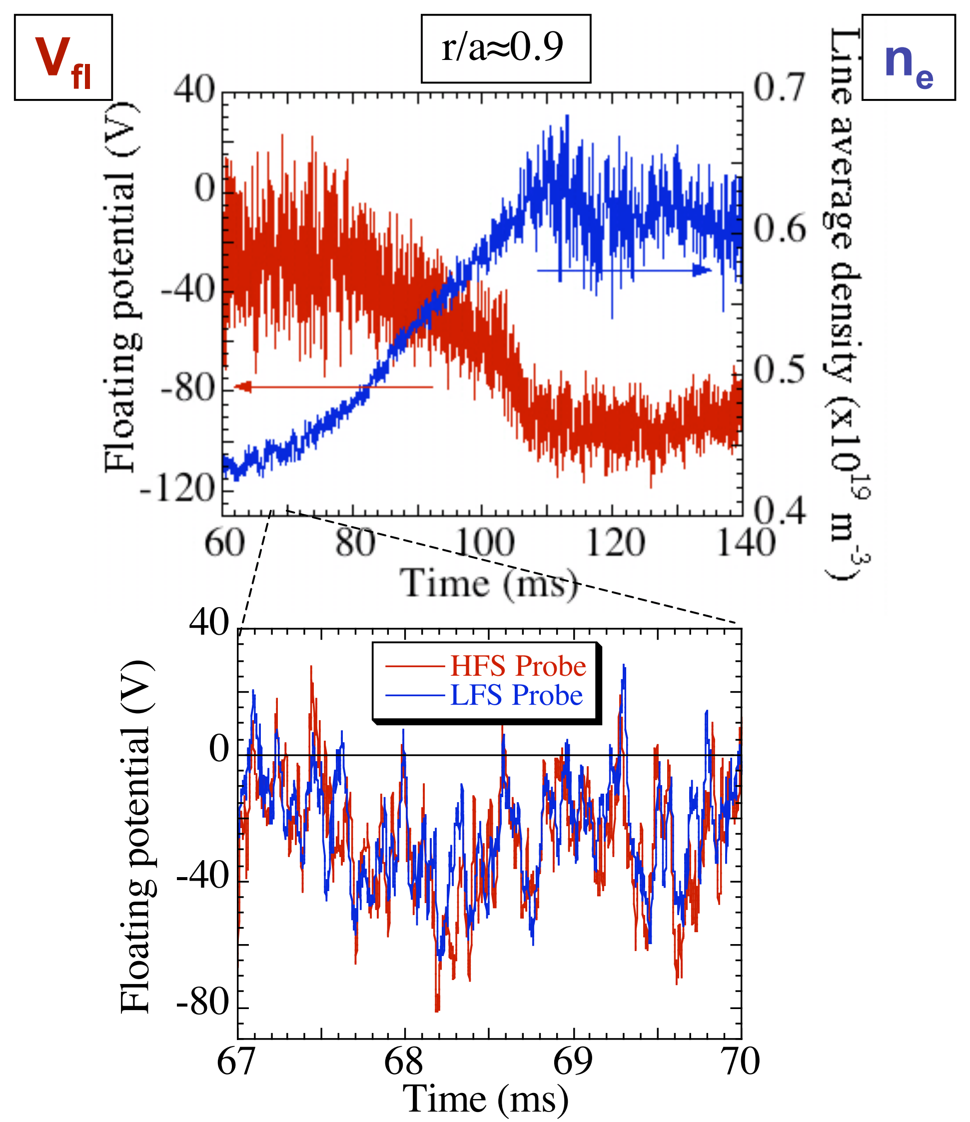
- **Edge sheared flows are developed at the same threshold density in the two toroidal positions.**



C. Hidalgo, et al., Plasma Phys. Control. Fusion **46** (2004) 287

Time scales for the spontaneous shear layer development in TJ-II



M.A. Pedrosa, et al., 15th Stell. Workshop (2005)

- **Slow time scale, in the range of the particle confinement time (tens of milliseconds) that evolves with plasma density.**
- **Fast time scale with transient events that take place in a time scale of the order of tens of μs (few turbulence correlation times).**

Toroidal correlation

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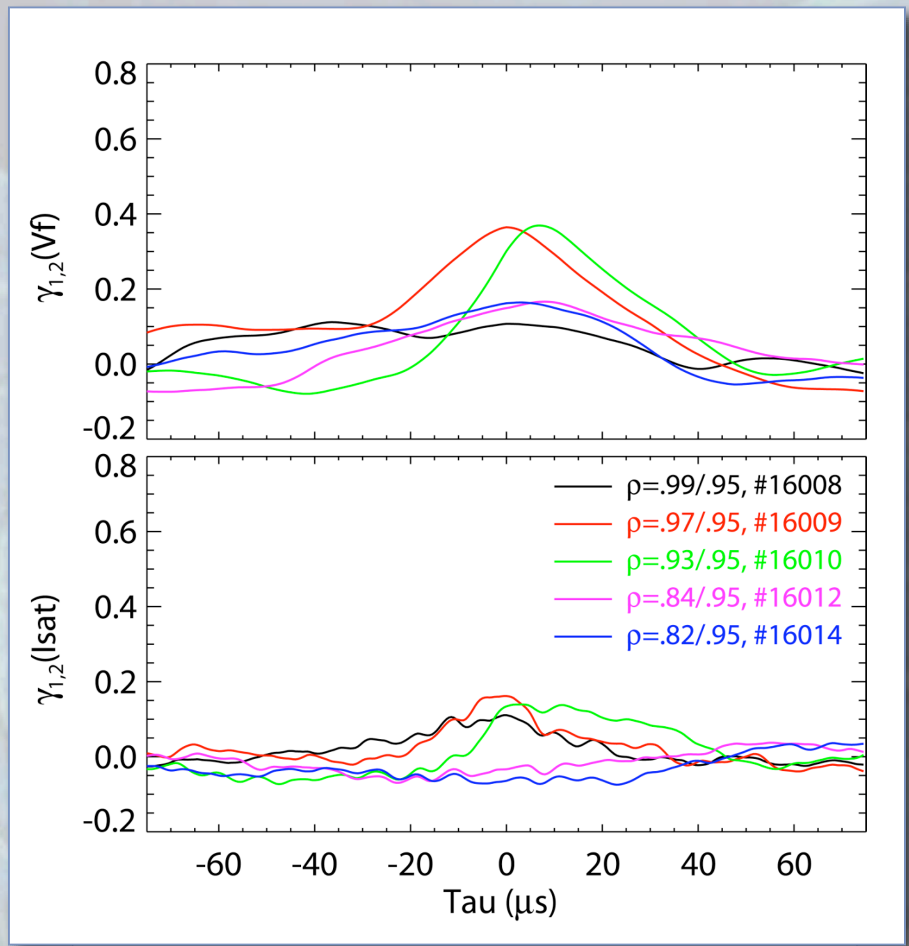
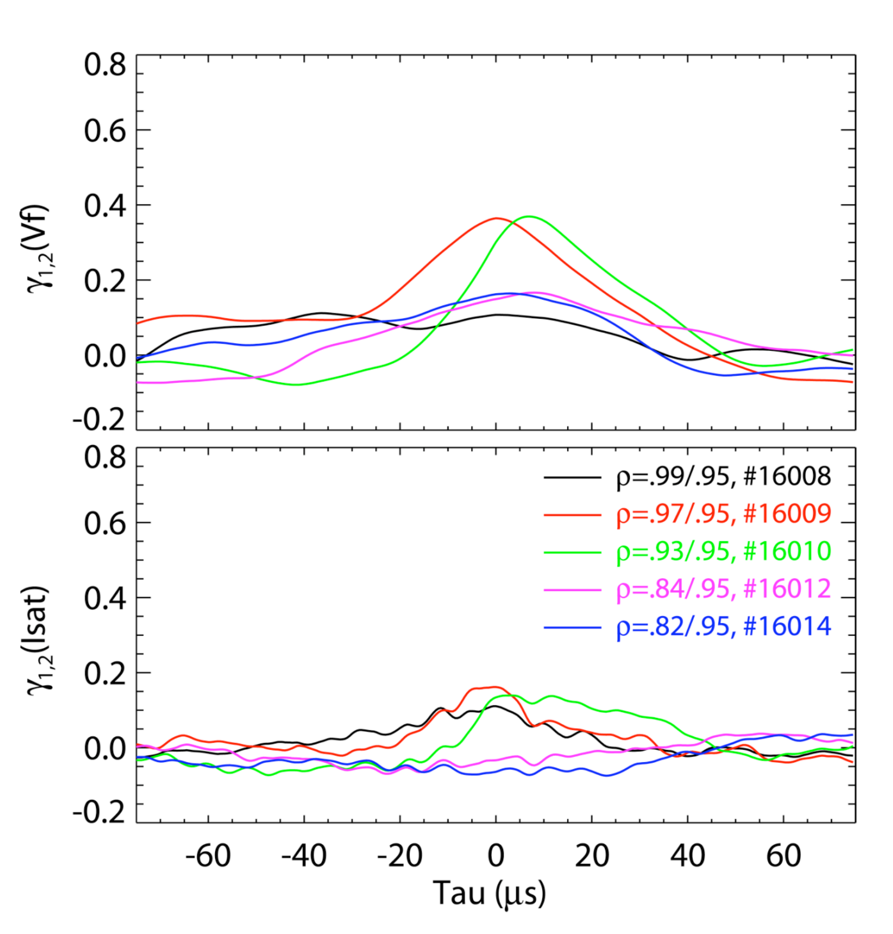
- **Significant toroidal correlation for low frequency potential fluctuations, but not for density.**

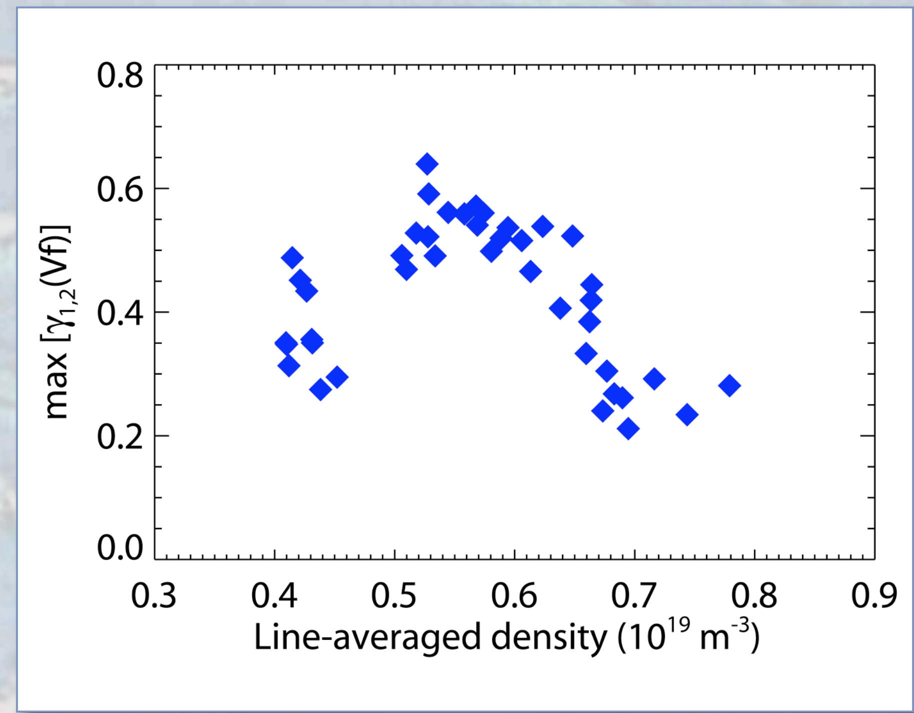


M.A. Pedrosa, et al., P2-012 16th Stell. Workshop (2007)

Toroidal correlation

- Significant toroidal correlation for low frequency potential fluctuations, but not for density.
- Maximum correlation at the threshold density.





M.A. Pedrosa, et al., P2-012 16th Stell. Workshop (2007)

2-D visualization of edge shear layer in TJ-II

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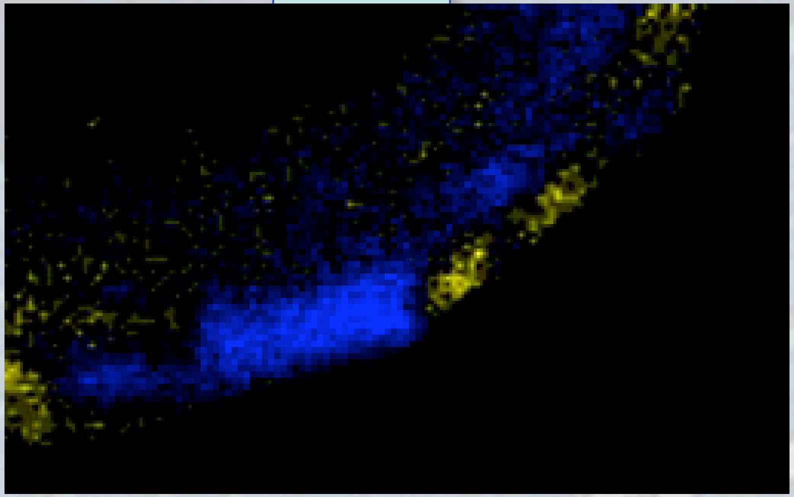
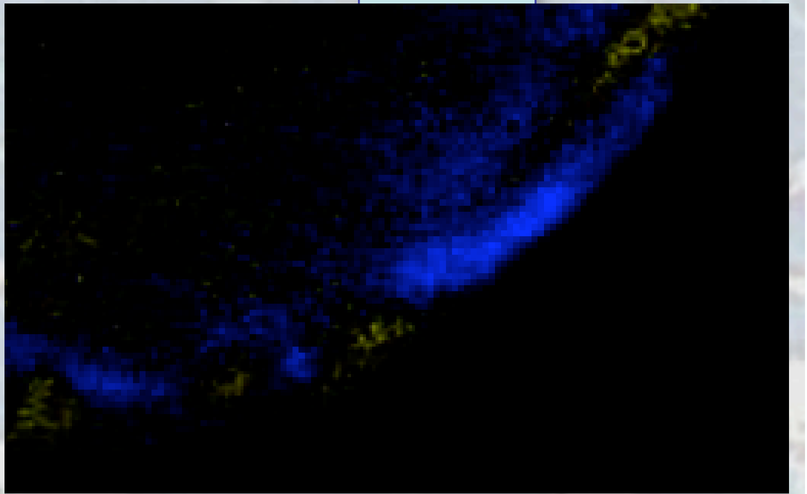
- The reversal in the ExB rotation has been 2-D visualized using Ultra Fast Speed cameras.
- Edge sheared flows can be developed on a time scale of few tens of μs.

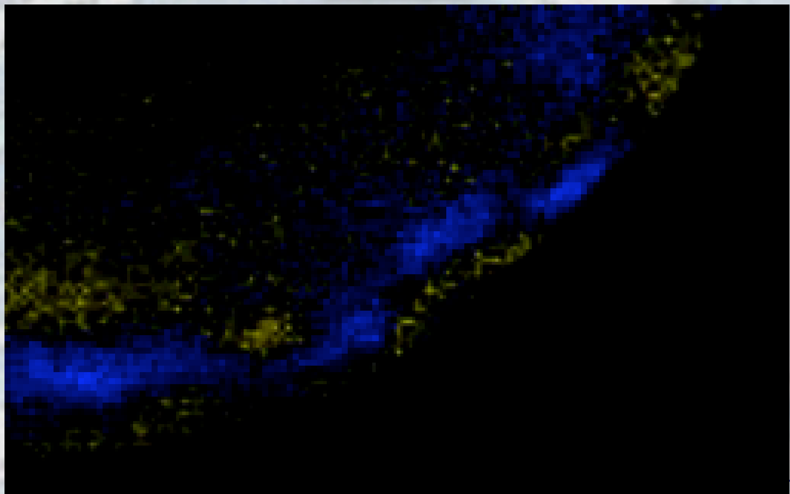
$n < n_{cr}$



$n > n_{cr}$



$n \approx n_{cr}$



J.A. Alonso, et al., Plasma Phys. Controll. Fusion **48** (2006) B465

Effect of externally induced electric fields in TJ-II

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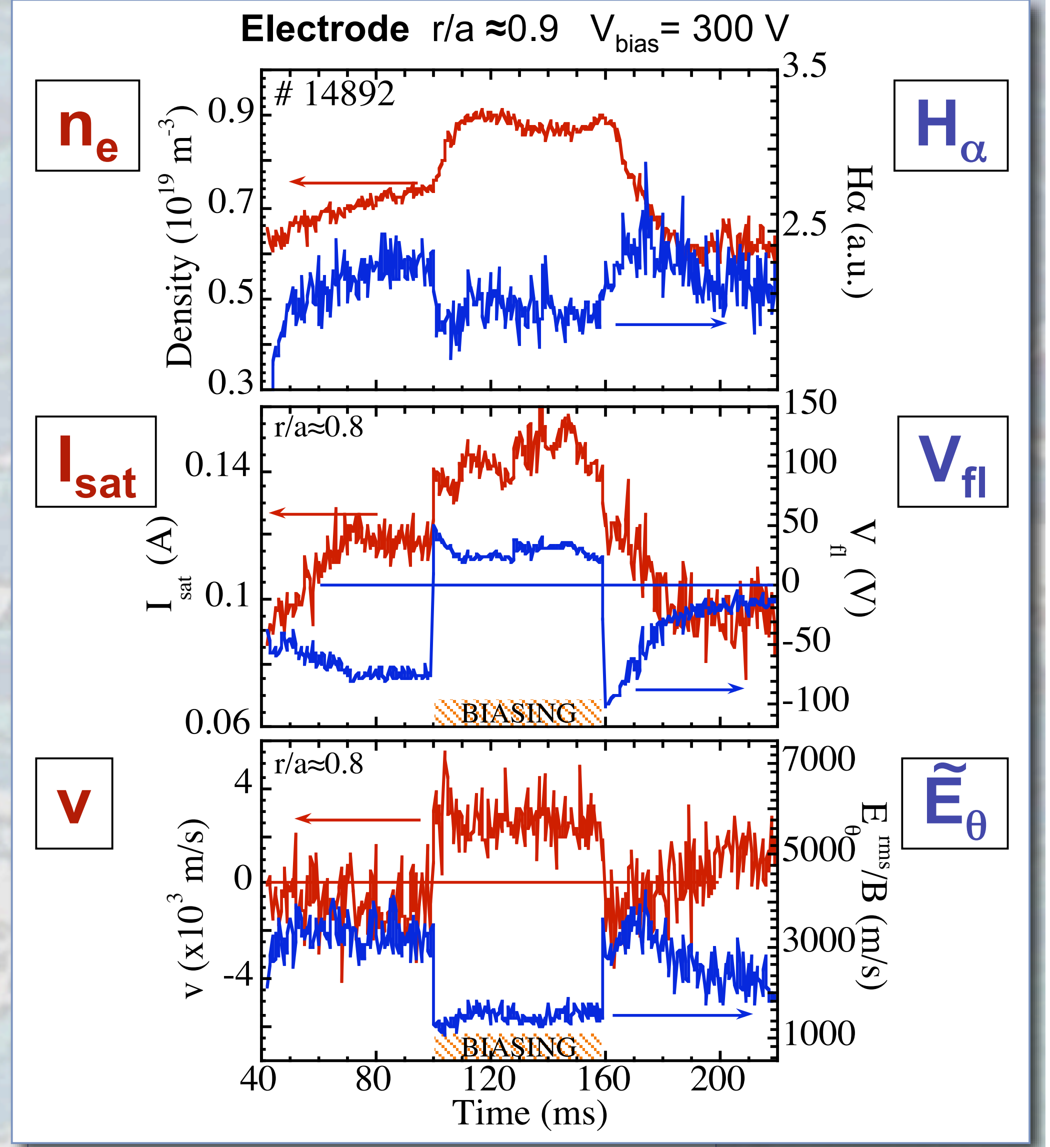
Biasing induced improved confinement

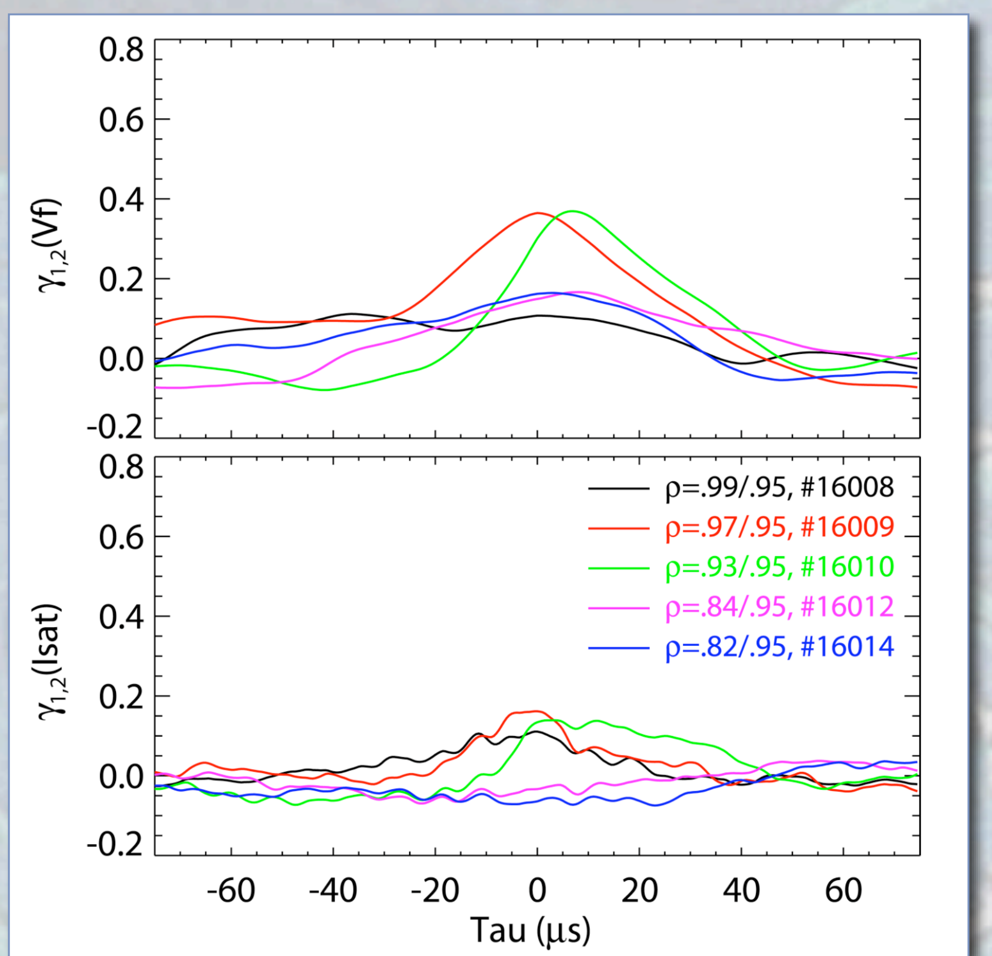
- **Gradient increase in edge density profiles**
- **Development of positive electric fields**
- **Reduction of edge turbulence**



C. Silva, et al., Czech. J. Phys. **55** (2005) 1589

Toroidal correlation in presence of externally induced electric fields

- **Correlation between potential signals increases in the presence of externally applied electric fields.**



M.A. Pedrosa, et al., P2-012 16th Stell. Workshop (2007)

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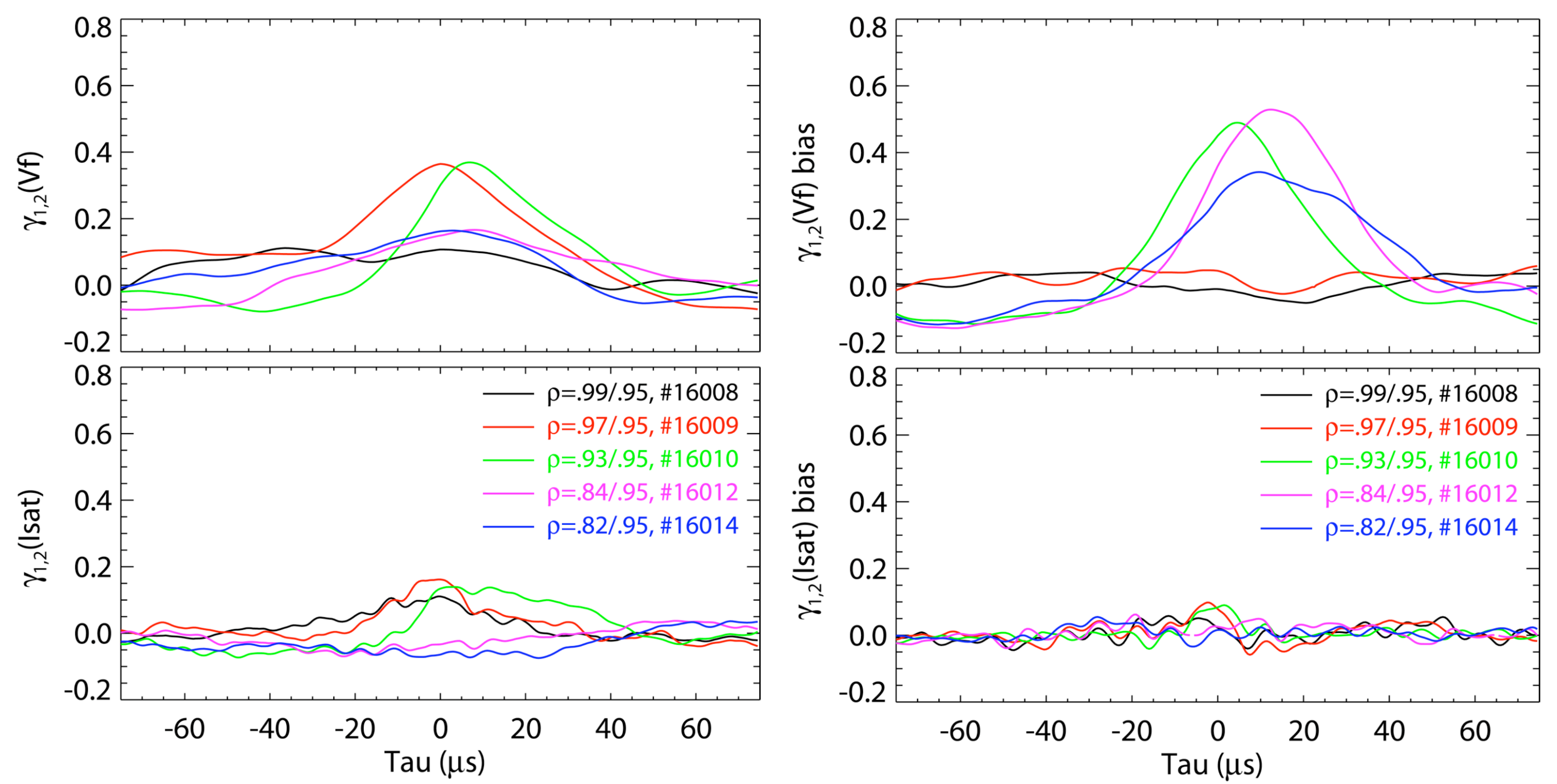
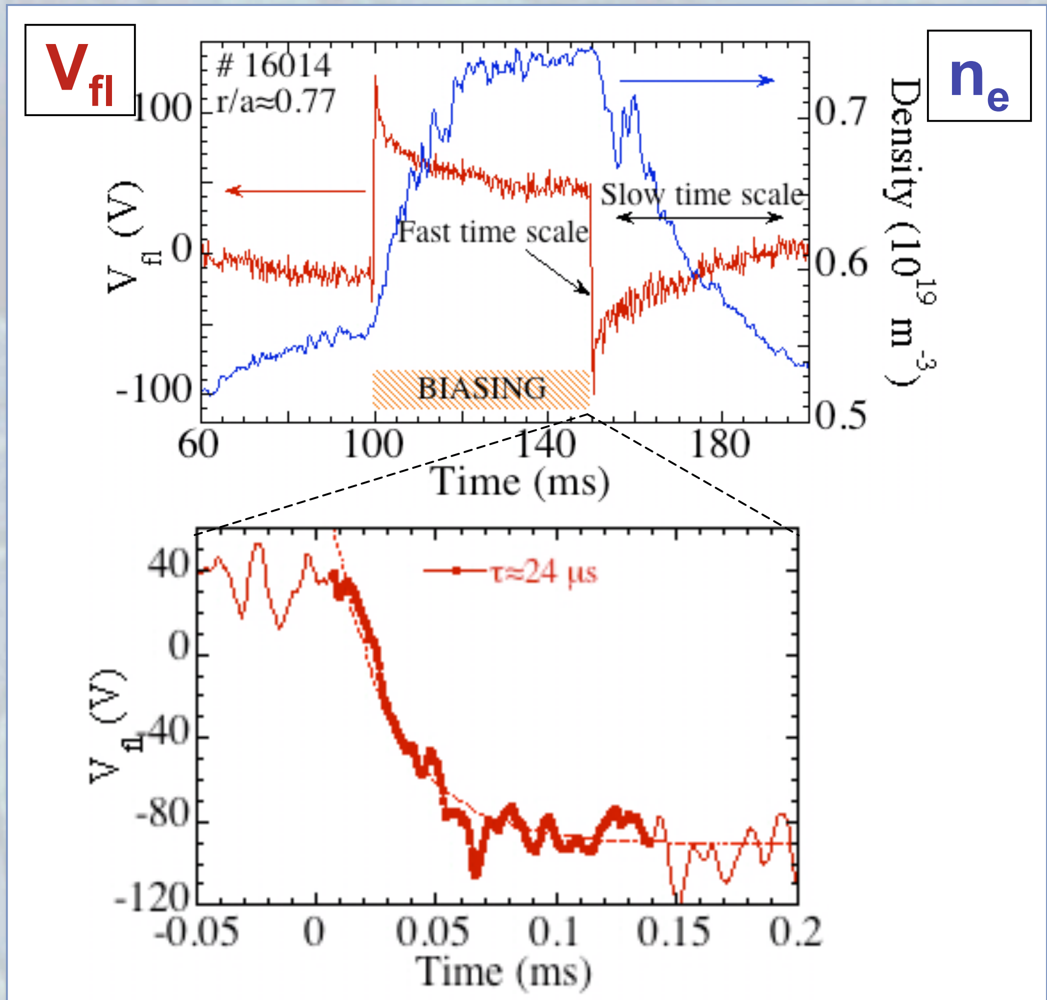


M.A. Pedrosa, et al., P2-012 16th Stell. Workshop (2007)

Time scales for the externally induced shear flow damping



Two time scales for shear flow relaxation:

- **slow time scale, of the order of the particle confinement time (10 ms)**
- **fast time scale of the order of characteristic turbulence time scales (10 – 90 μs)**

$$V_{fl}(t) = V_{max}\, exp\left(-\frac{t}{\tau}\right) + V_{min}$$

τ is the exponential relaxation time

Time decay rate of the flow, once the driving force is switched off, can be a measure of the shear flow damping time.

Fast time scale for the externally induced shear flow damping

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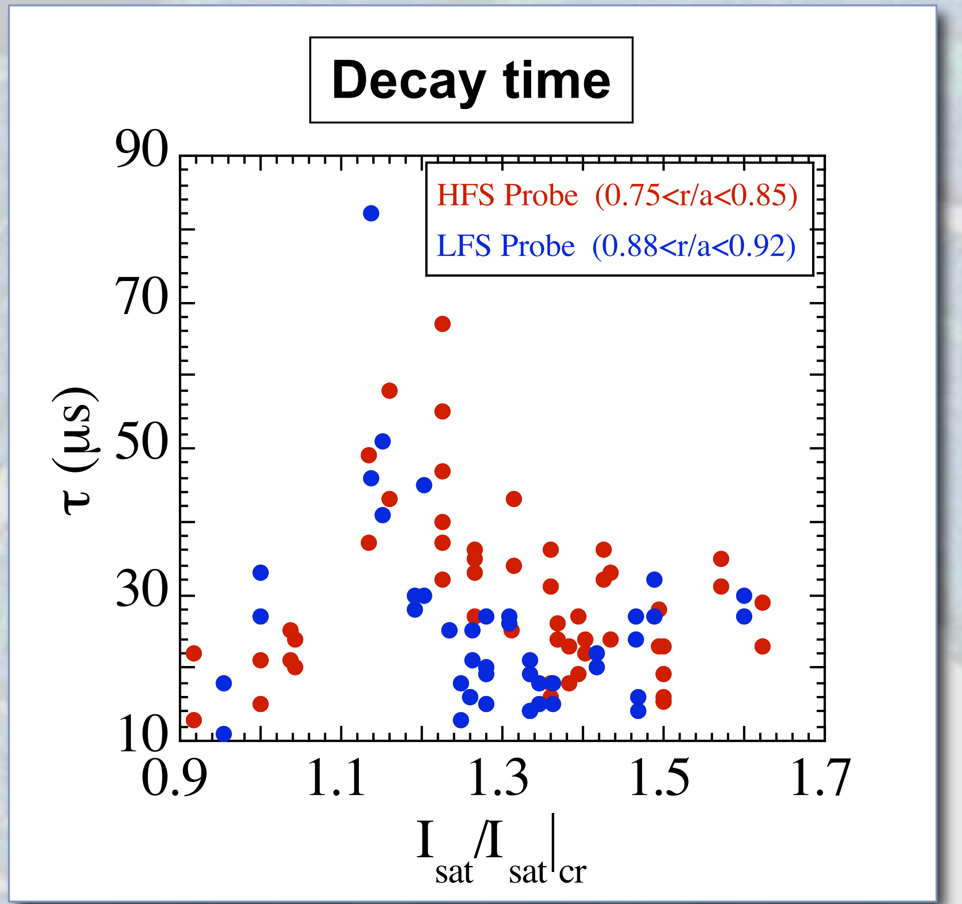
- Turbulence damping mechanisms are likely to apply for short time scales.
- Results suggest an increase in decay times above the critical value of the control parameter (i.e. the local density gradient), that is, once edge perpendicular shear flow is fully developed.



Comparison between relaxation time scales in different devices

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This result can help to quantify the importance of anomalous versus neoclassical mechanisms on the damping physics of radial electric fields and flows in fusion plasmas.

DEVICE	TJ-II Stellarator[1]	CASTOR Tokamak[1,2]	HSX Stellarator[3]
Major radius (m)	1.5	0.4	1.2
Magnetic field (T)	1	1	0.5
Line Average Density (m^{-3})	(0.4 - 1) x 10^{19}	1 x 10^{18}	0.5 x 10^{18}
Relaxation time (μs)	10 - 90	10 - 30	15 - 50

(1) M.A. Pedrosa et al., Plasma Phys. Controll. Fusion (2007)
(2) M. Hron et al.,30th EPS Conference 2003
(3) S.P. Gerhardt, J.N. Talmadge, et al., Phys. Rev. Lett. 94 (2005) 015002, Phys. Plasmas 12 (2005) 056116.

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Model coupling shear flow and turbulence

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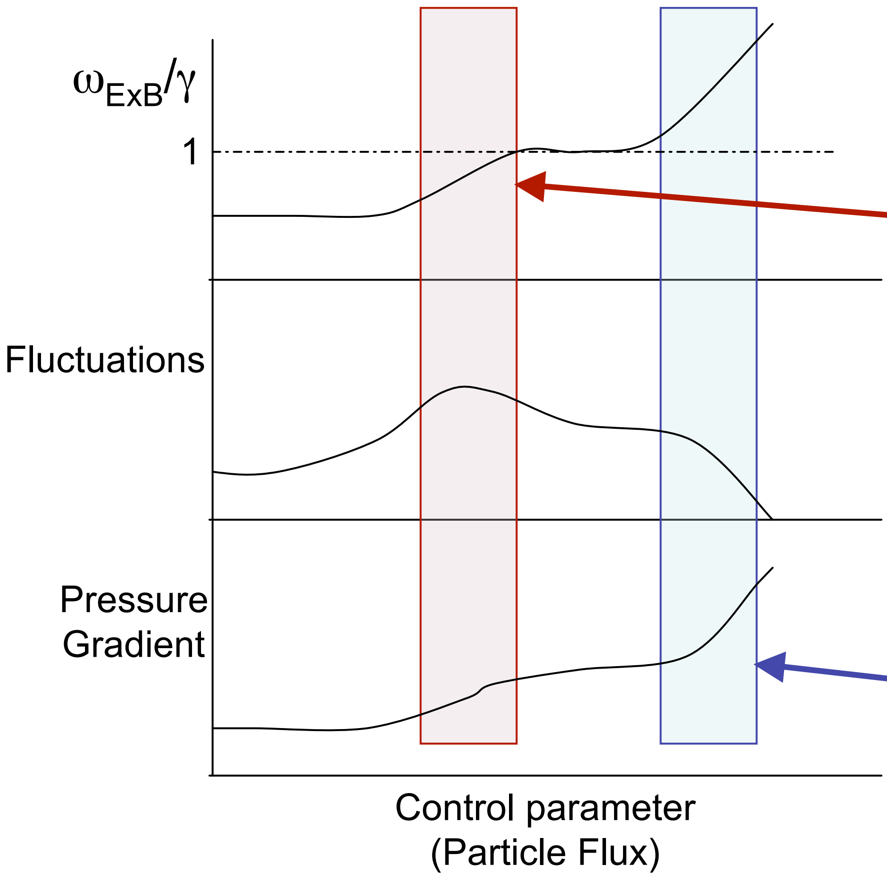
Model for L to H-mode transition:

ELECTRIC FIELD ⟷ FLUCTUATIONS



Second-order phase transition

Controlled by shear flow amplified via Reynolds stress

CHARACTERISTICS:

- ***Continuous transition***
- ***Symmetry breaking***
- ***Critical slowing down***

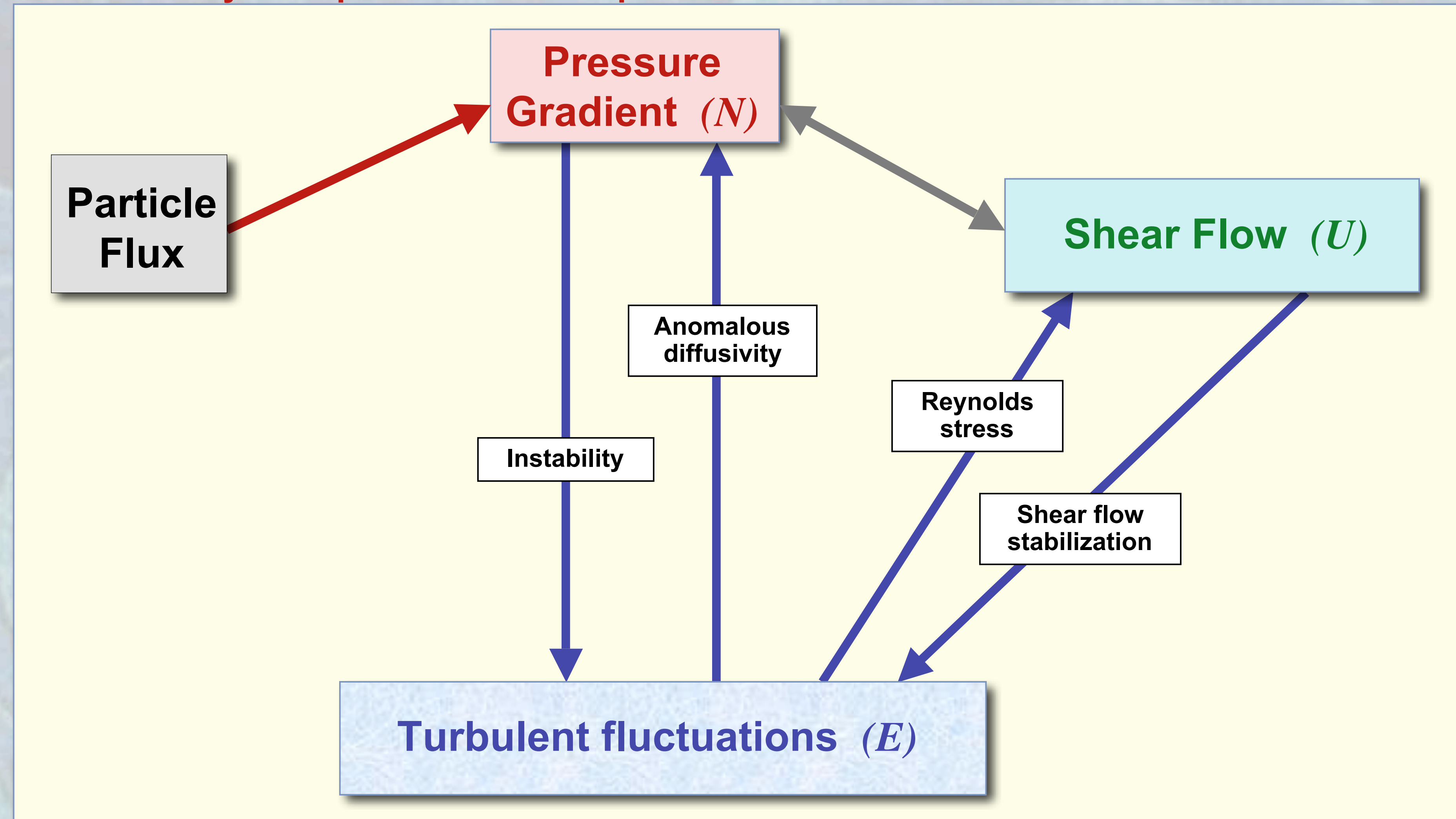
First-order phase transition

Suppression of turbulence by Pressure gradient

Describes H-mode

Model coupling shear flow and turbulence

- **The emergence of the plasma edge shear flow layer in TJ-II as density increases can be described by a simple second-order phase transition model.**



B.A. Carreras, L. García et al., Phys. Plasmas **13** (2006) 122509

Model coupling shear flow and turbulence

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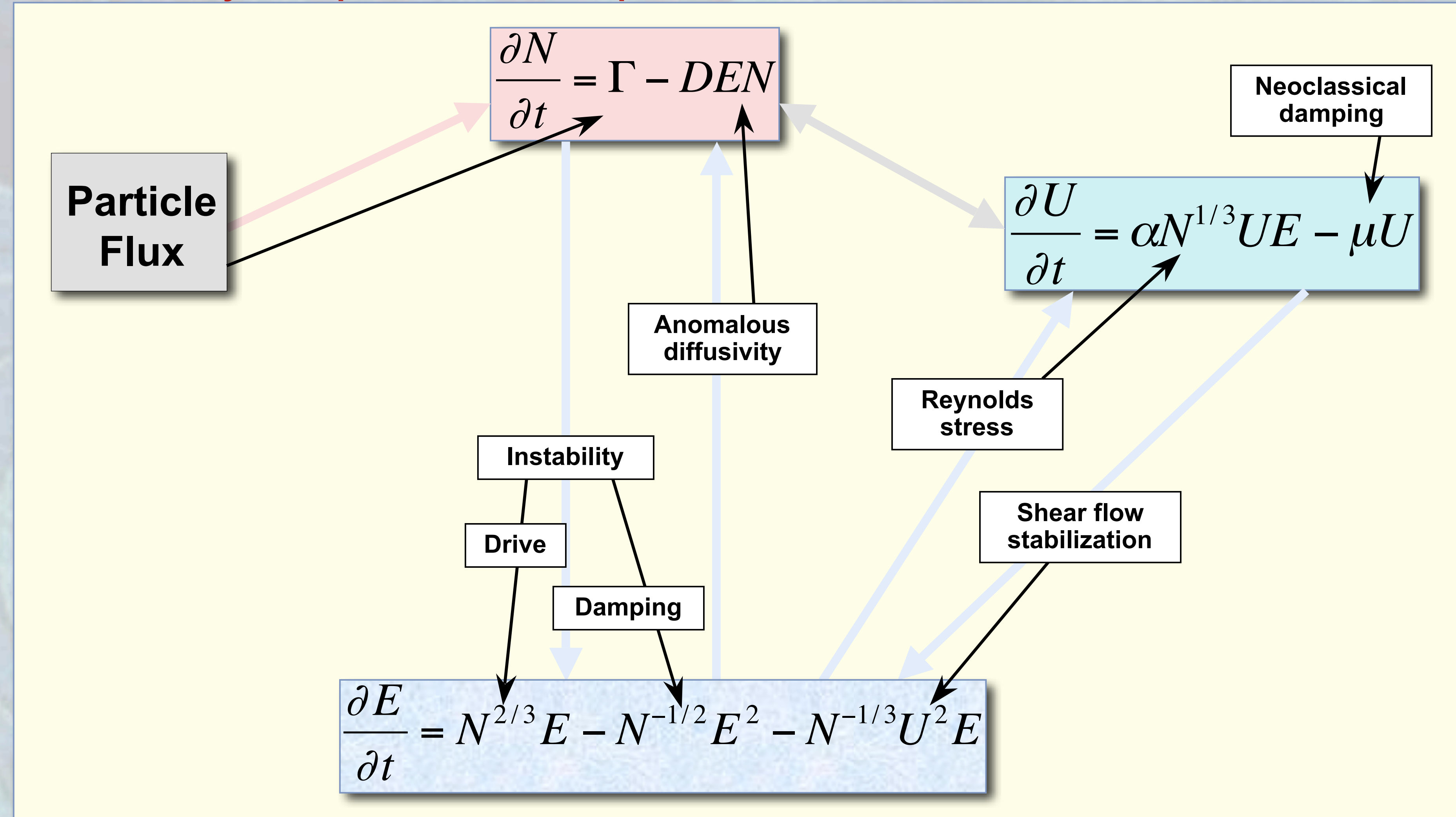

B.A. Carreras, L. García et al., Phys. Plasmas **13** (2006) 122509

Model coupling shear flow and turbulence

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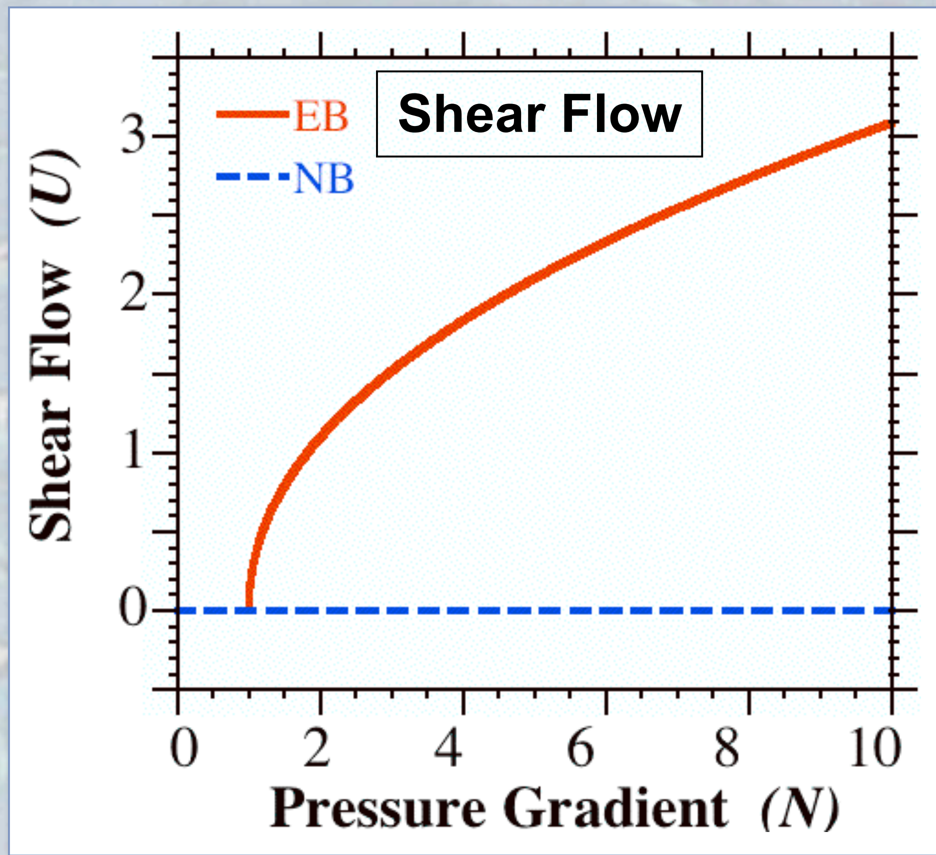
- **Normalizing to the values at the critical point the model gives two solutions with no free parameters:**

✓**without Barrier (NB)**

$$U_{NB} = 0$$

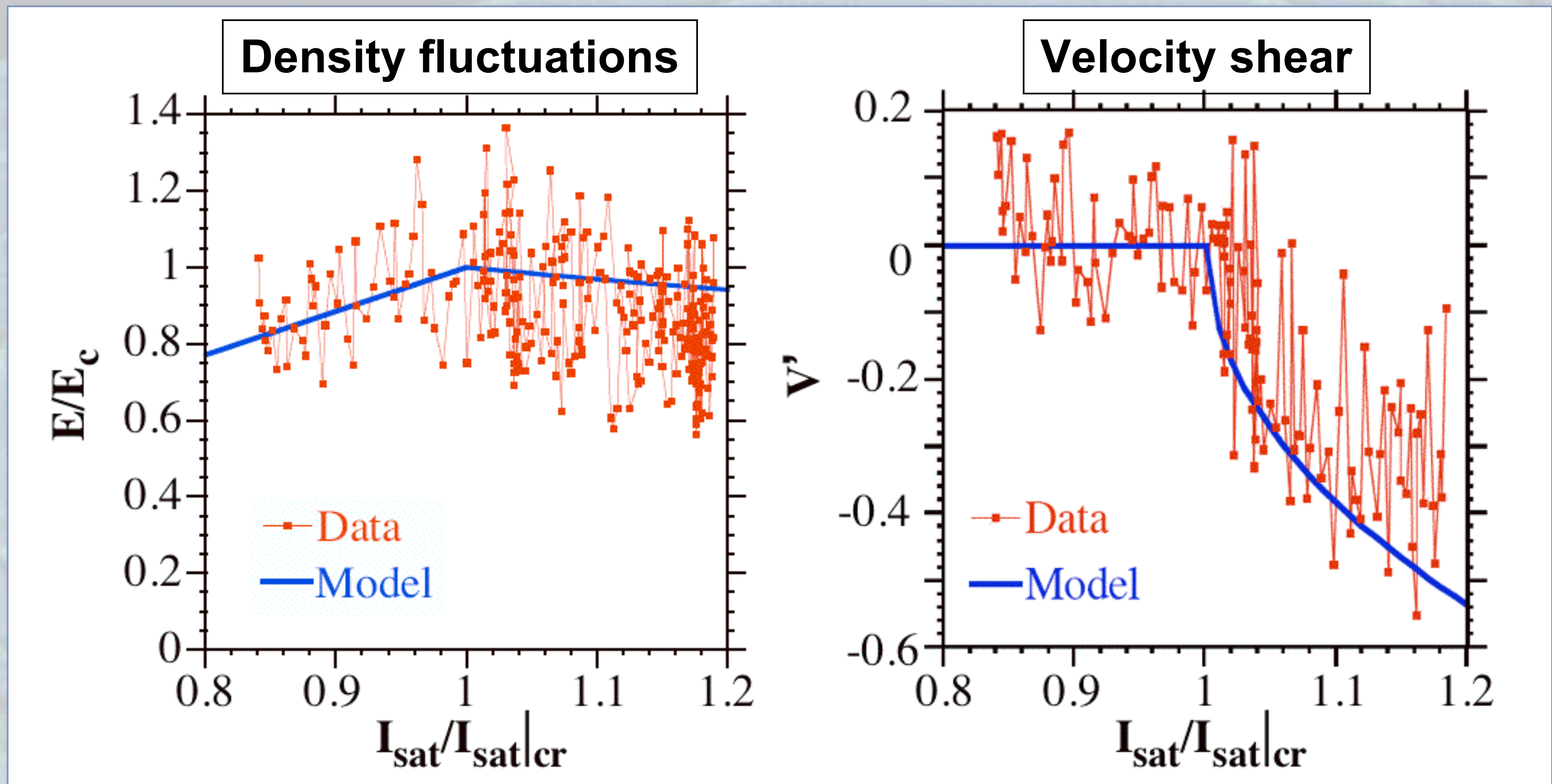
✓**with Edge Barrier (EB) that exists when density gradient is above a critical value. Above this value there are two possible states (NB and EB).**

$$U_{EB} \propto N_c^{1/2} \sqrt{\frac{N}{N_c} - \left(\frac{N}{N_c}\right)^{1/2}}$$



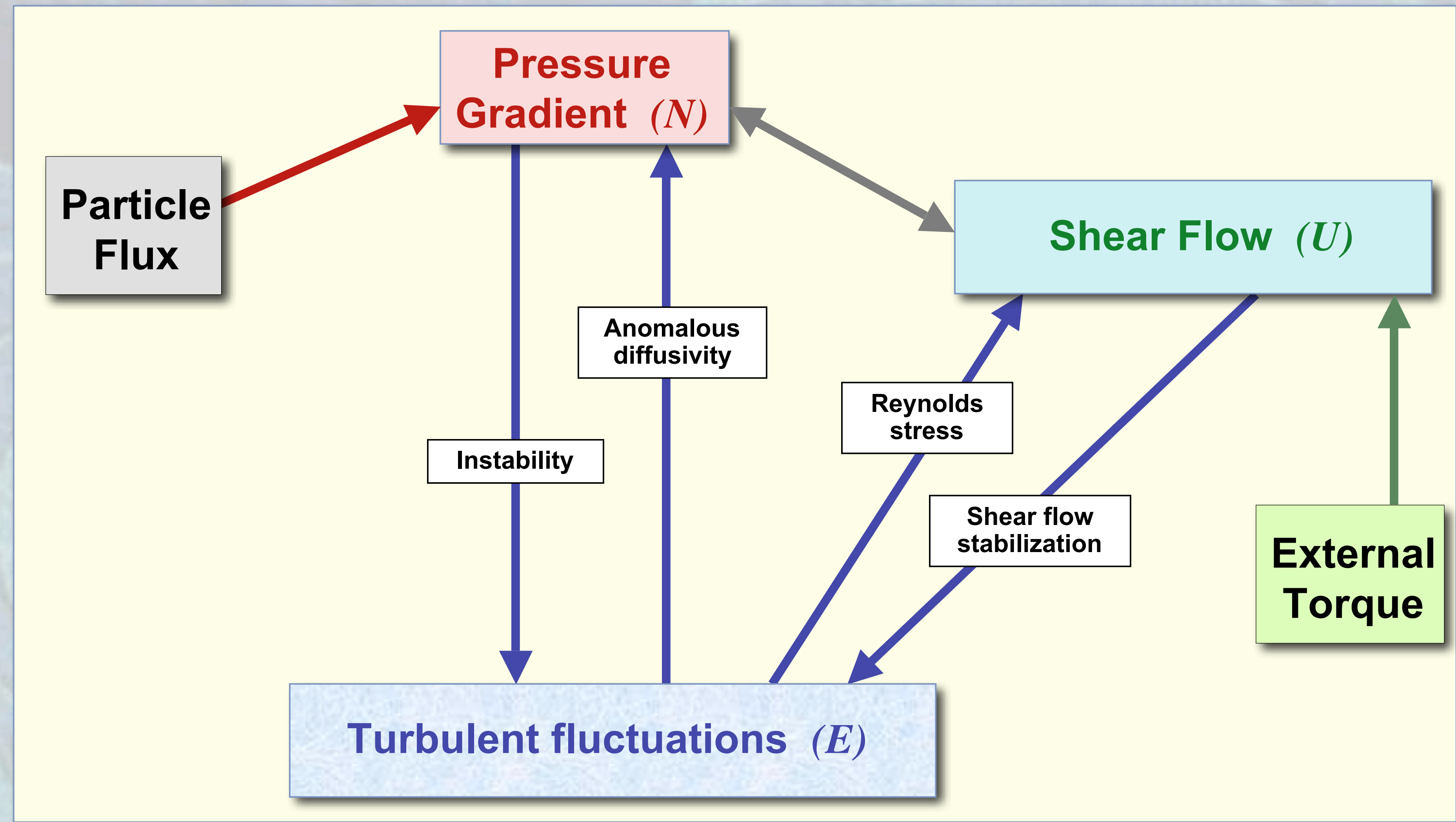
Comparison with experimental results

- **This model captures the qualitative features of the transition near the critical point for density ramp experiments.**
- **Ion saturation current normalized to the value for critical density has been considered as a control parameter and phase velocity as the order parameter.**



Model coupling shear flow and turbulence

- The properties of the damping rate of flow in TJ-II have been investigated in the framework of the previously shown model with the addition of an external drive.



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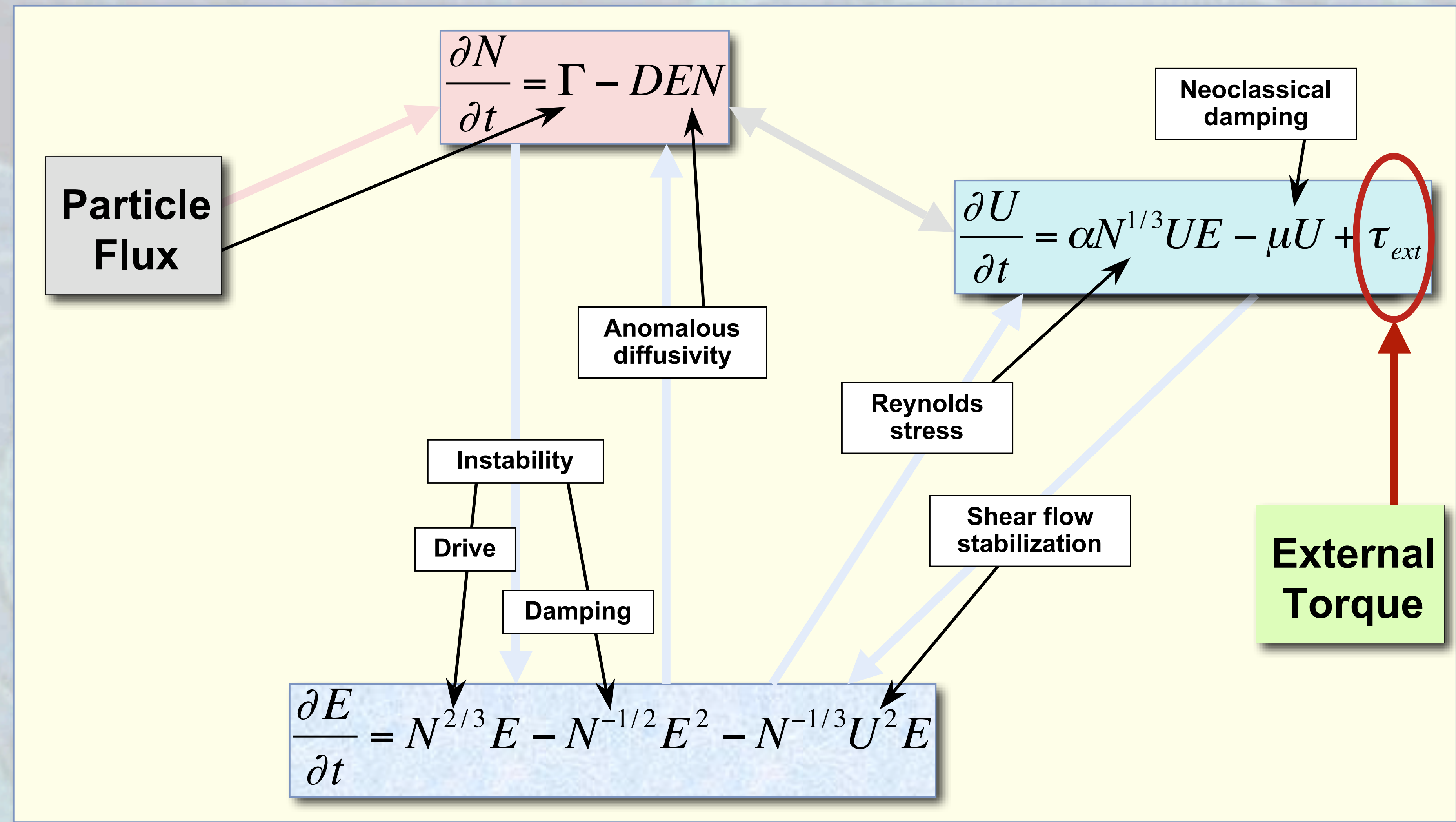
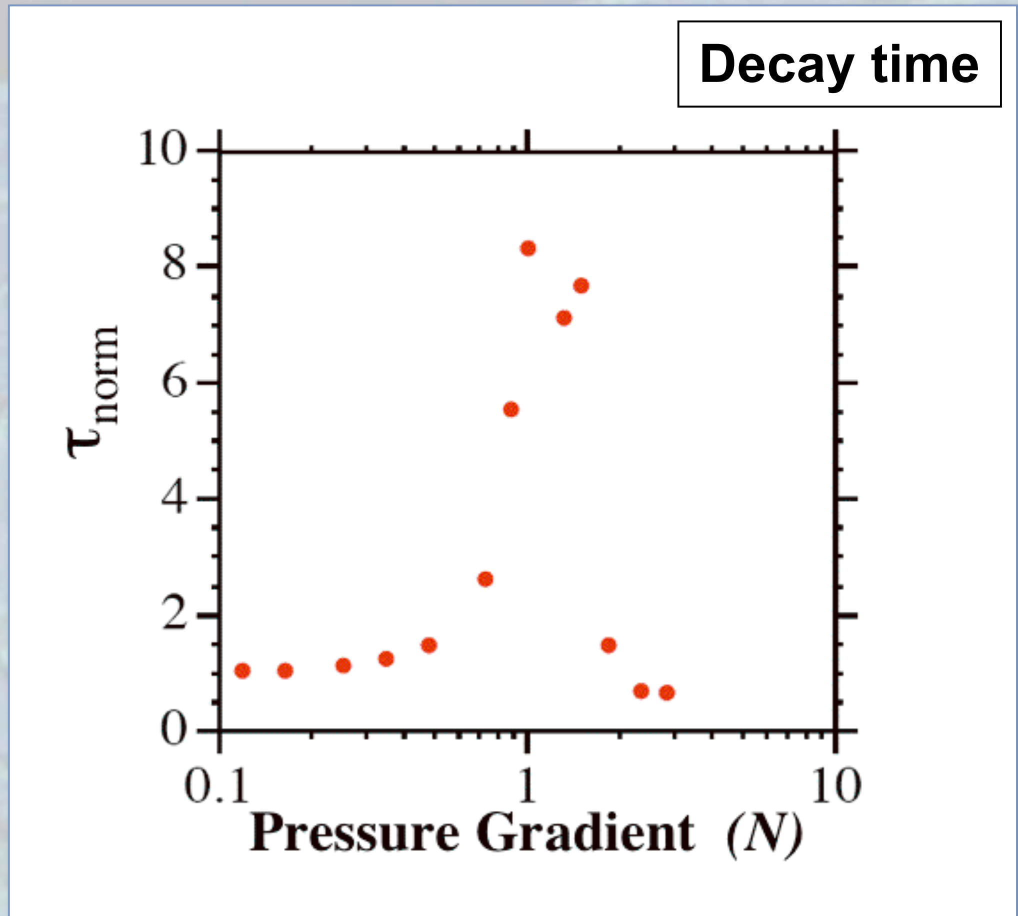


Comparison with experimental results

- The results of the fast decay time from the model equations show exponential behaviour and are also consistent with the experimental data.
- The time decay as a function of the input flux show a sharp peak near the critical point.



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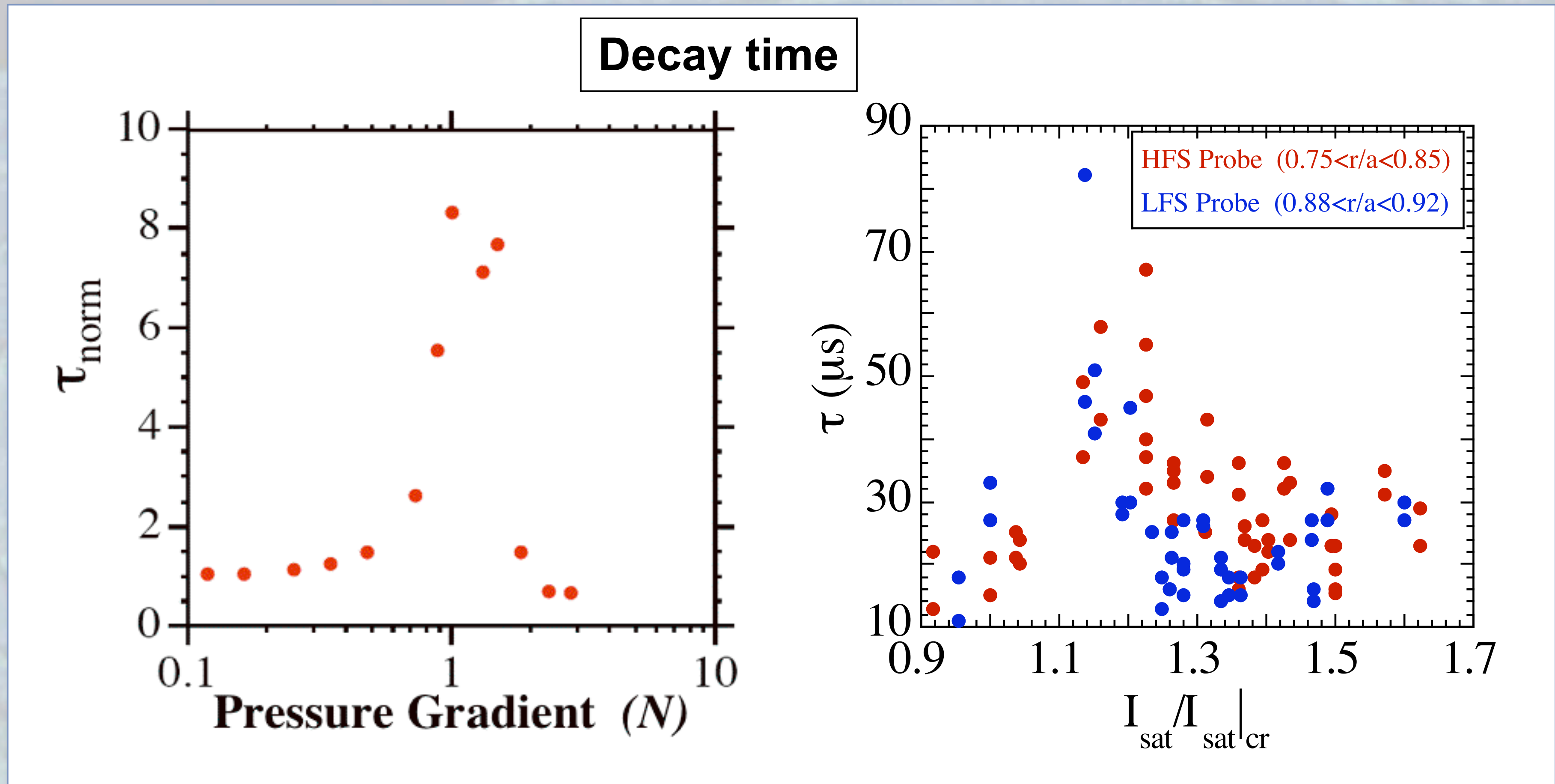

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Summary and Conclusions

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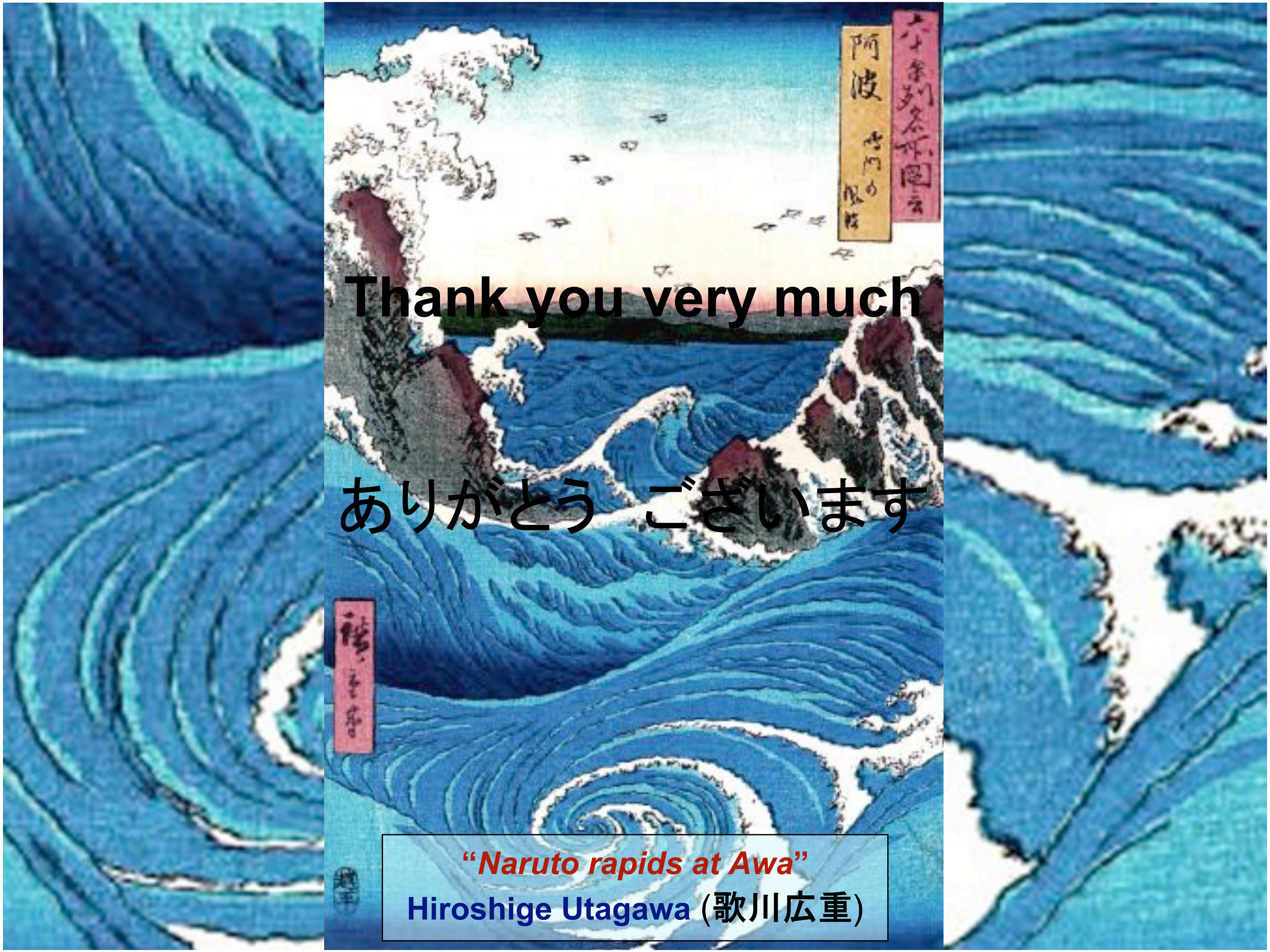
- ✓ The development of the naturally occurring velocity shear layer in TJ-II requires a minimum plasma density / gradient. Sheared flow and fluctuations appear to be organized near marginal stability in TJ-II.
- ✓ The decay time scale of plasma potential measured in TJ-II when the external torque is switched off, is (as in other devices) in the range of the turbulence characteristic times. Results in TJ-II suggest an increase in decay times once edge perpendicular shear flow is fully developed.
- ✓ Significant correlation has been found between potential signals 180º toroidally apart. Correlation is maxima for plasma density close to the threshold for shear flow development and increases with externally applied electric fields.
- ✓ The emergence of the plasma edge sheared flow as a function of plasma density can be explained using a simple second-order phase transition model, that reproduces well experimental data and the qualitative characteristics of the transition near the critical point. Adding an external torque in the model the main features of the flow decay rate can be also reproduce.
- ✓ *These results can help to understand the physics responsible for the generation of shear flow, pointing out the important role of turbulence on the driving/damping physics of the radial electric fields and flows in fusion plasmas.*



"Naruto rapids at Awa"
Hiroshige Utagawa (歌川広重)