Control of Turbulence in Toroidal Plasmas

Ulrich Stroth
Christian-Albrechts-Universität zu Kiel

Outline

1) Microscopic properties of plasma turbulence

- characterisation of plasma turbulence
- driving forces and transport

2) A plasma turbulence experiment

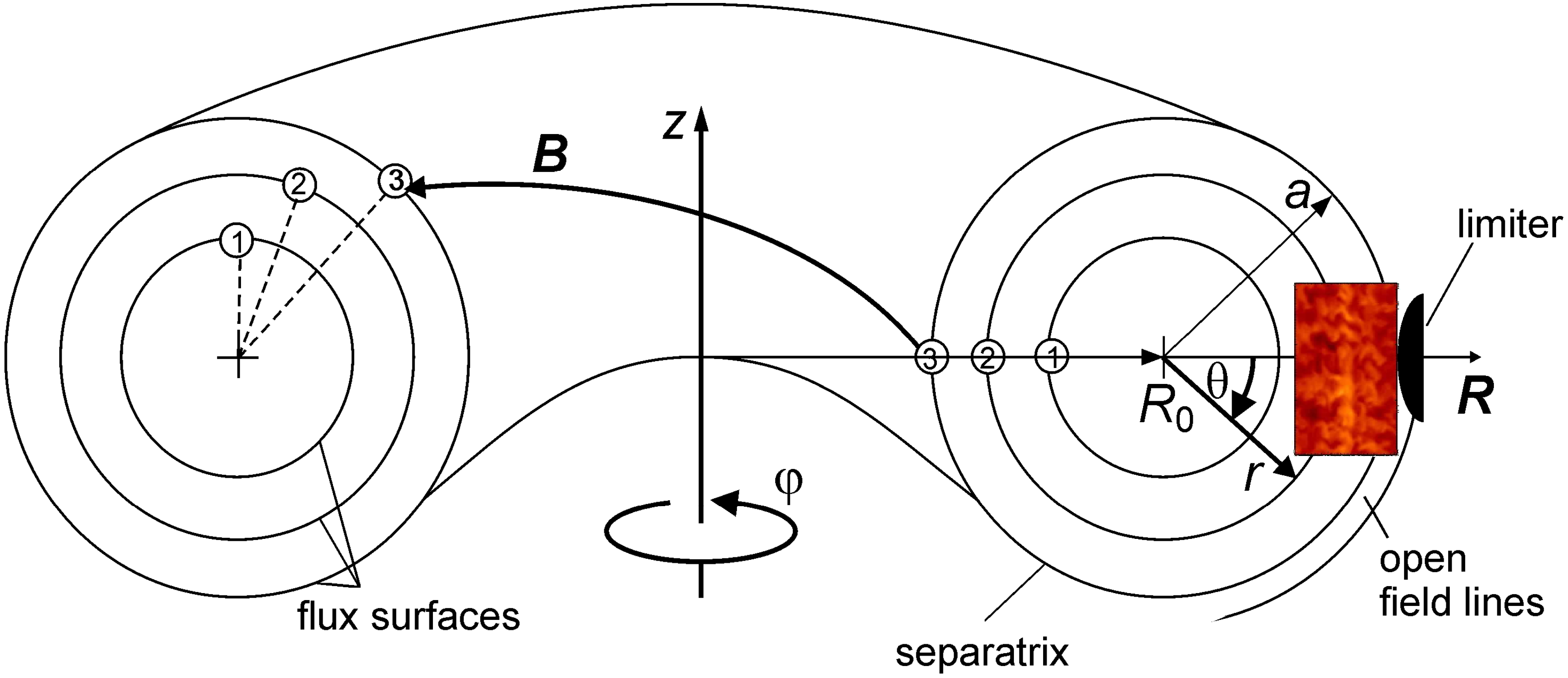
3) Control of turbulence

- by configuration optimisation
- by sheared background plasma flows

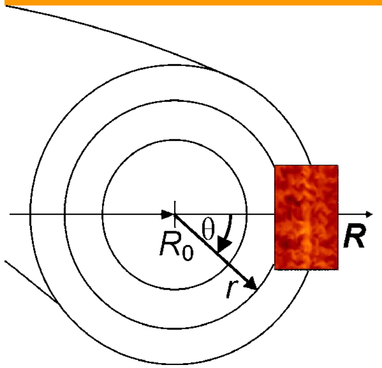
1.1

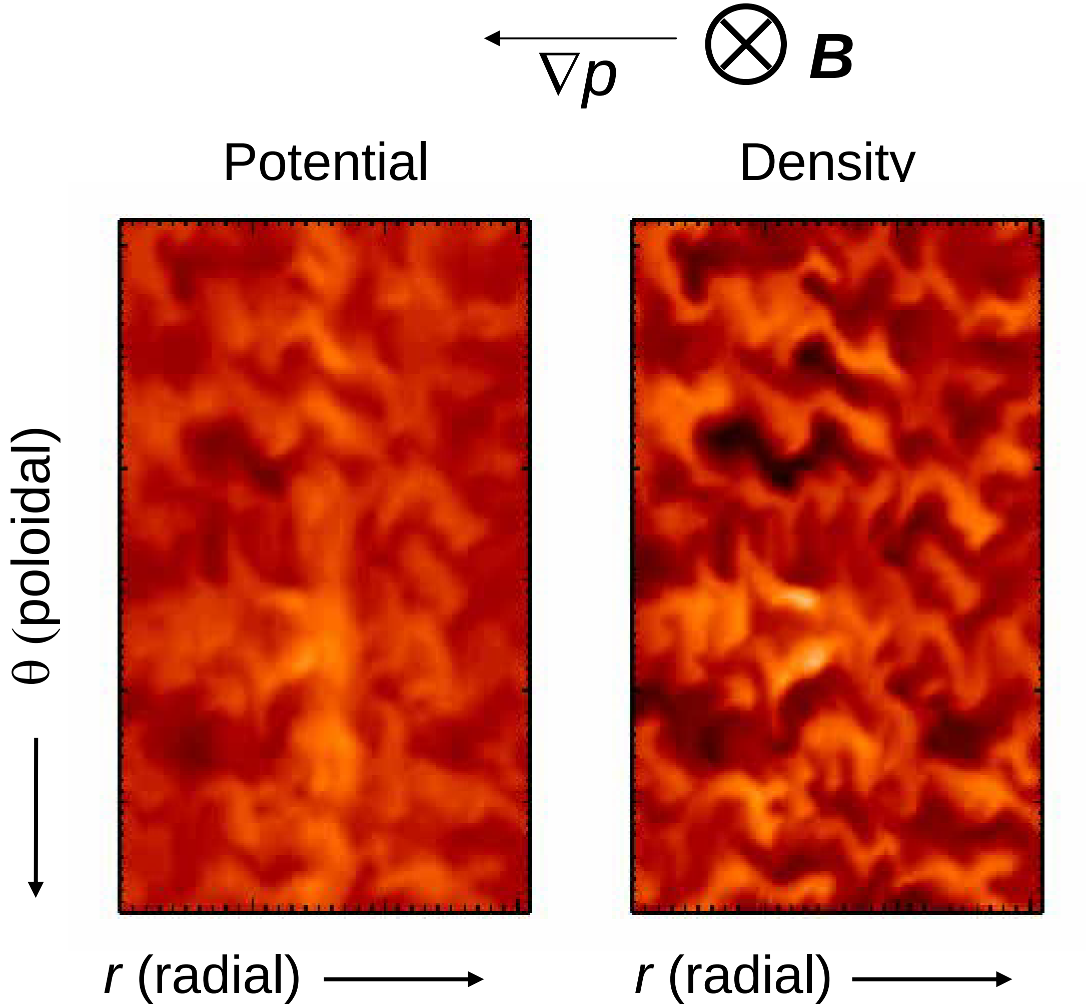
Characterisation of plasma turbulence

Toroidal plasmas



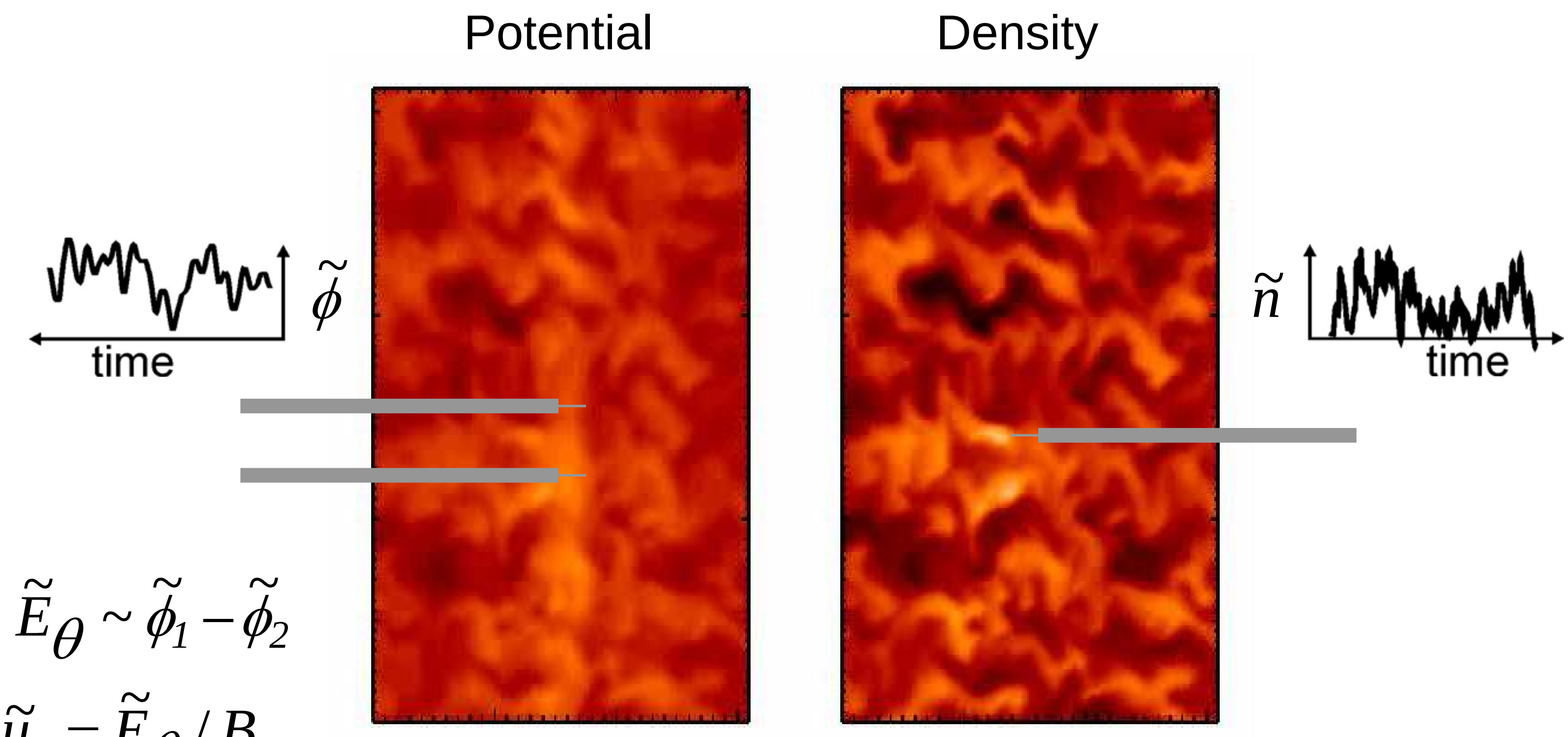
Characterization of turbulence





DALF3 code, B. Scott PPCF 97

Characterization of turbulence



$$\tilde{E}_\theta \sim \tilde{\phi}_1 - \tilde{\phi}_2$$

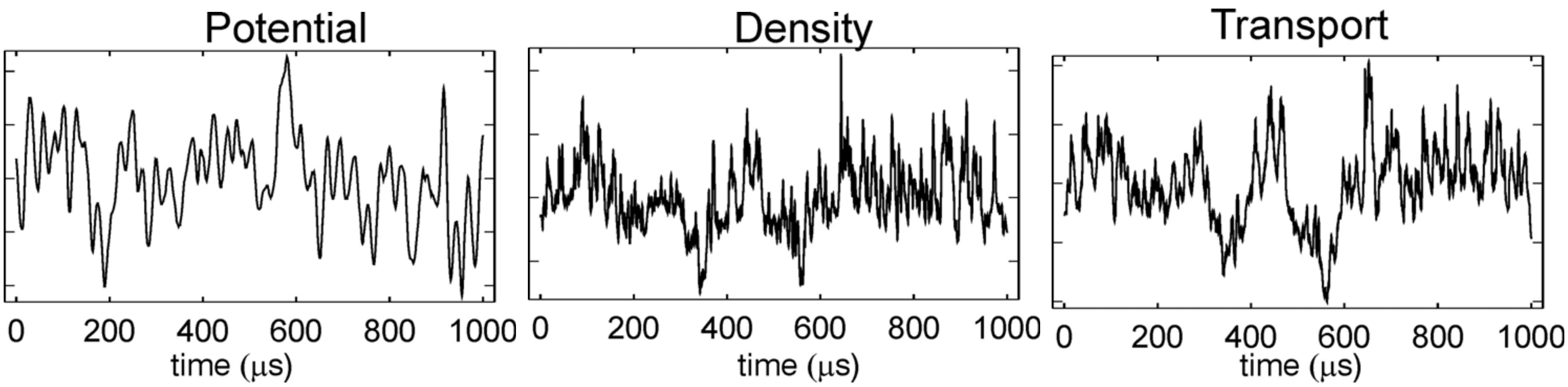
$$\tilde{u}_r = \tilde{E}_\theta / B$$

Turbulent transport

$$\Gamma \sim \tilde{n} E_\theta$$

Measurements with a transport probe

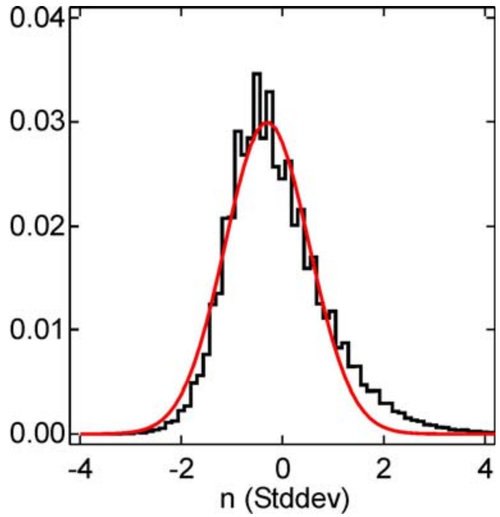
Time traces from TJ-K


Potential

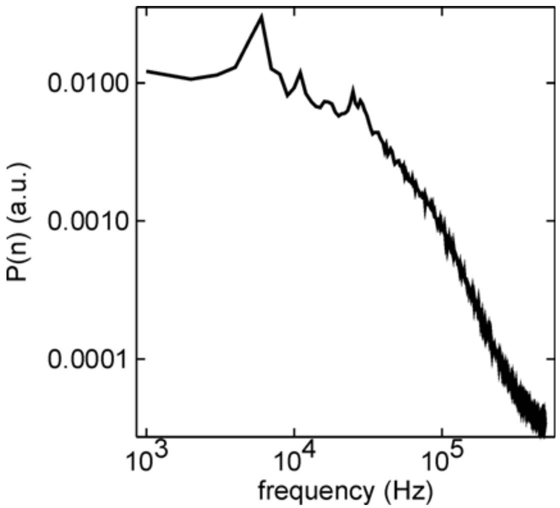
Density

Transport

PDF

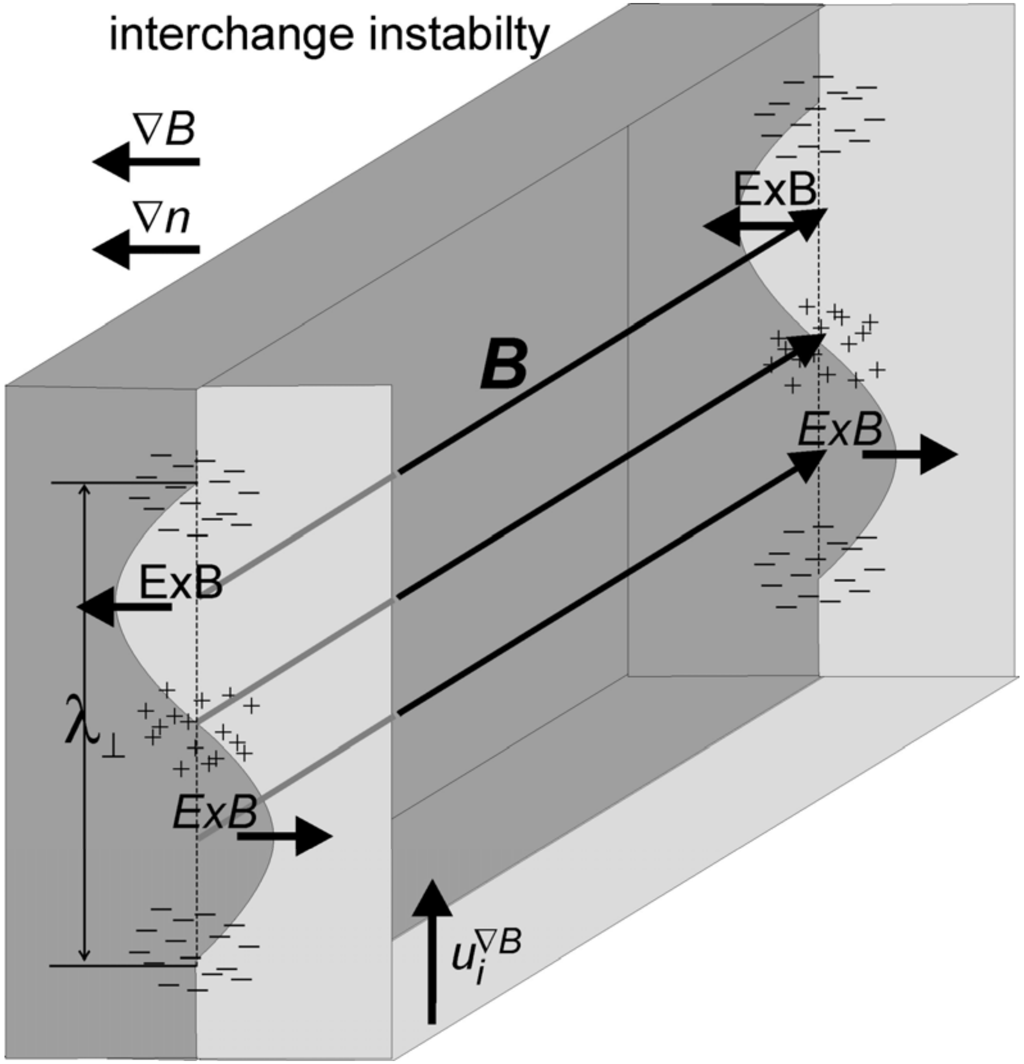


Spectra



1.2
Driving forces and transport

The linear interchange instability (hot plasma core)



Perturbations are

- constant on field linie
- with cross-phase(n,ϕ) = $\pi/2$
- destabilised by curvature

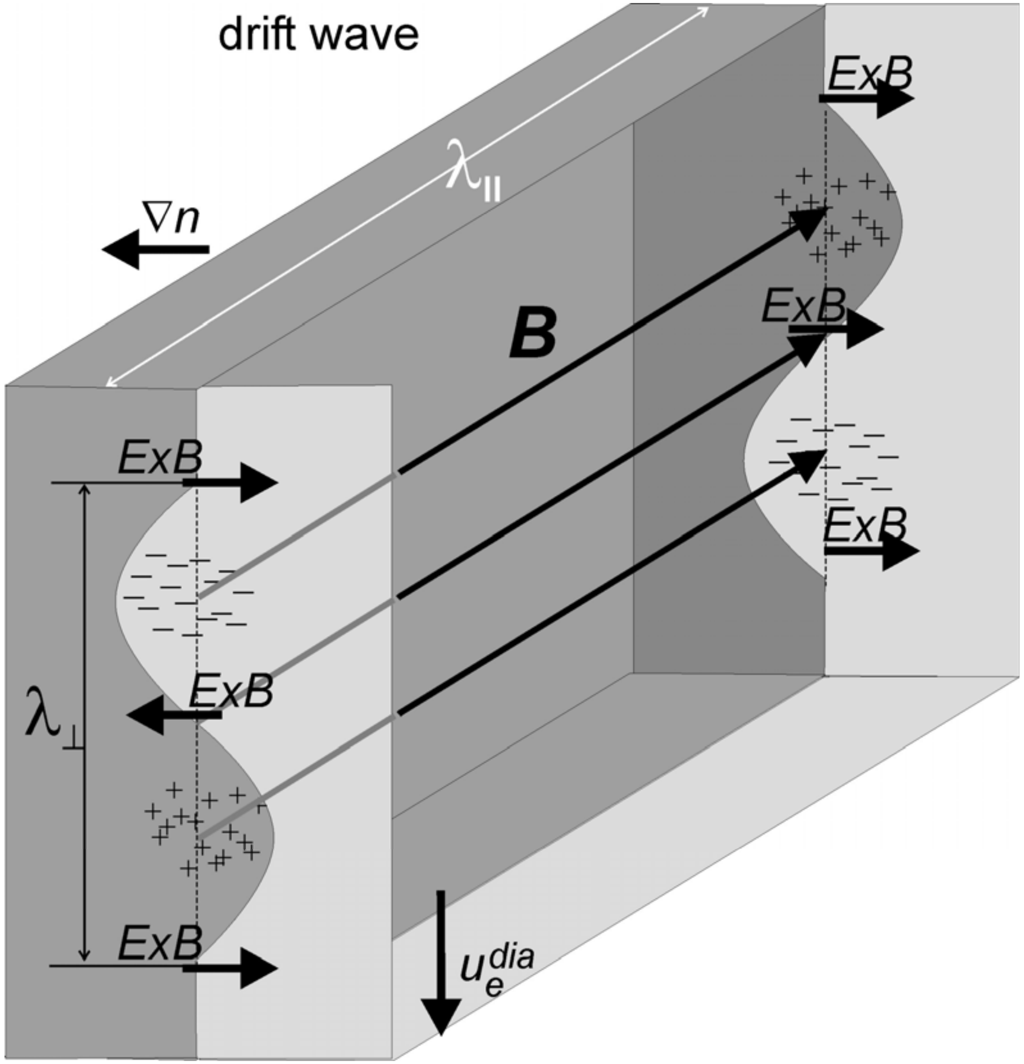
Related instabilities:

- ITG, ETG, TEM

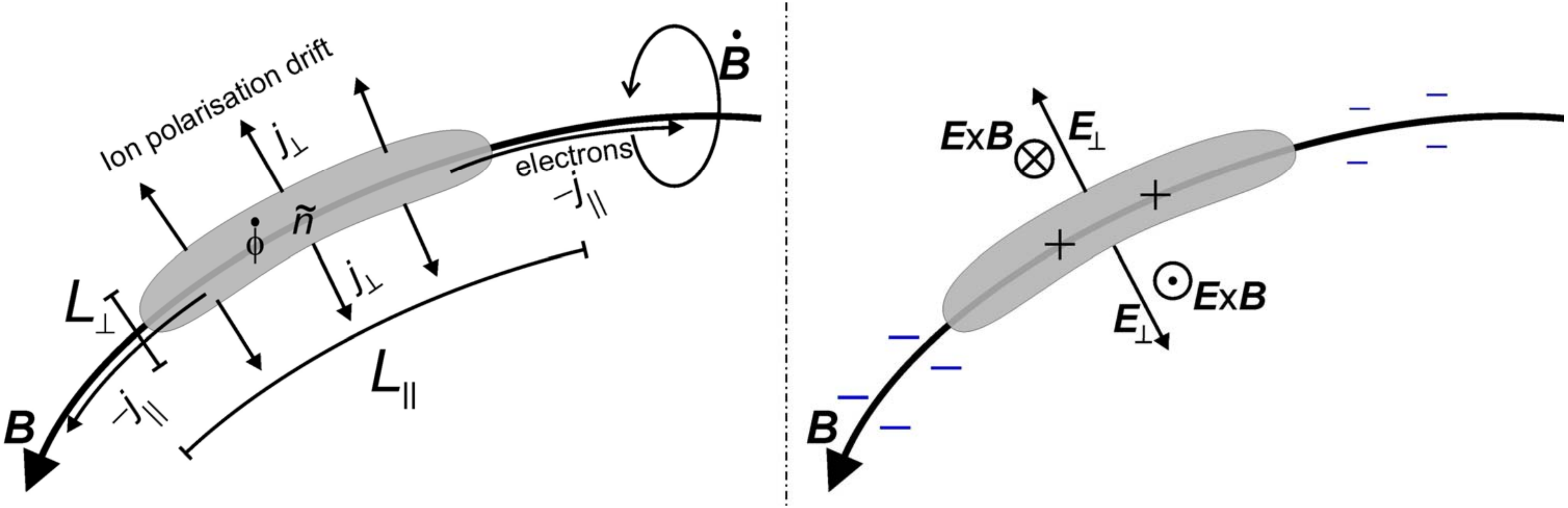
The linear drift-wave instability (cold plasma edge)

Perturbations are

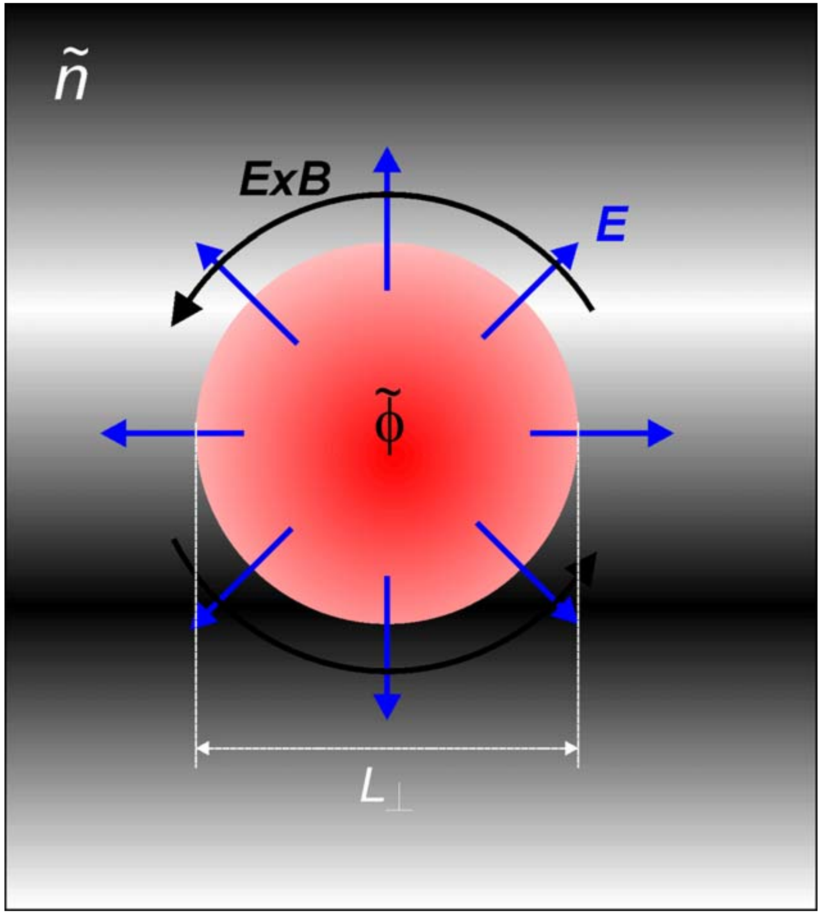
- with finite parallel wave length
- cross-phase $(n,\phi) \approx 0$
- destabilised by resistivity



Microscopic structure of DW turbulence



Electrostatic Turbulent Transport



Mixing length estimate of the **diffusion coefficient**:

$$D = L_\perp^2/\tau \times \sin\gamma$$

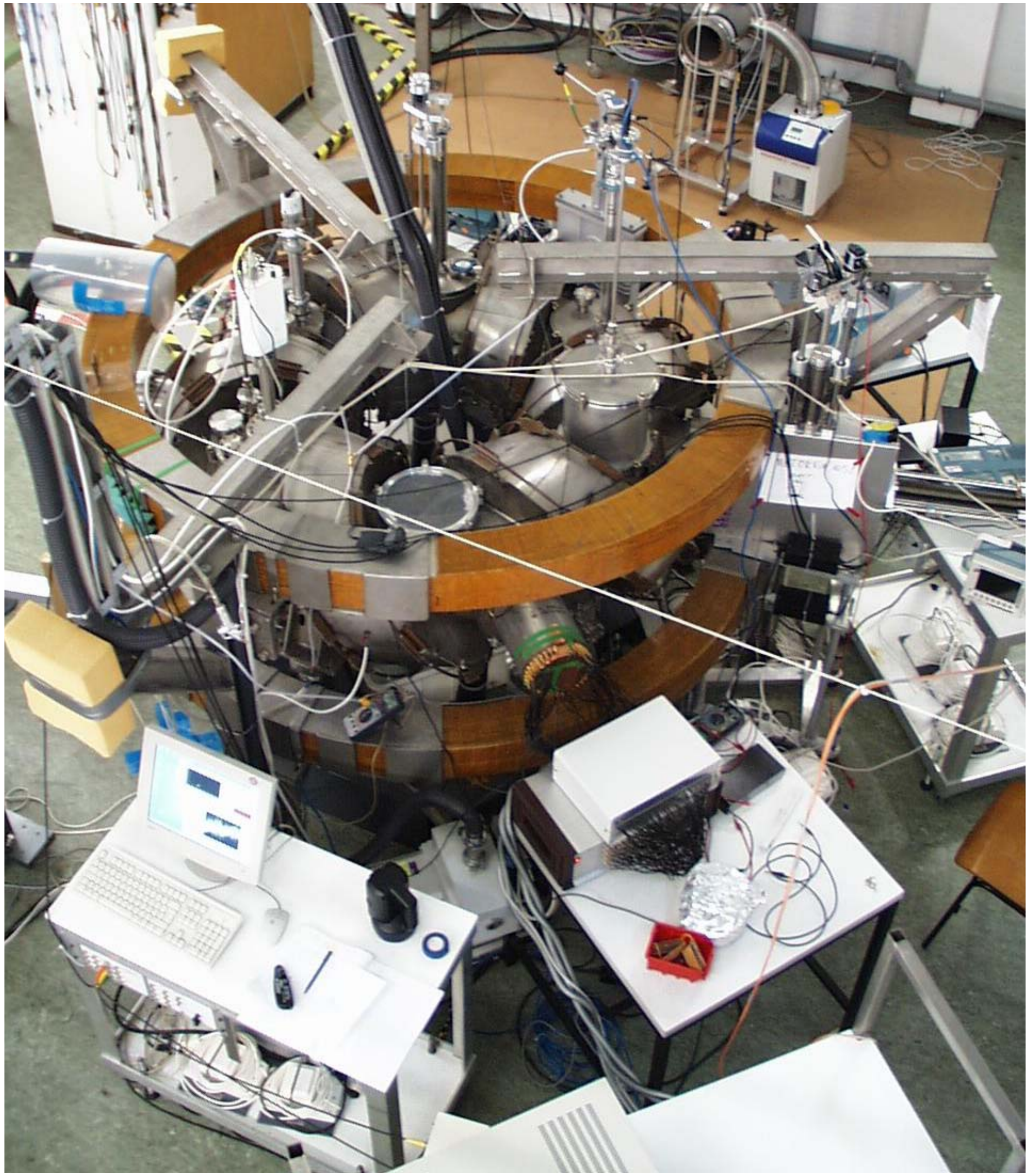
Transport if density and potential fluctuate out of phase.

Cross-phase: $\gamma \neq 0$

2

The plasma turbulence experiment TJ-K

The torsatron TJ-K

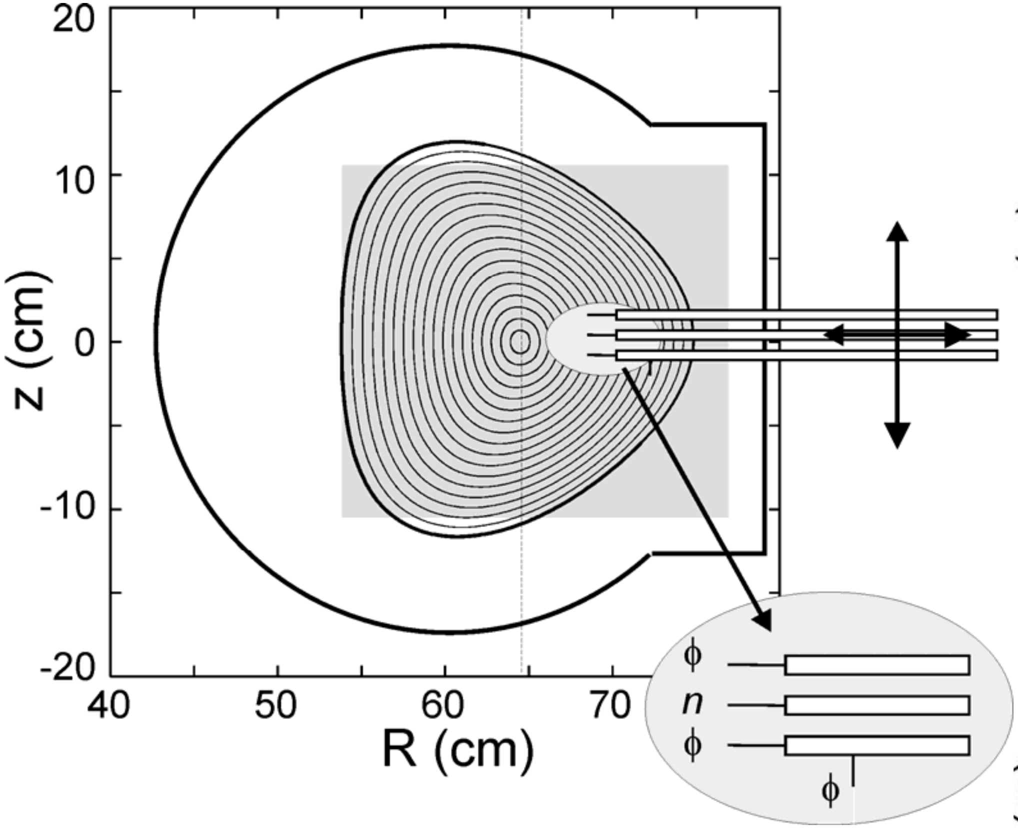


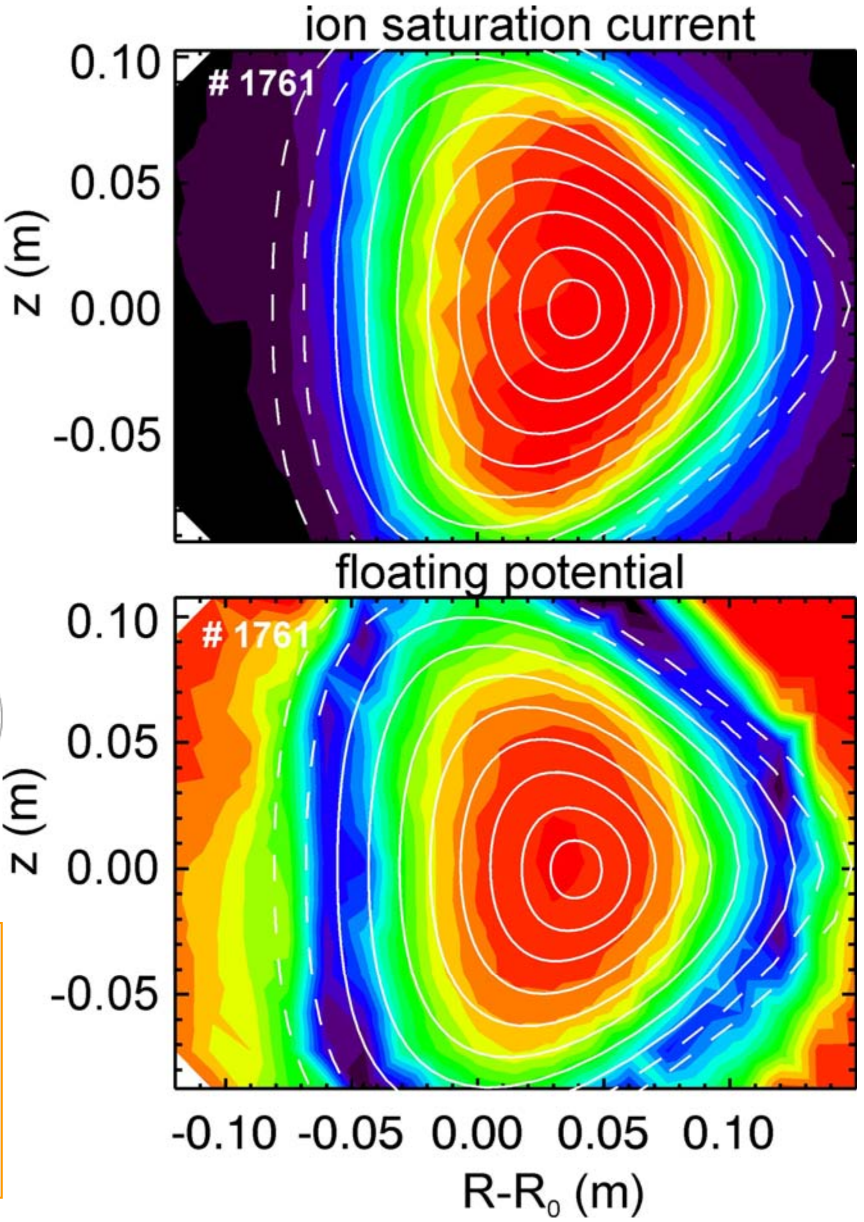
$l = 6$, $m = 1$
$R = 0.6$ m
$a = 0.1$ m
iota ≈ 1/3
$B < 0.3$ T

Helikon 27 MHz, 3 kW
ECRH 2.45 GHz, 6 kW

Previously: TJ-IU at Ciemat

Transport probe



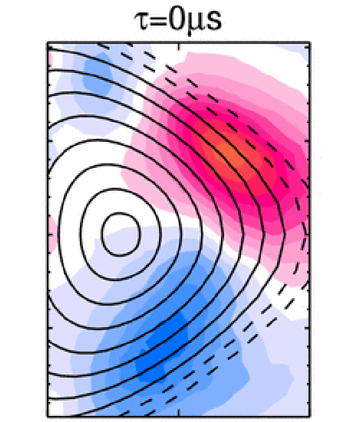


Probes 2D plasma cross-section:

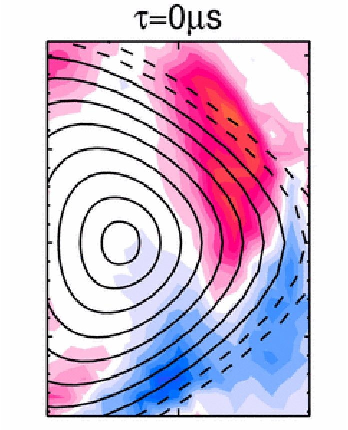
- equilibrium profiles
- fluctuations
- correlation with fixed probe

Space-time evolution by conditional averaging

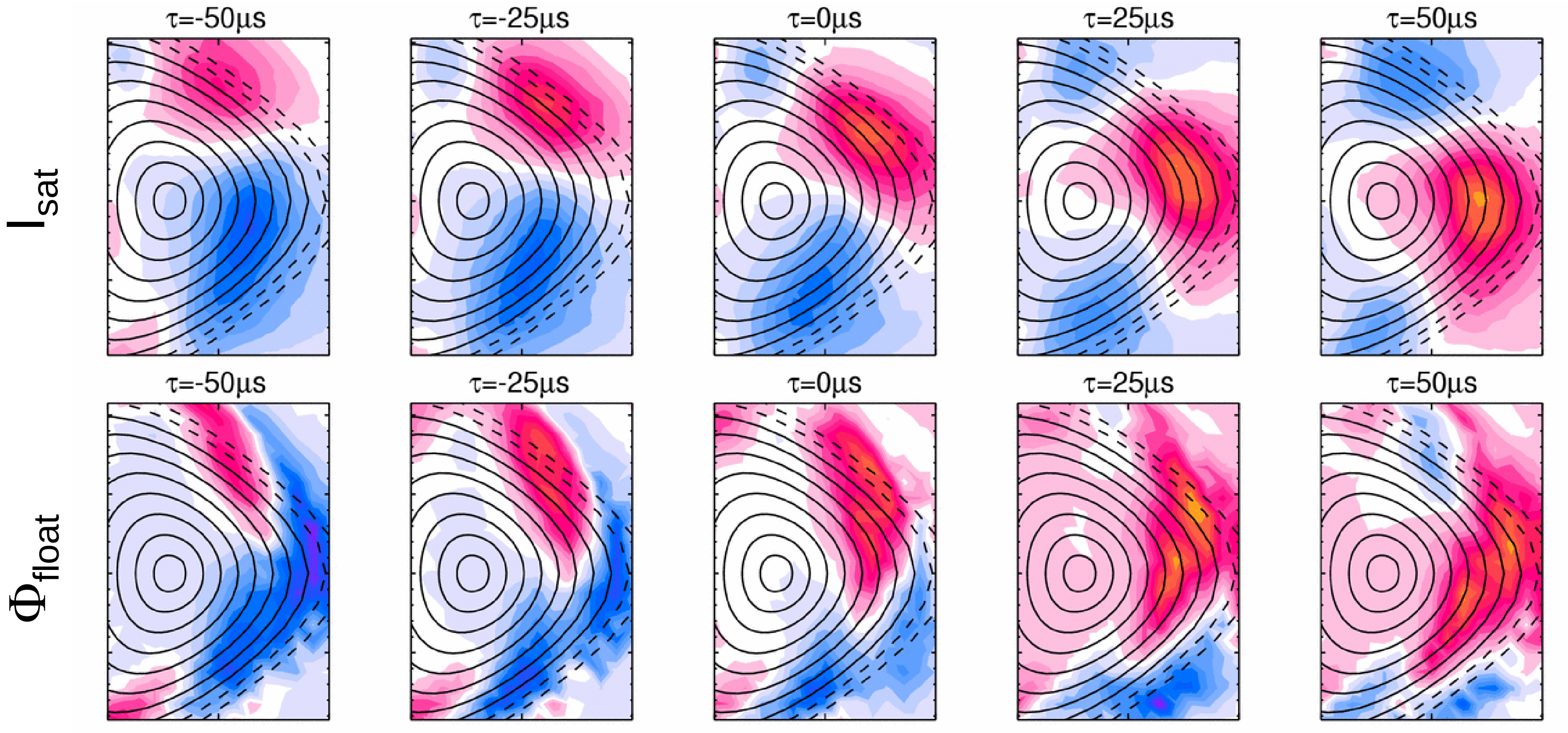
I_{sat}



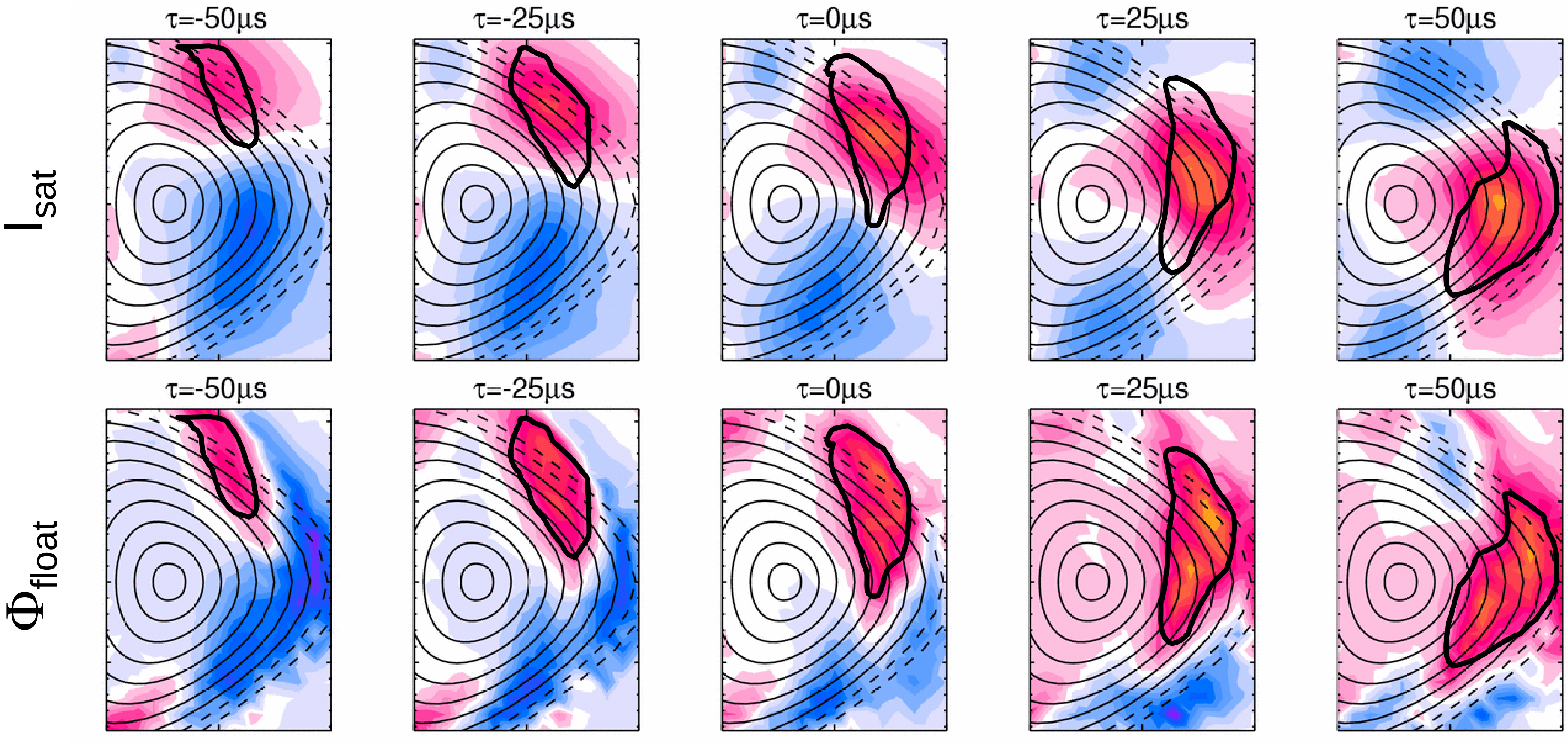
Φ_{float}



Space-time evolution by conditional averaging



Space-time evolution by conditional averaging

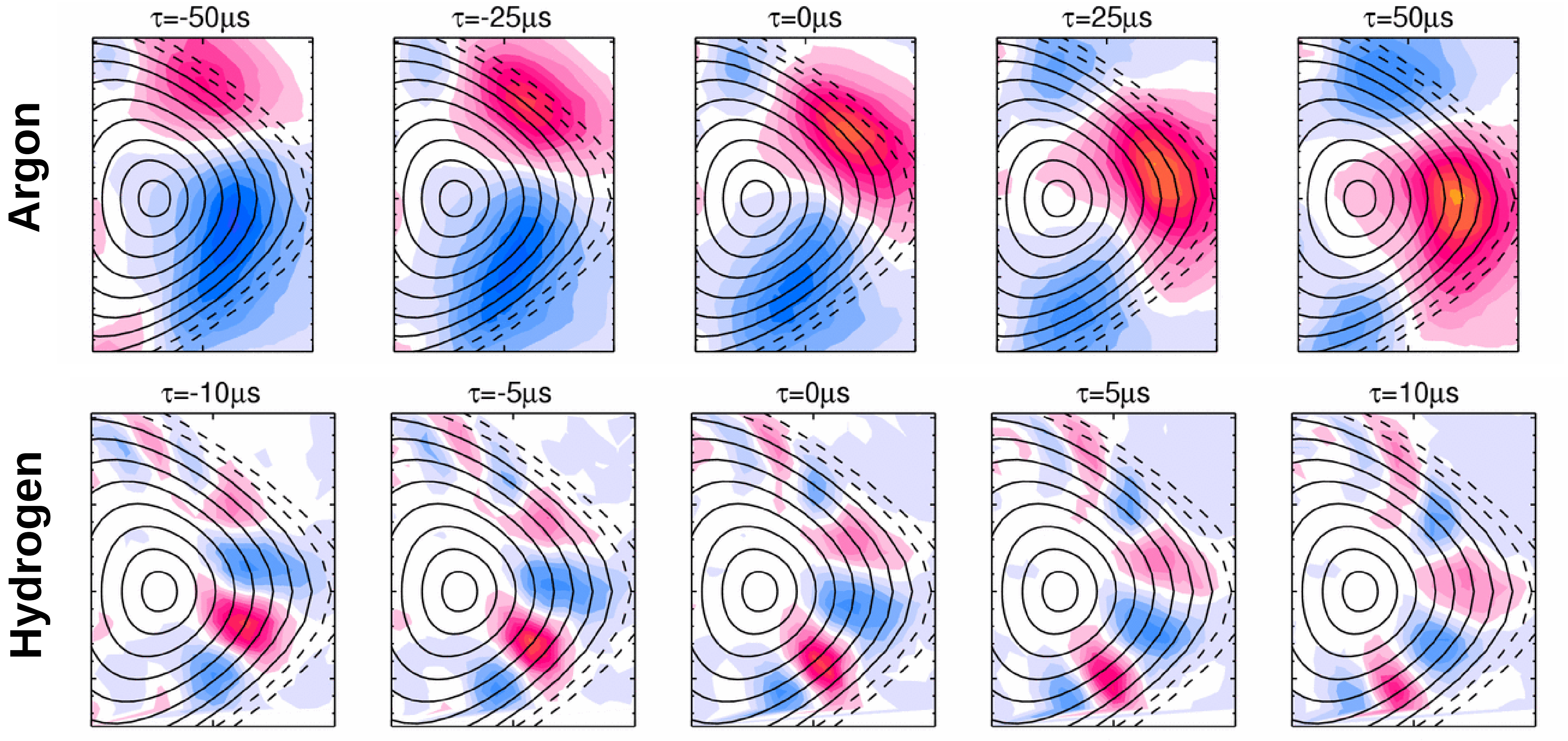


ECRH, Argon

Perpendicular structure:

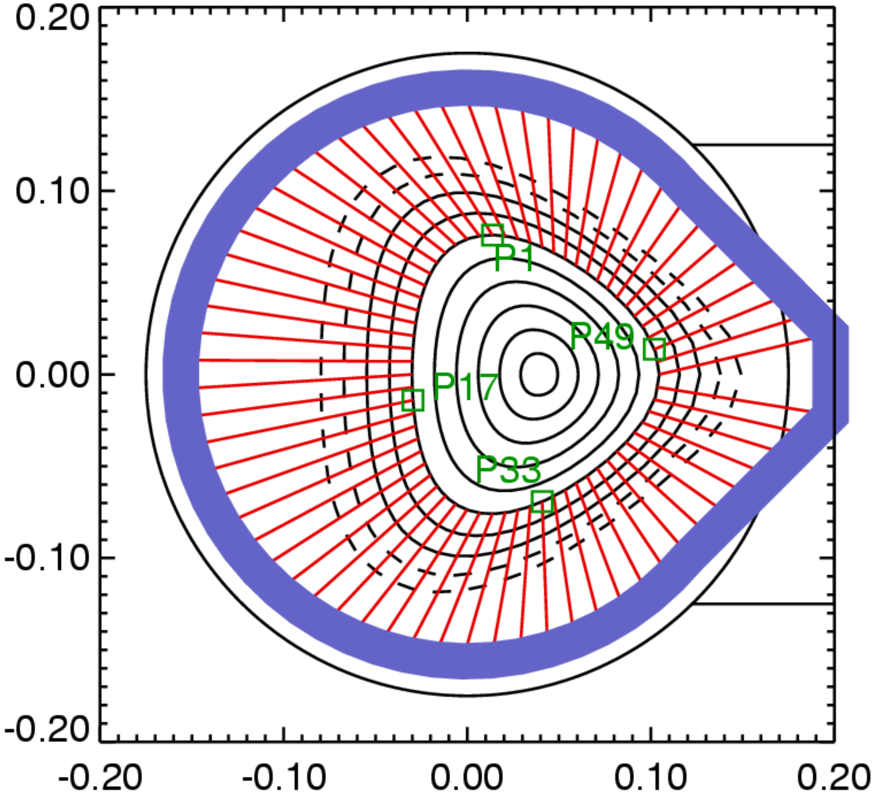
- correlation time: τ = 100-200 μs
- correlation length: *L* = 5 cm
- small cross-phases

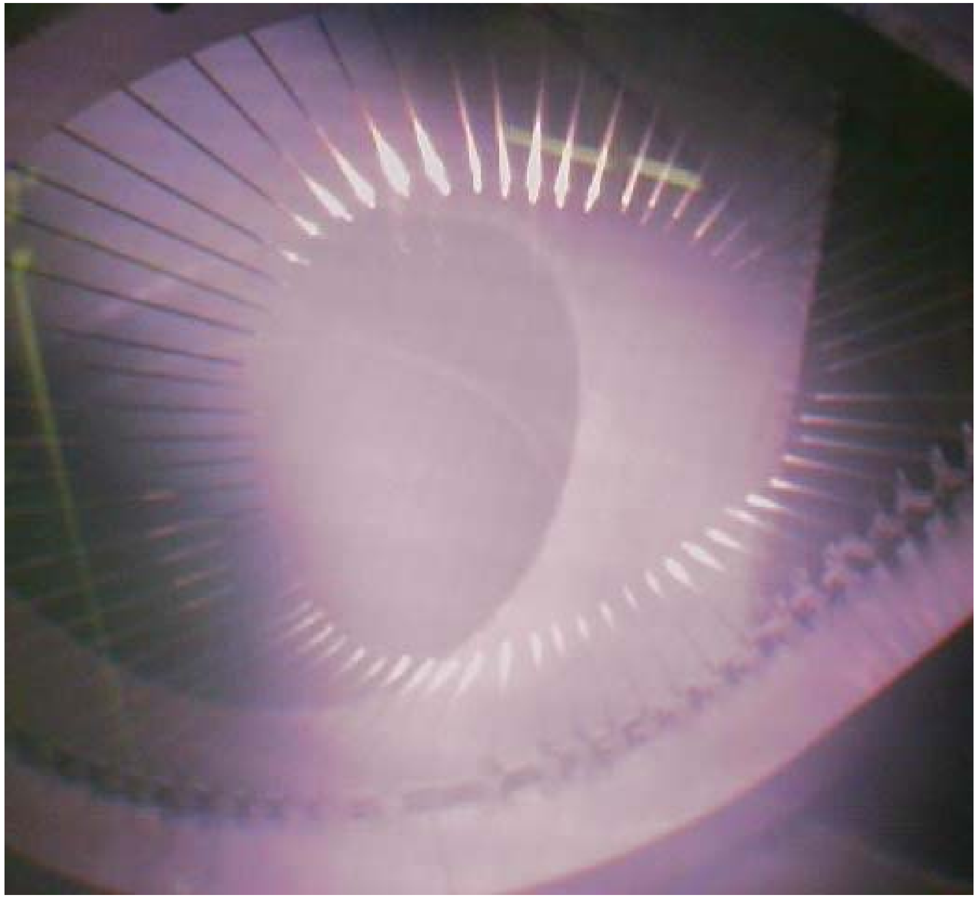
ρ_s dependence from conditional averaging



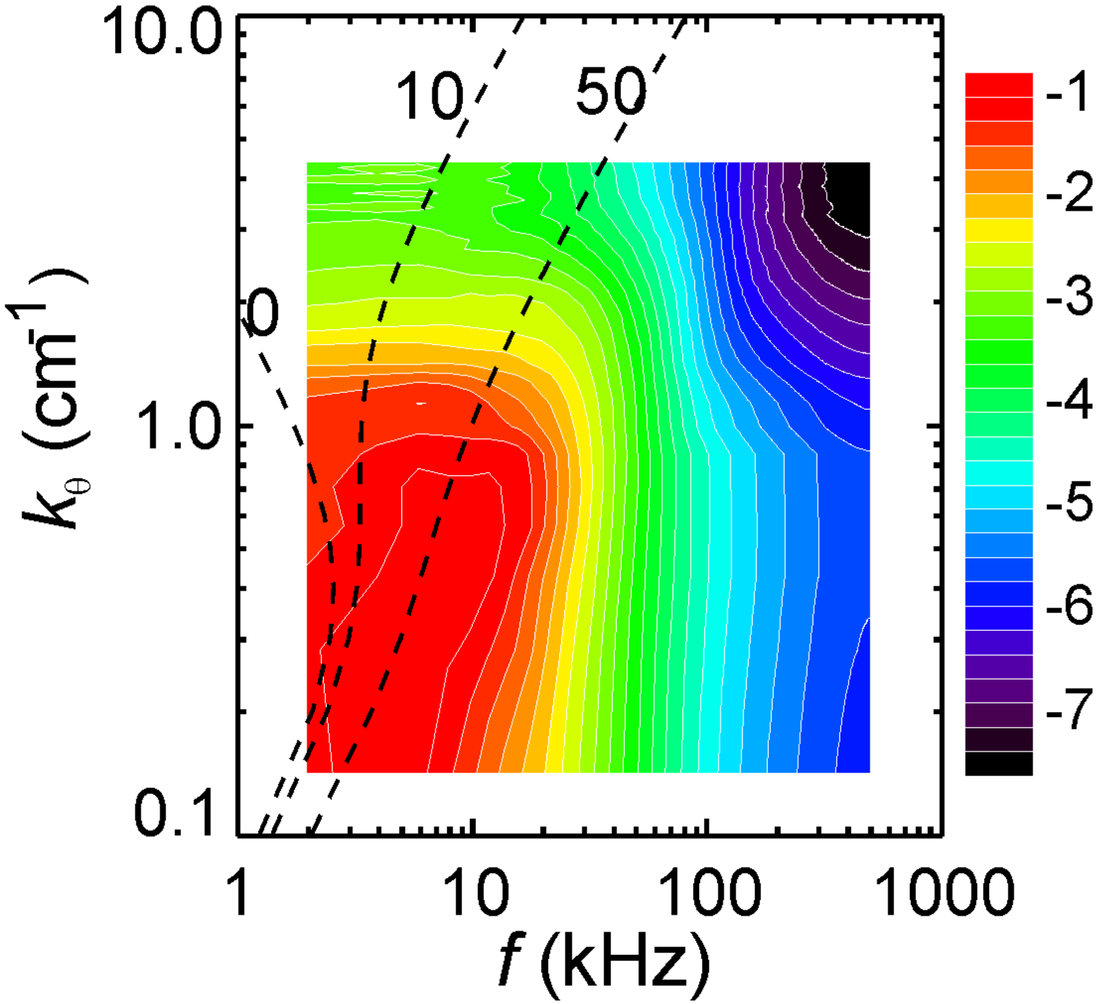
Size depends on ion mass or ρ_s

Poloidal Langmuir probe array





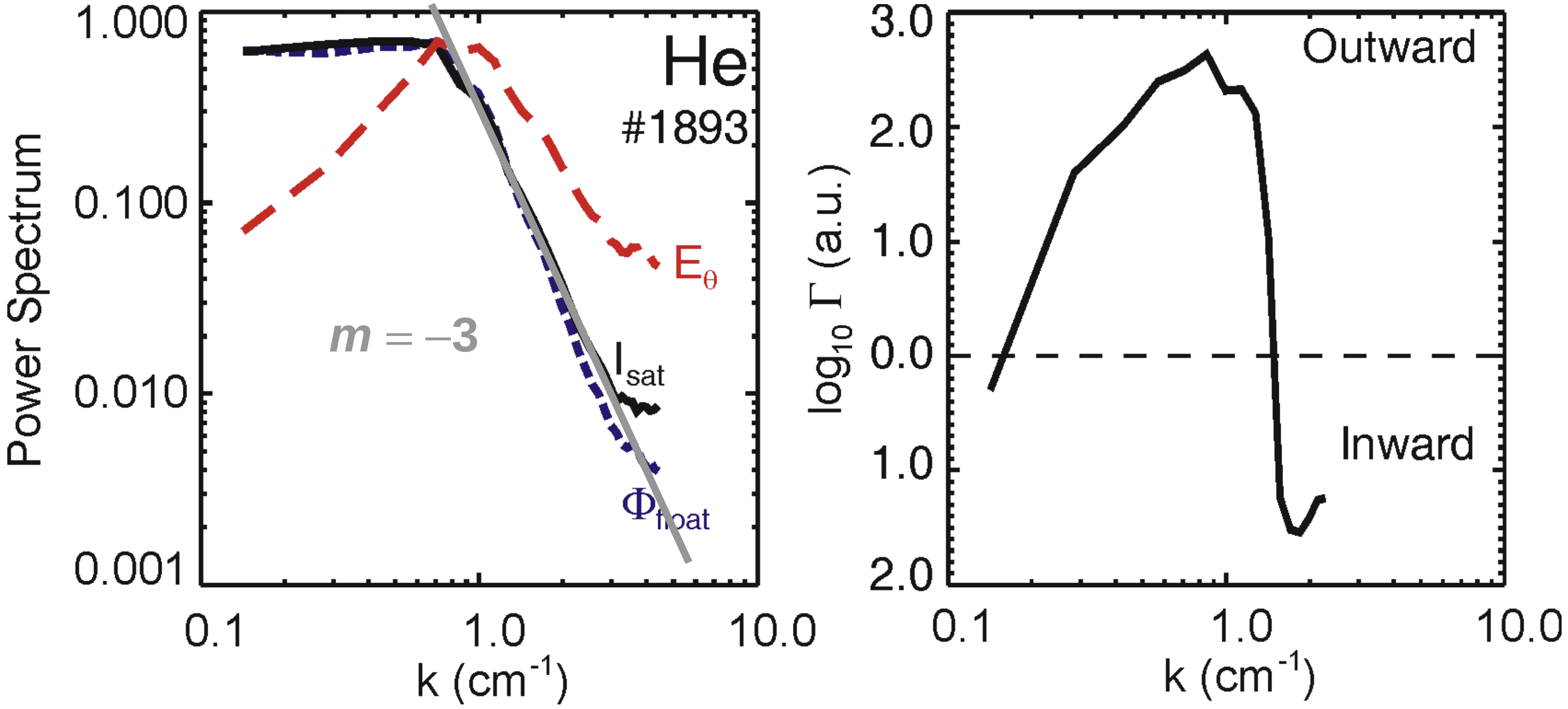
Spectral density of ion-saturation current fluctuations



Broad spectrum indicates fully developed turbulence

Lechte, PhD, submitted to PPCF

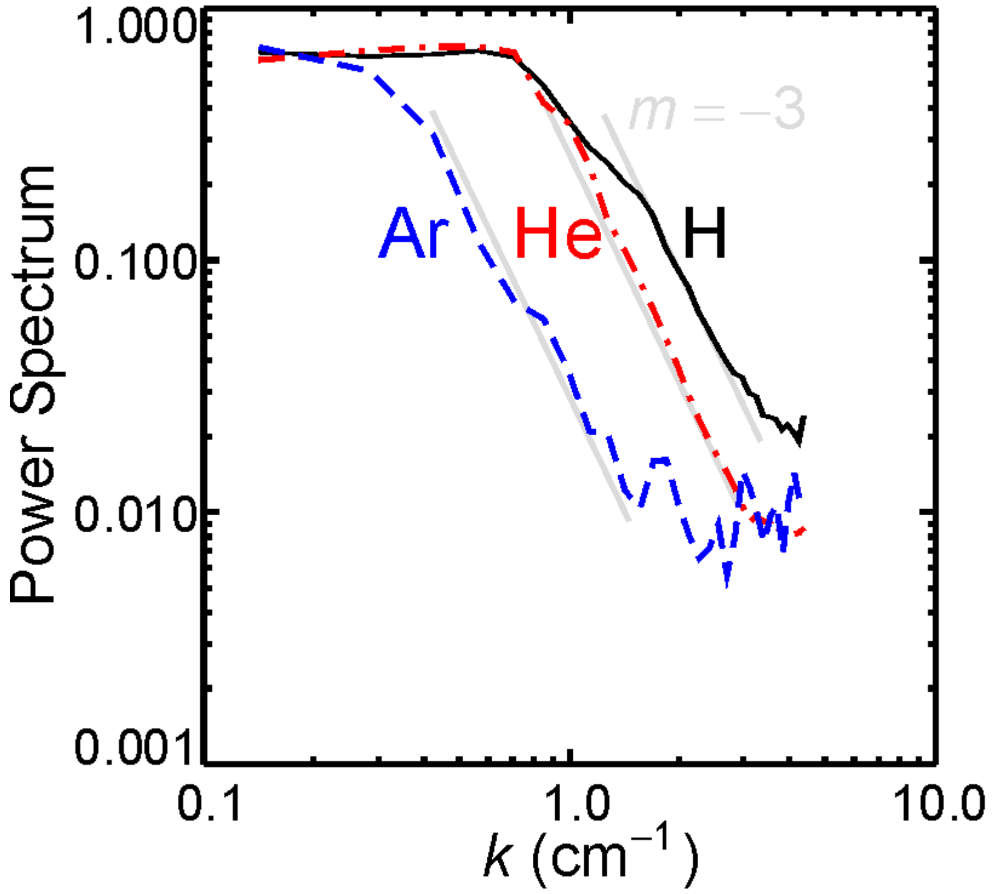
Wave-number spectra and transport



Results:

- – transport at intermediate scales
- – slope in power spectrum –3
- – outward transport at small scales?

Wave-number spectra and ρ_s scaling

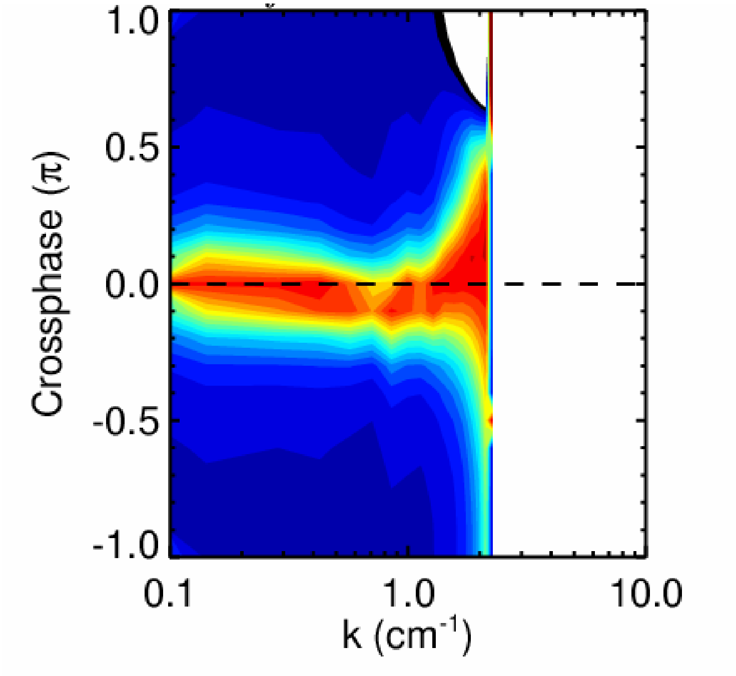


Results:

- spectral index of -3
- ρ_s scaling on all scales

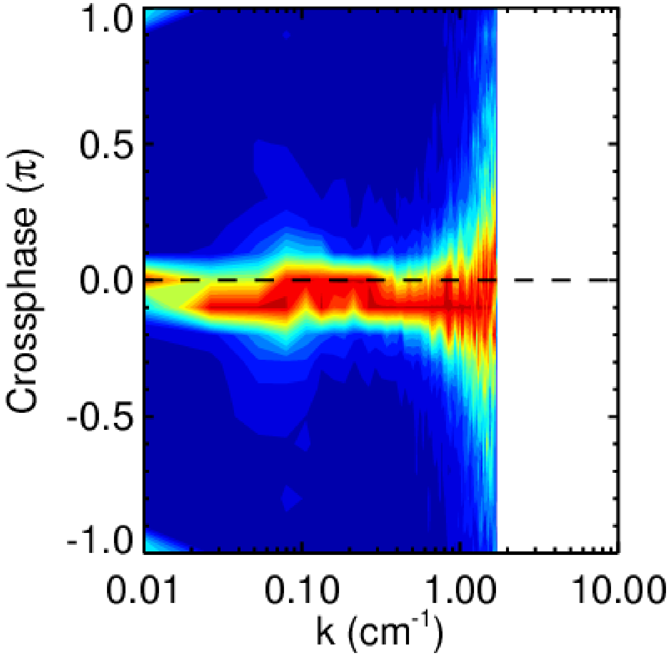
Experimental and simulated cross-phase spectra

ECRH discharge



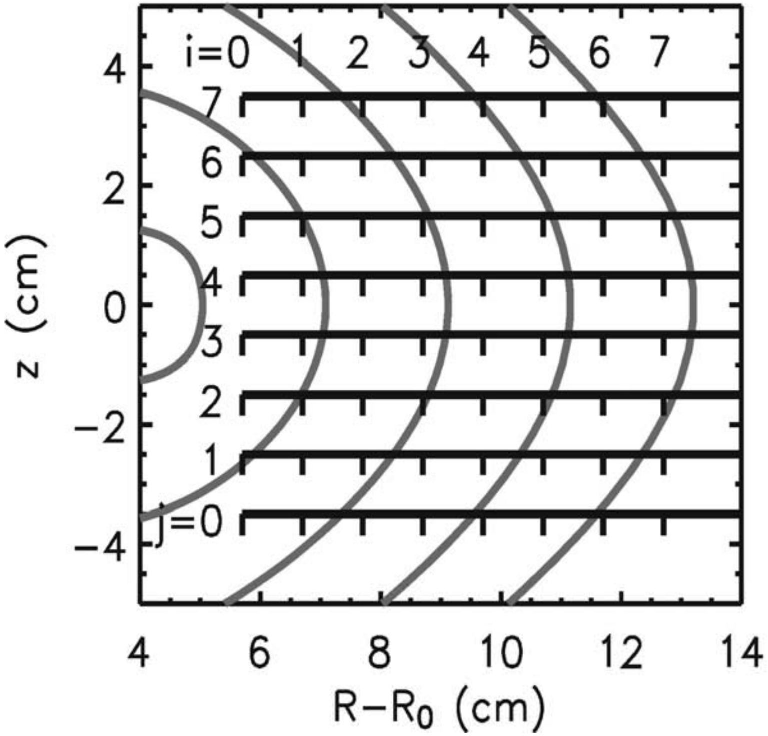
Simulation

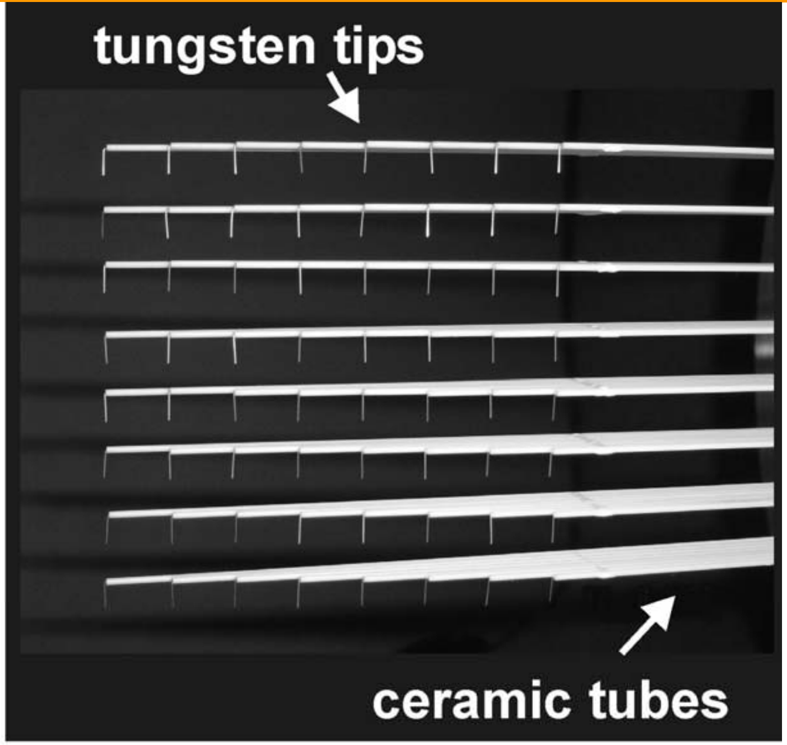
(DALF3, Scott PPCF 1997)

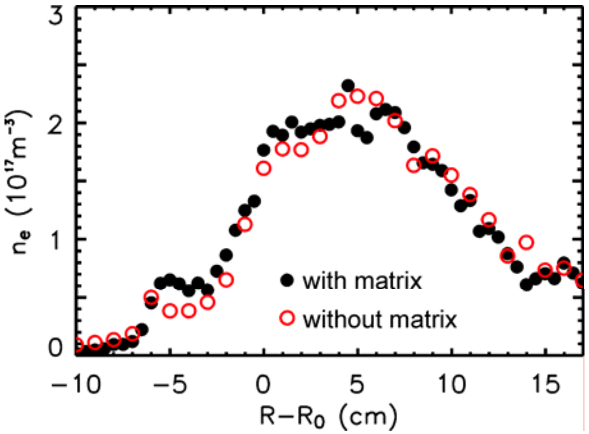


Small cross-phases on all scales are in agreement with drift-wave simulation

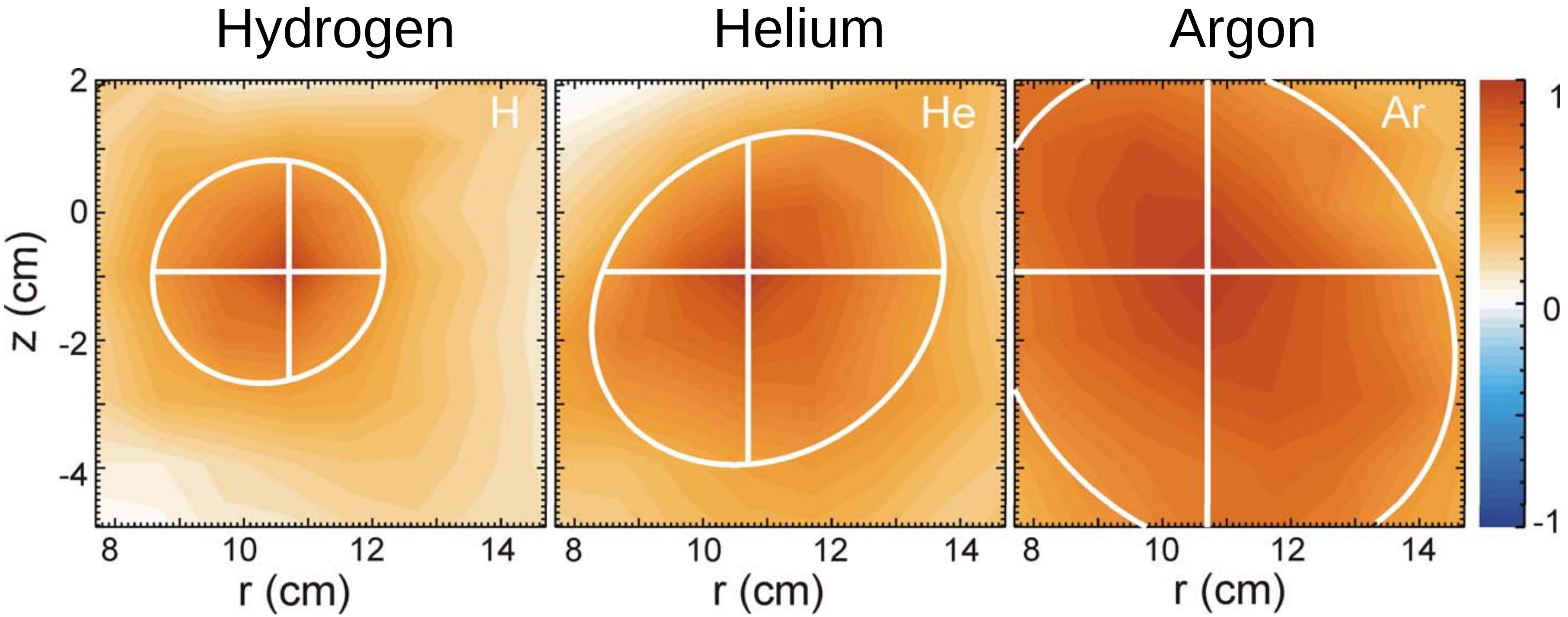
The 8x8 Langmuir probe matrix







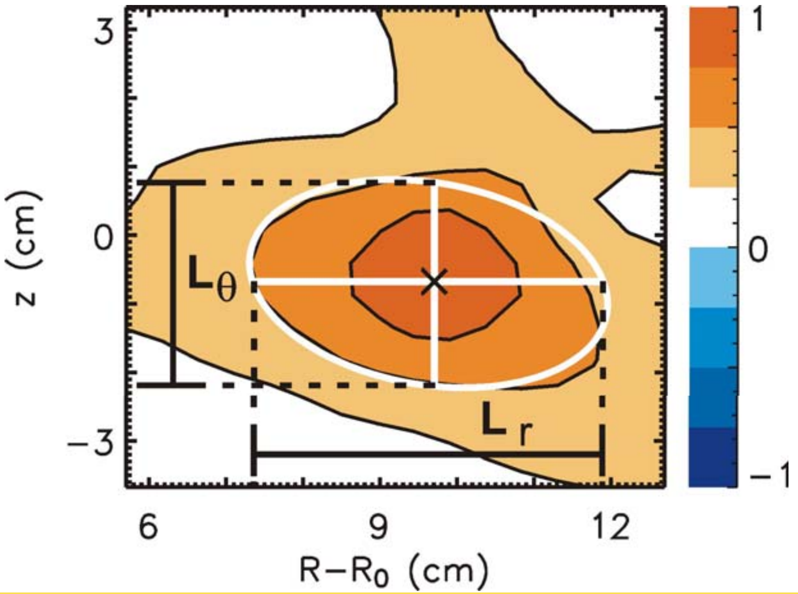
Structure size increases with ρ_s



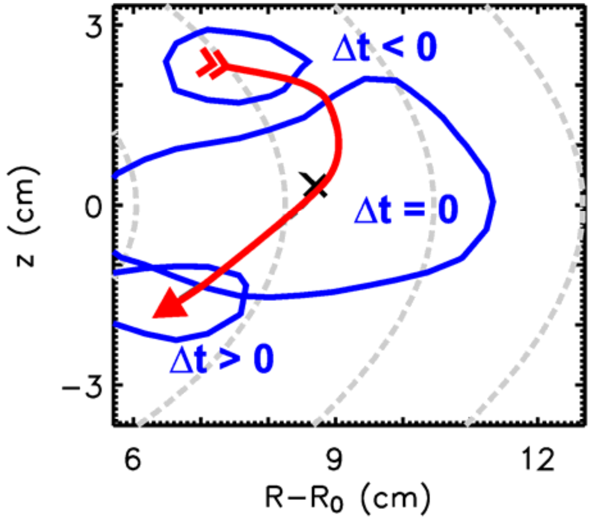
ρ_s increases by factor of 10, structure by 3

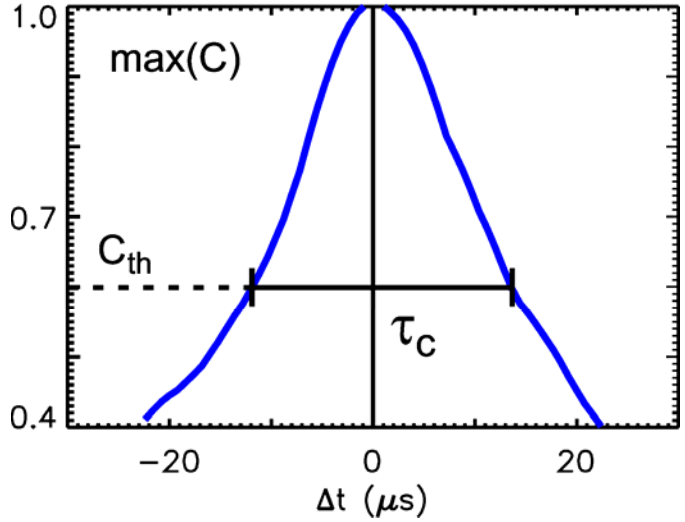
Correlation length and time

Correlation lengths



Correlation time





N. Mahdizadeh, PPCF submitted

Scaling of characteristic lengths and times

$$L \sim \rho_s = \frac{\sqrt{m_i T_e}}{eB} \qquad T \sim \frac{a}{c_s} = a\sqrt{\frac{T_e}{m_i}}$$

Gyro-Bohm scaling of diffusivity

$$D = \frac{L^2}{\tau} \sim \frac{\rho_s}{a}\frac{T_e}{eB} = \rho_* D_B$$

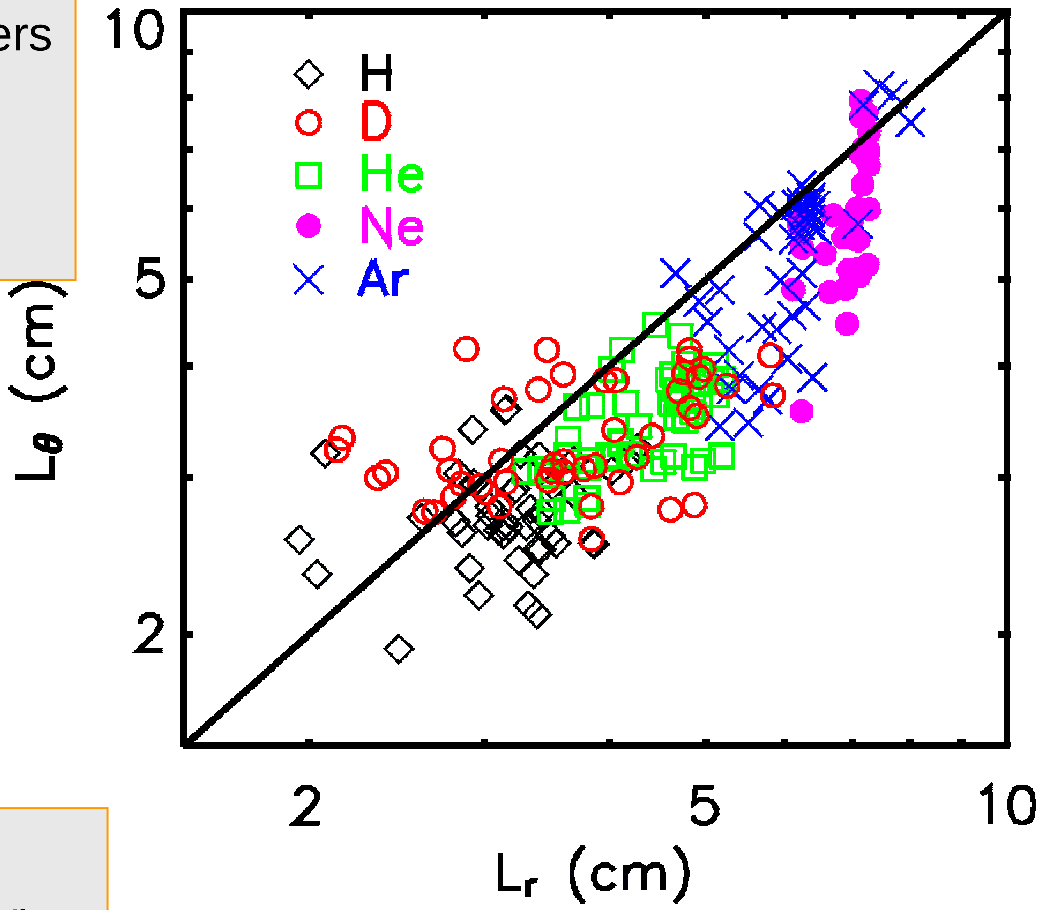
Corrections for non-constant phase

$$D \sim \rho_* D_B \sin \delta_{n\phi}$$

2D Structure Shape

Database:

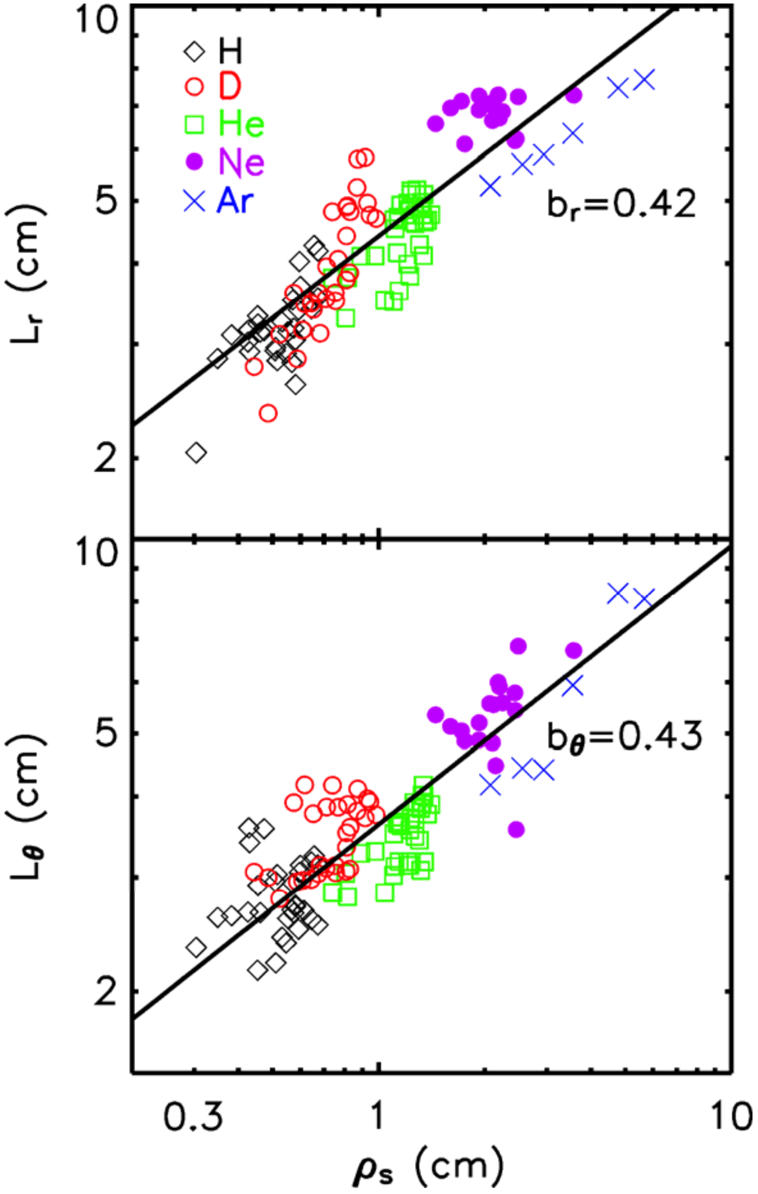
- H, D, He, Ne, Ar
- 2 gas pressures and heating powers
- 2 magnetic fields
- 3 radial positions
- remove points with $\rho_s > L_n$



- radially elongated structures
- limitation due to system size for Ar

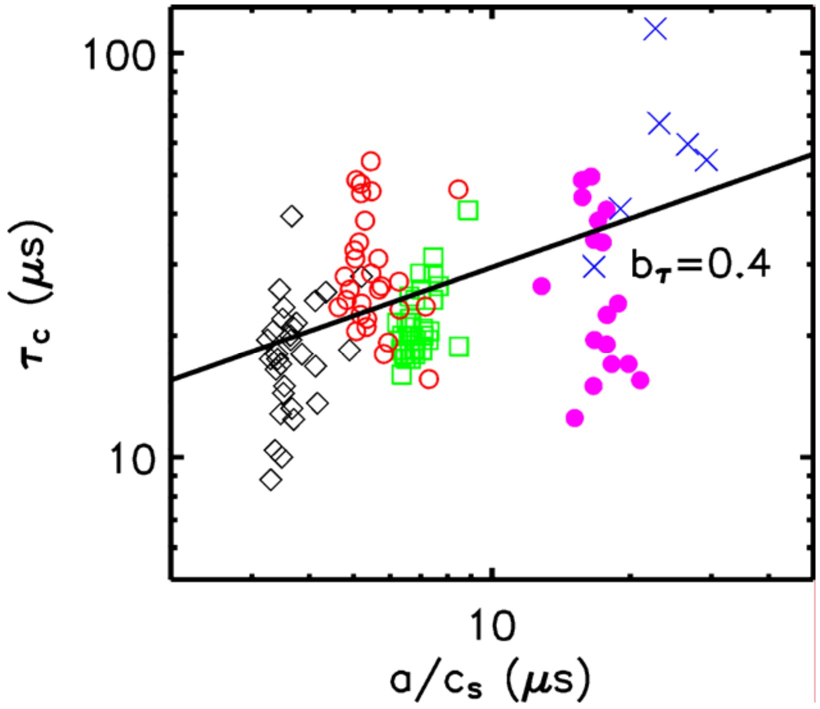
M. Ramisch submitted to PoP

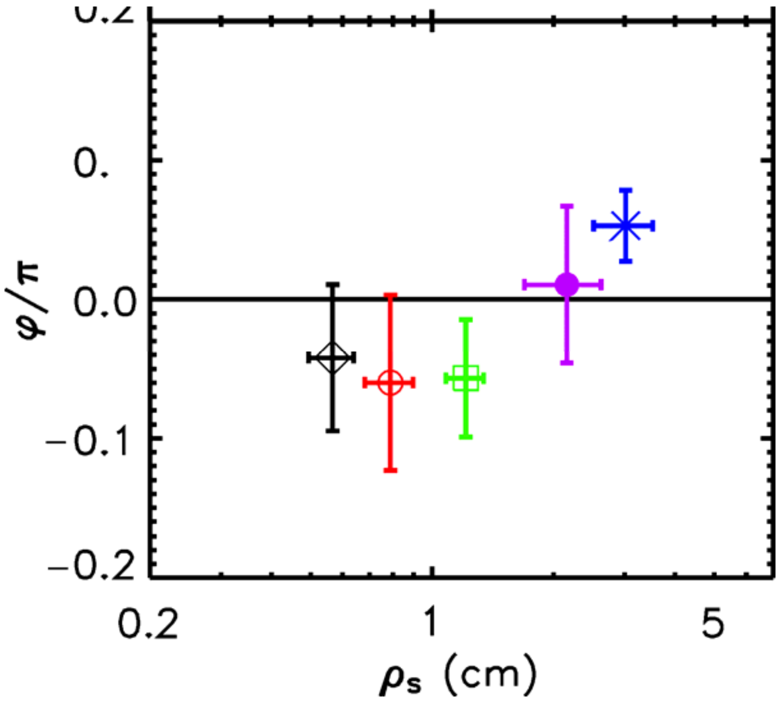
Scaling of Correlation Lengths



- scaling is less than linear
- no correlation with ν^* or β^*

Scaling of Correlation Lengths



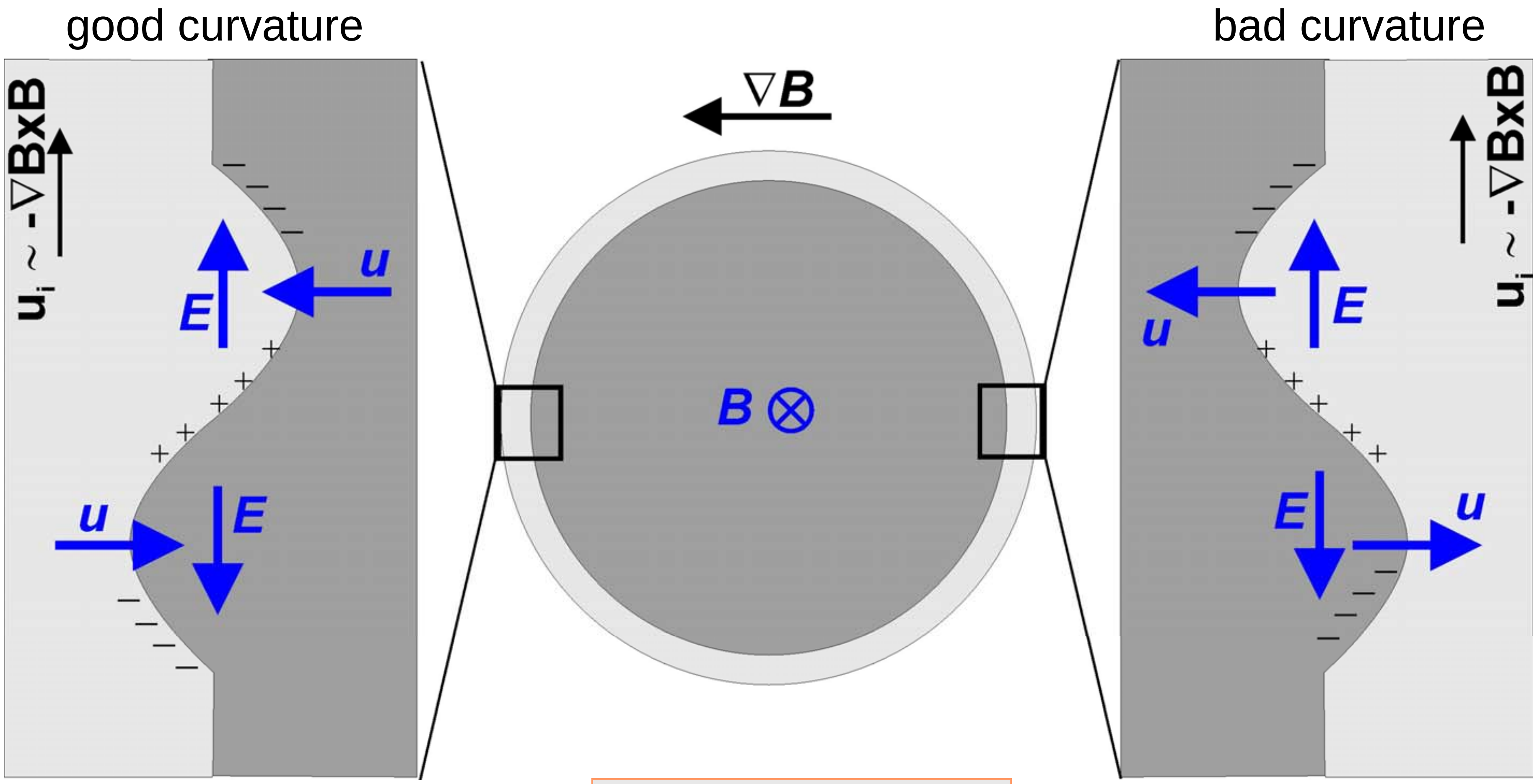


- – scaling is less than linear
- – no correlation with ν^* or β^*
- – cross-phase not constant

3.1

Turbulence control by optimisation of the magnetic configuration

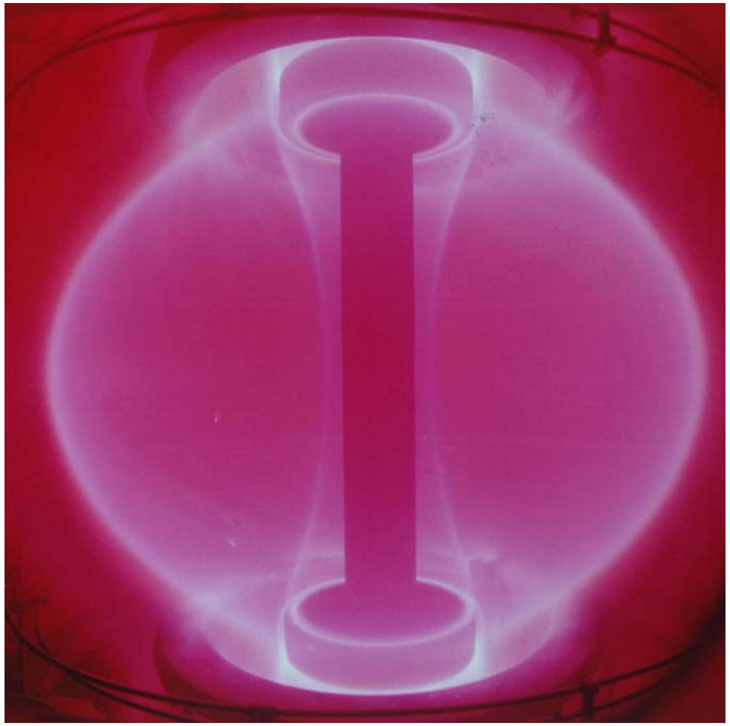
Interchange mode in regions of good and bad curvature

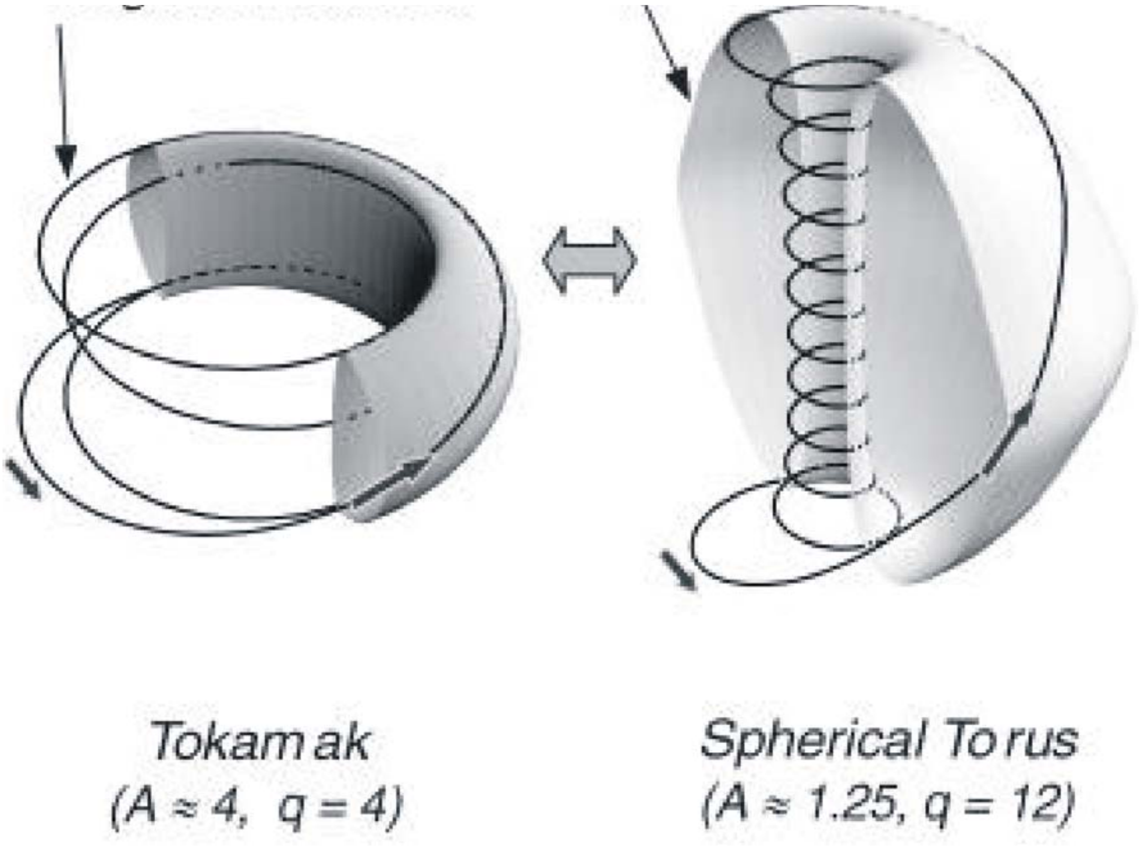


– small aspect ratio
– plasma shaping

Increase region of good curvature

Spherical tokamak

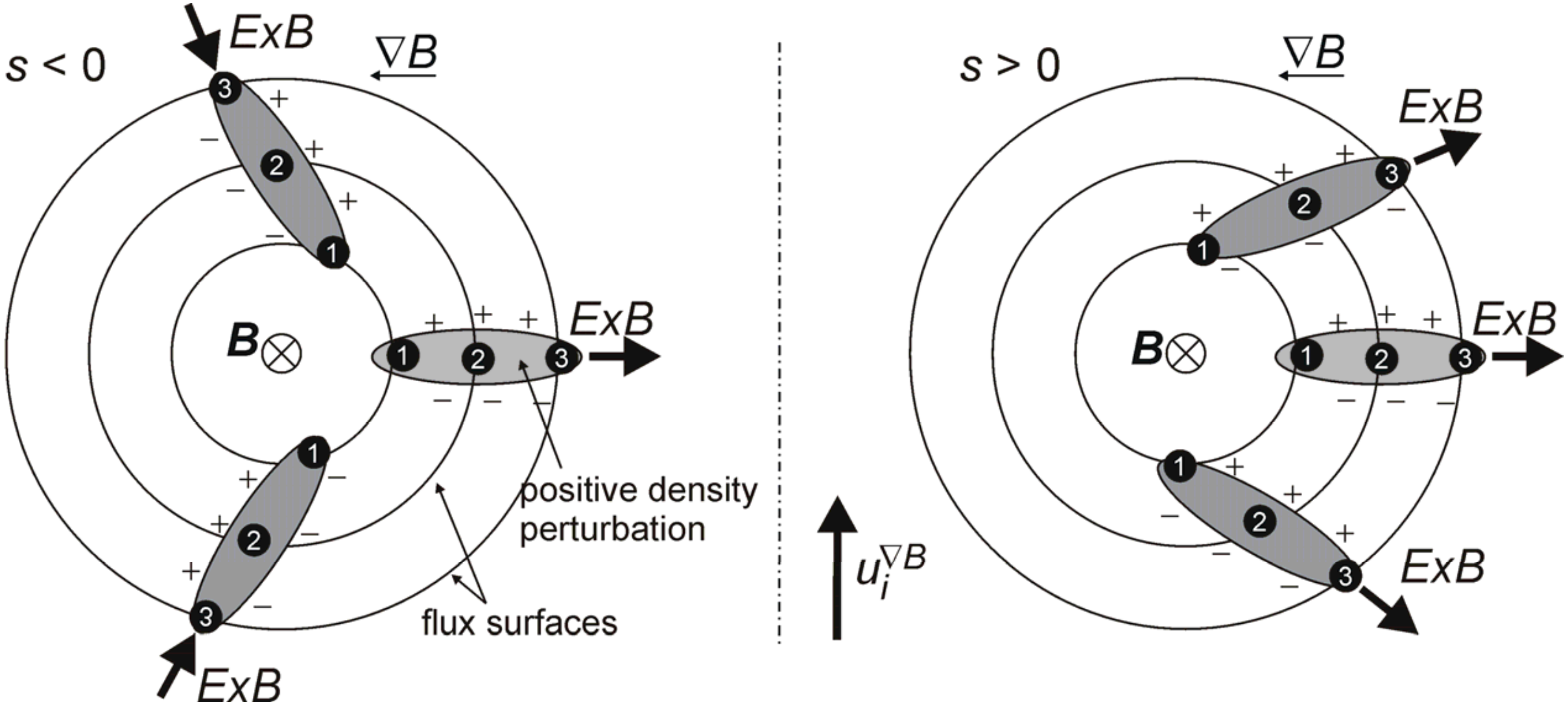




Create negative magnetic shear

negative shear

positive shear



–current drive

–non sationary profiles

3.2

Turbulence control by by sheared plasma flows

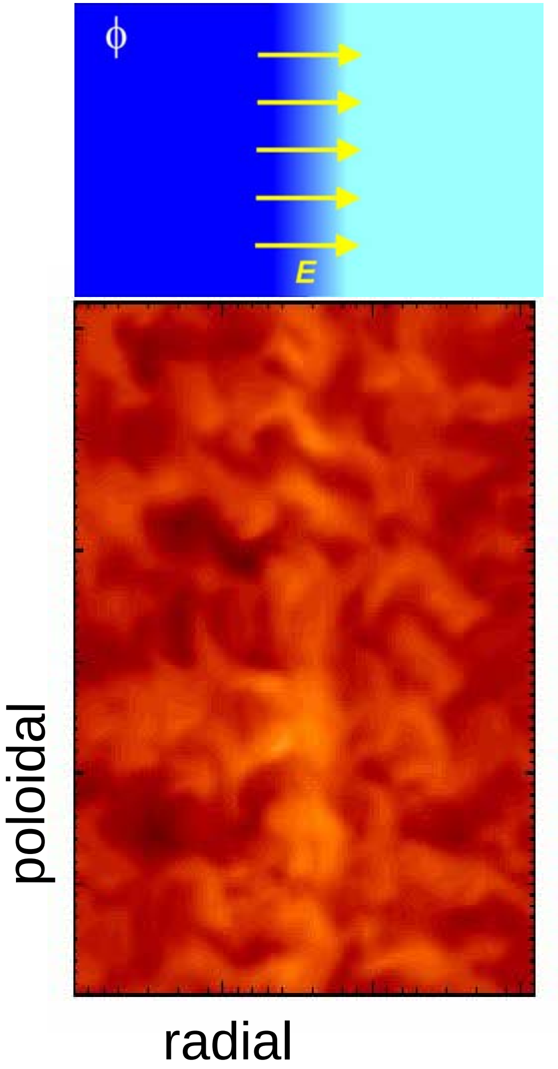
Spontaneous generation of zonal flows

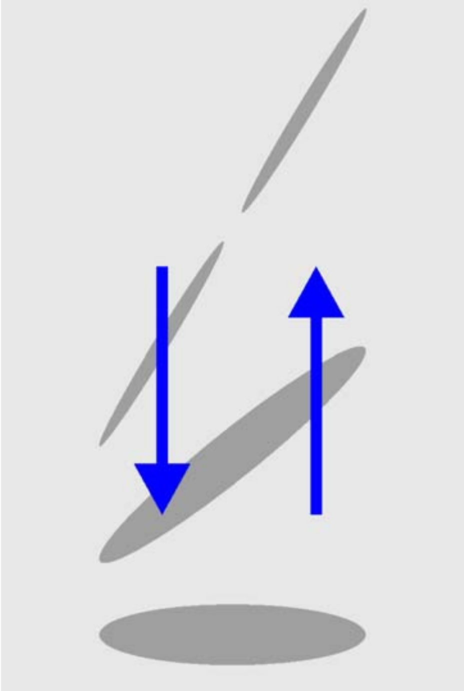
Found in

- rotating fluids
- atmospheres
- oceans

Magnetized plasmas

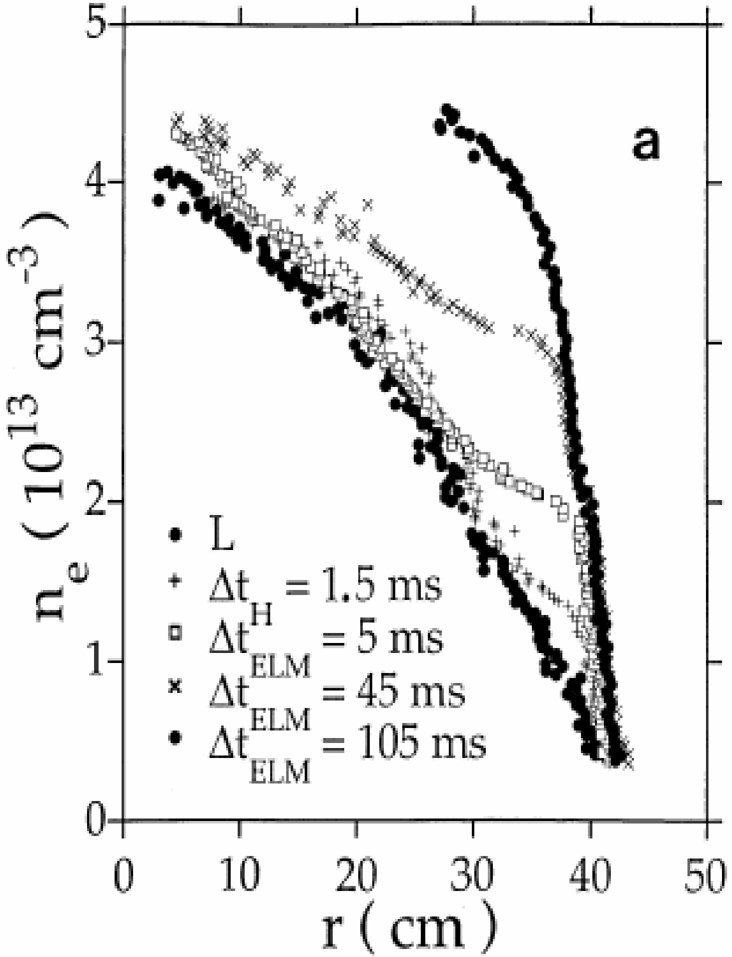
Jupiter atmosphere



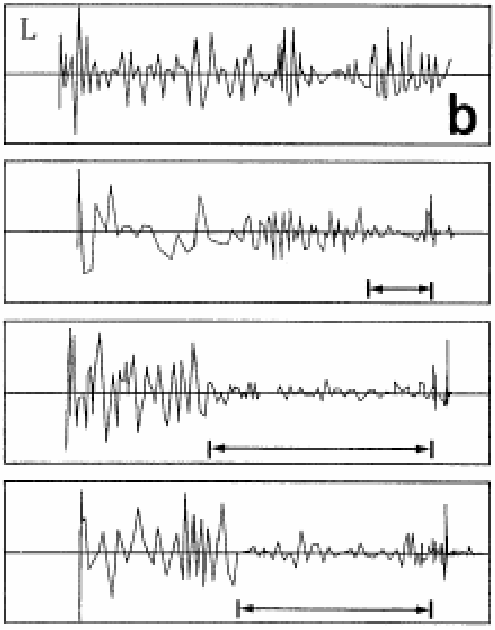


H mode: transition into improved confinement

edge transport barrier



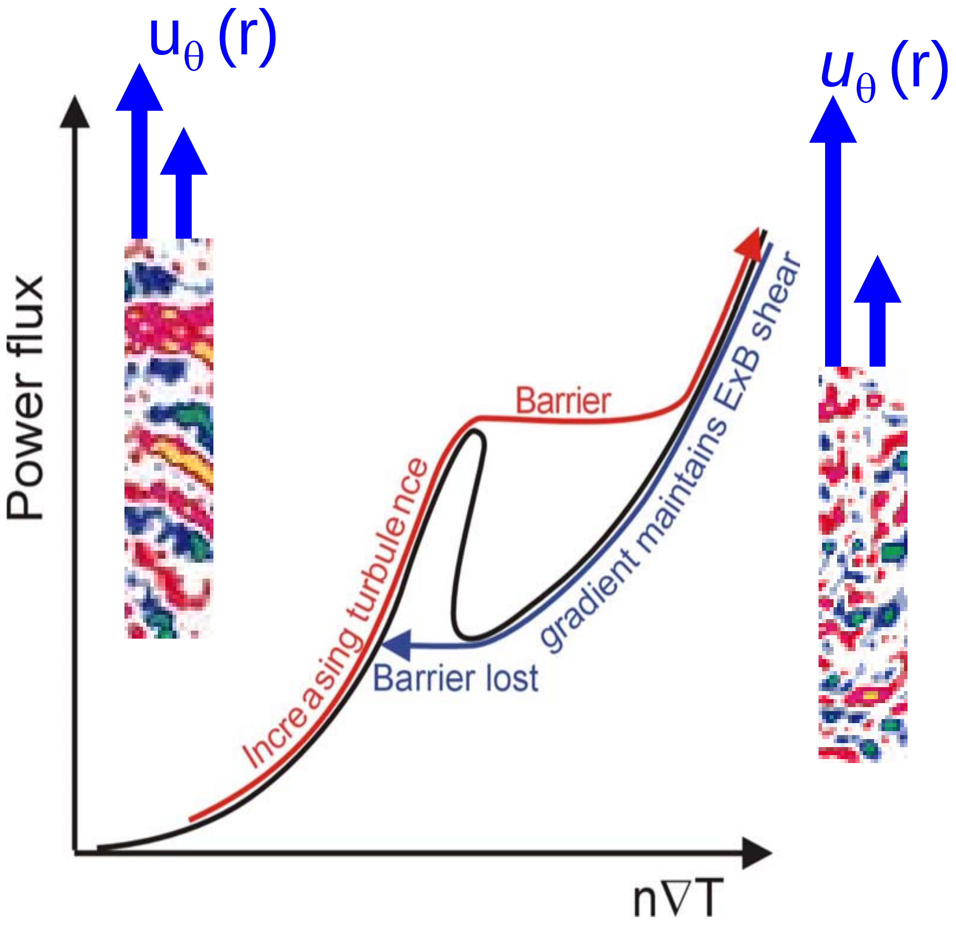
turbulence reduction



radius

Wagner et al, PRL 1982

Bifurcations in turbulent transport



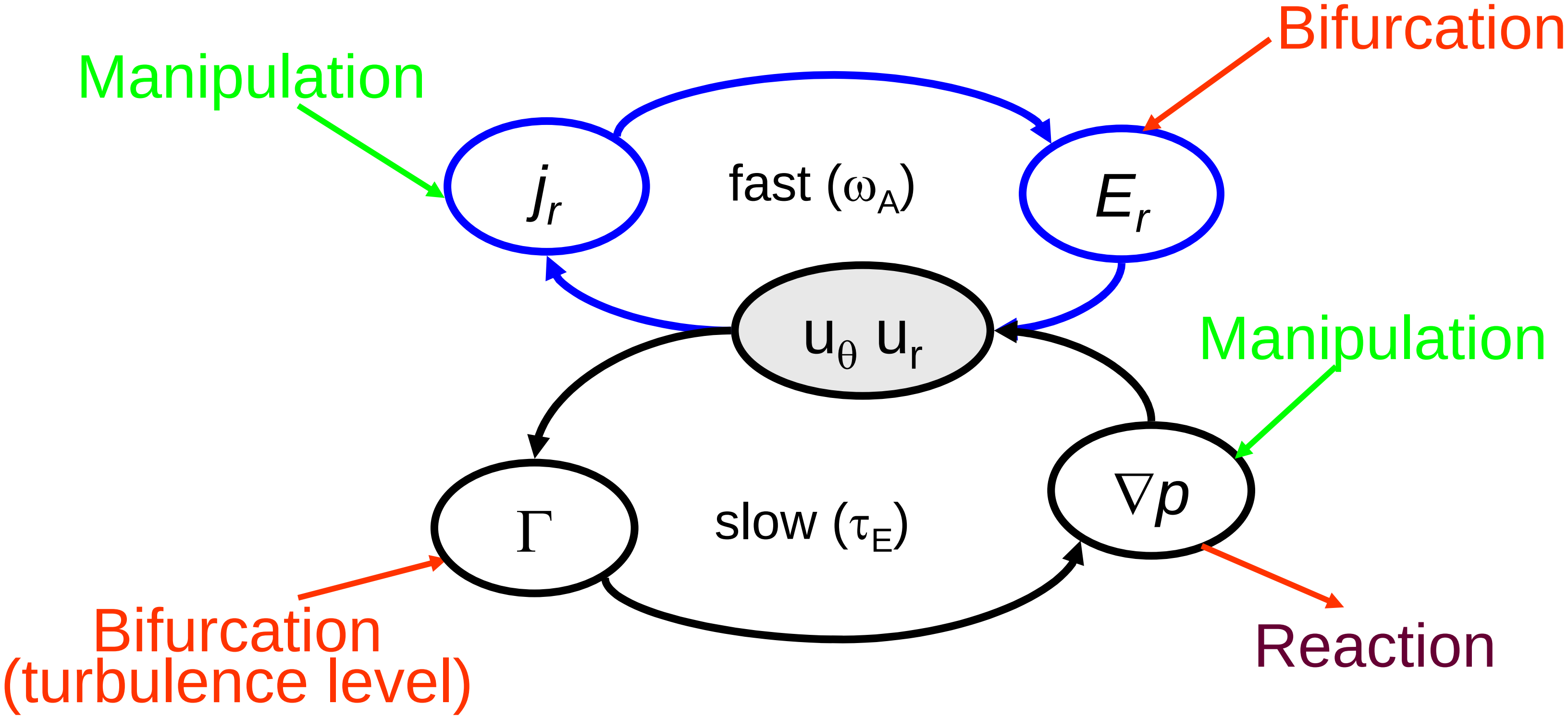
Mechanisms to control the electric field

Torques change radial force balance

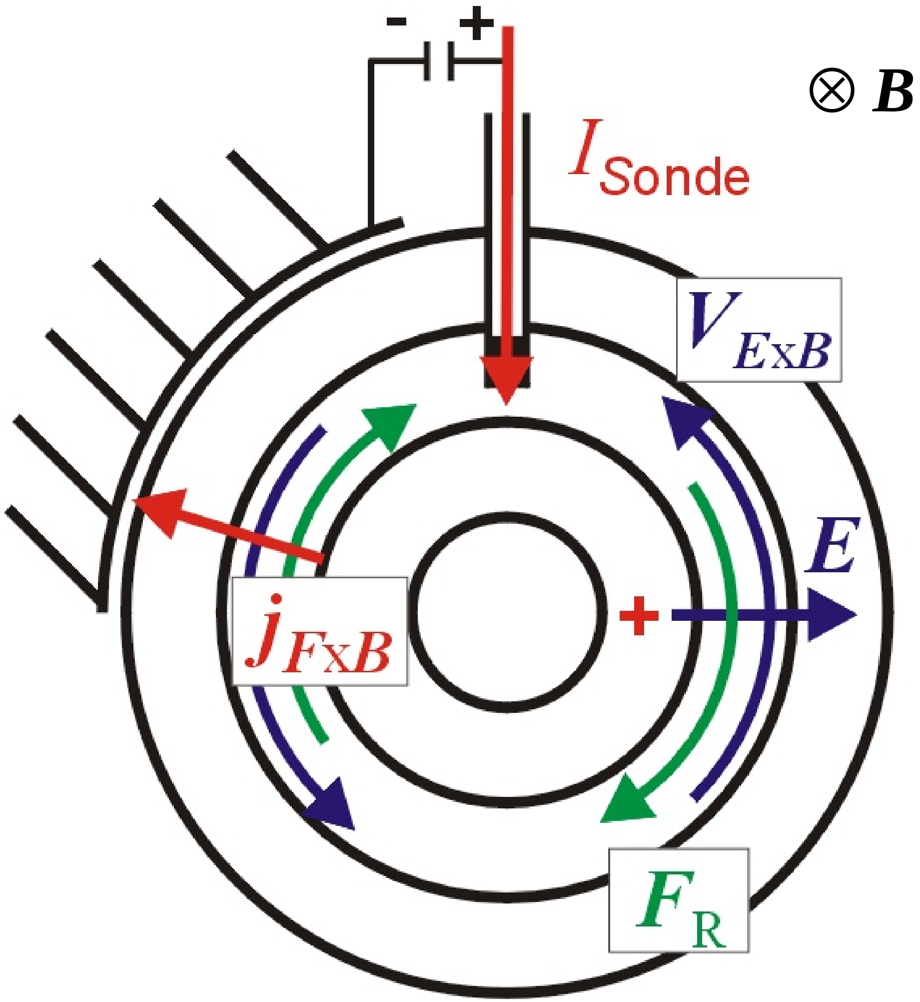
$$\varepsilon_\perp \frac{dE_r}{dt} = j_r^{neo} + j_r^{orbit} + j_r^{NBI} + j_r^{v\nabla v} + j_r^{bias}$$

Gradients react slowly

$$\frac{d}{dt}\nabla p \sim Source - \Gamma^{neo} - \tilde{\Gamma}(\nabla u_\theta)$$



Flow generation by plasma biasing



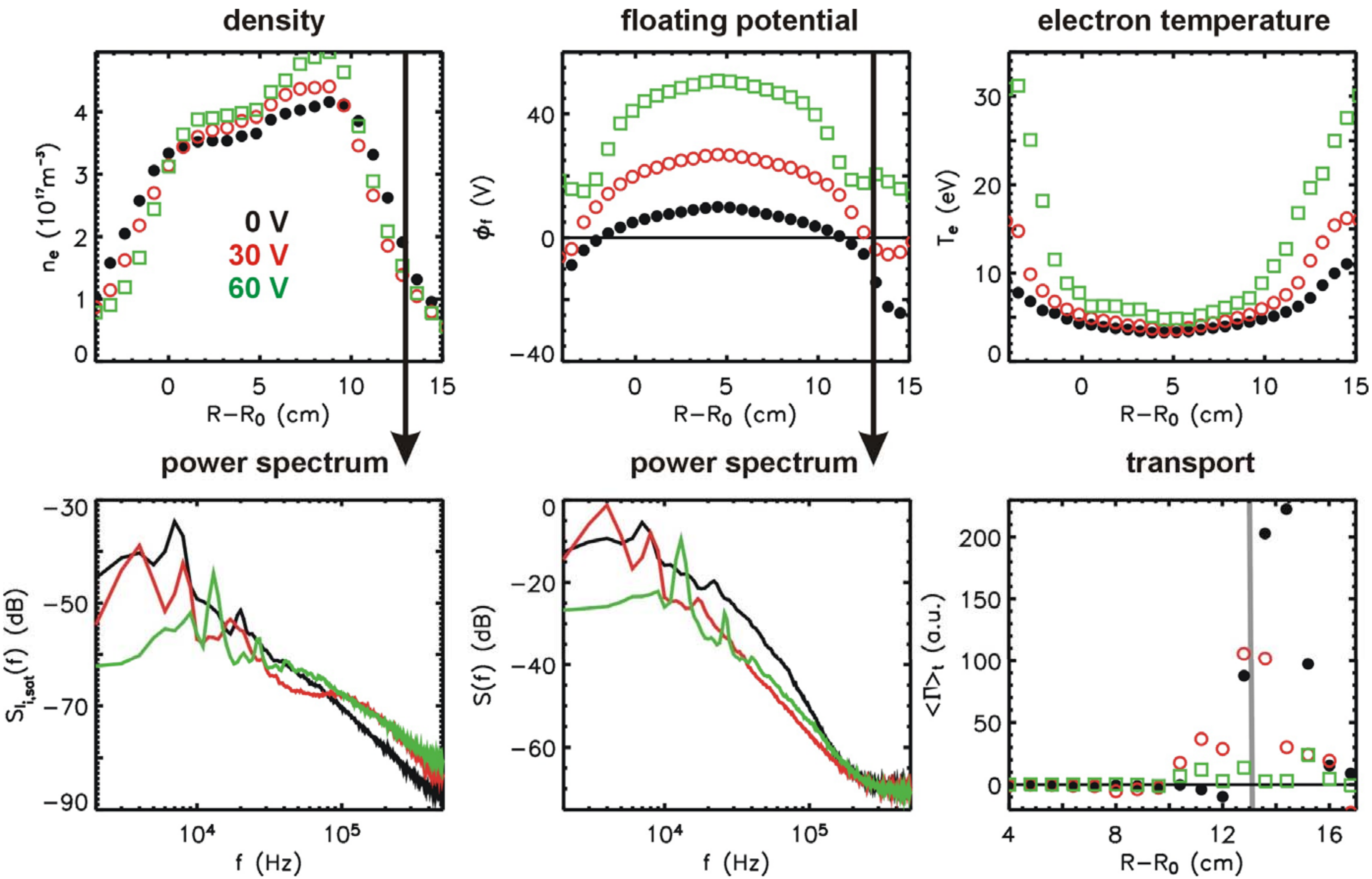
probe draws current

flow due to radial electric field

return current due to friction force

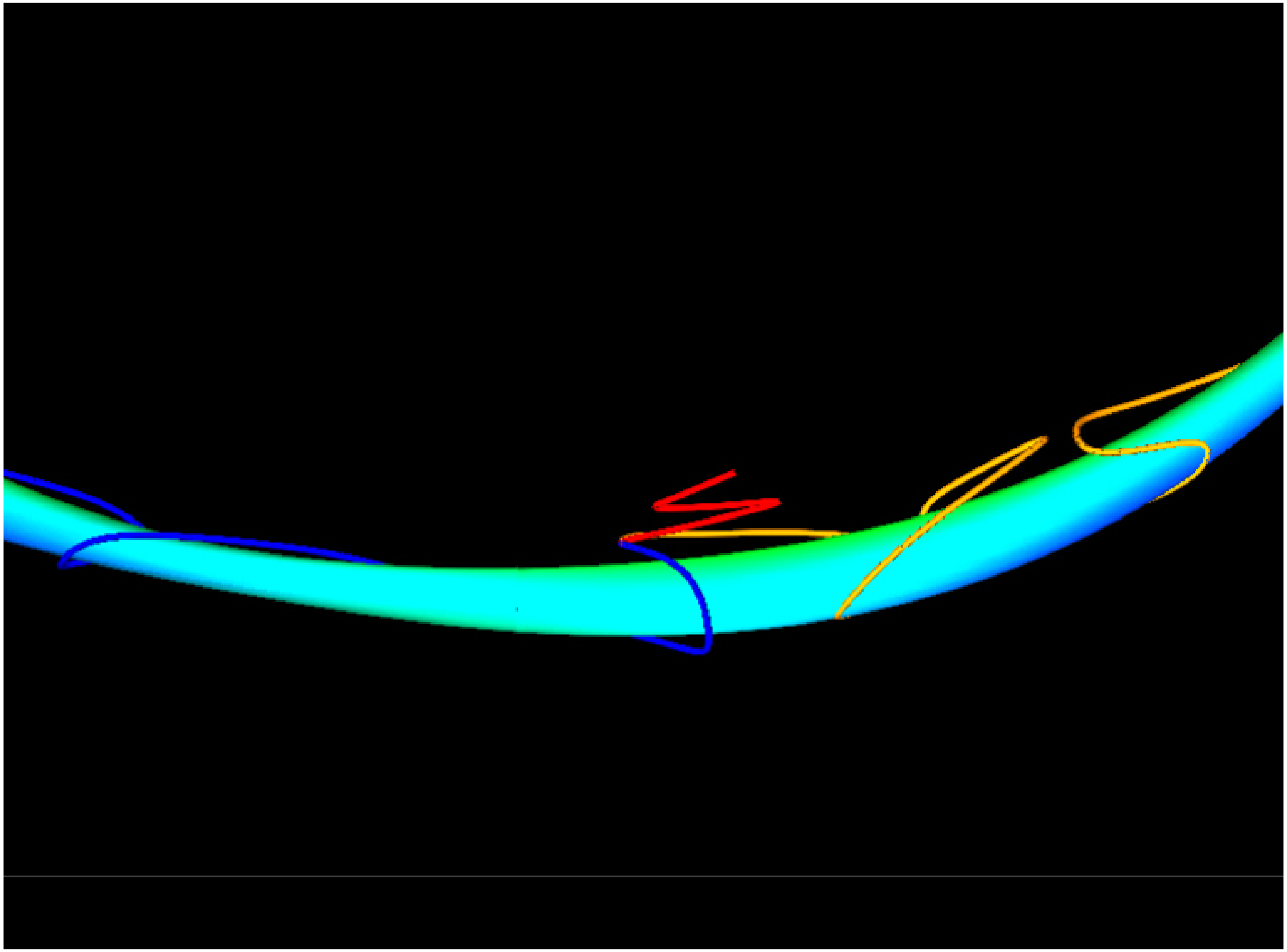
ambipolar flow at neoclassical E_r

Example from TJ-K

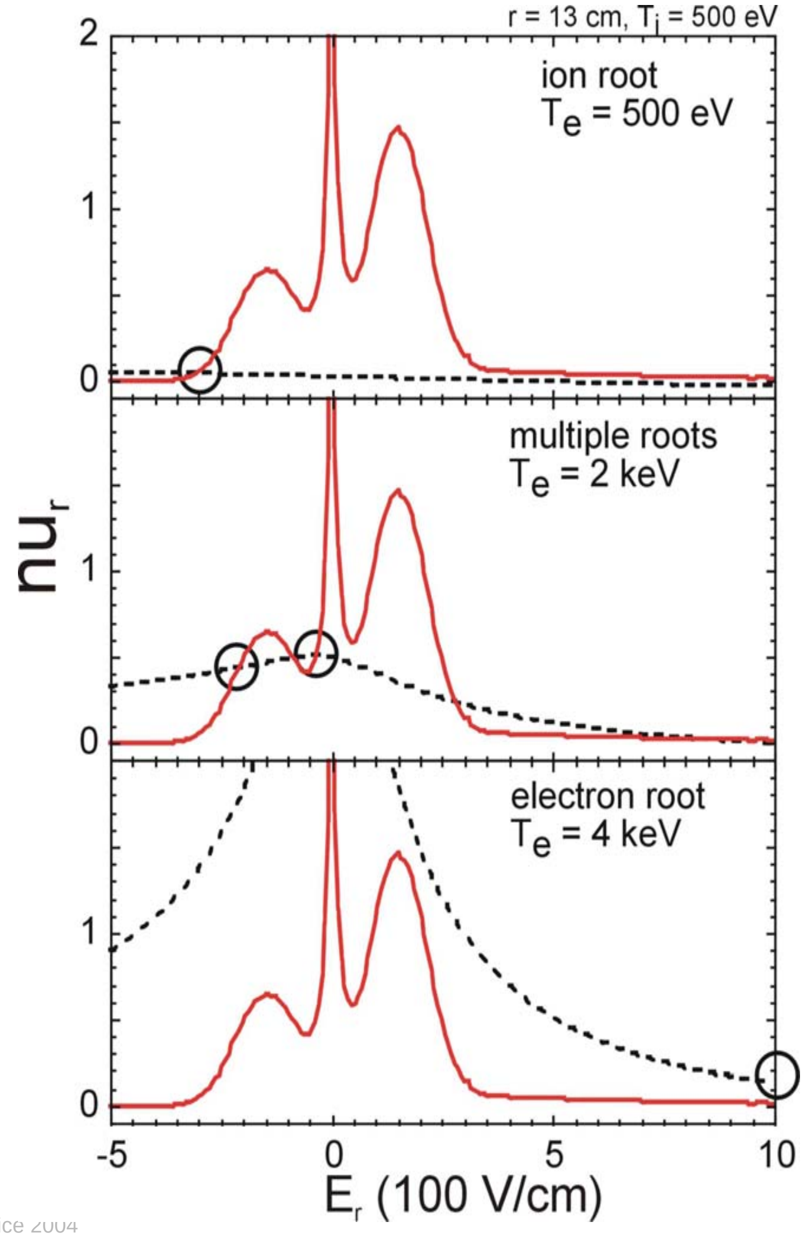


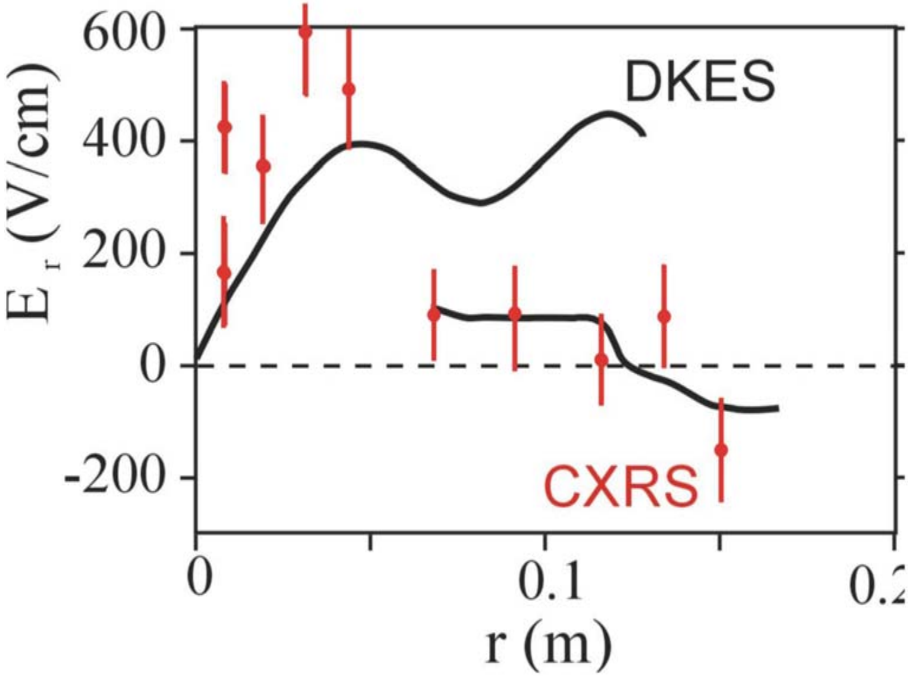
Particle orbits in an l=2 stellarator

Orbits for pitch angles $-\alpha$, 0, α

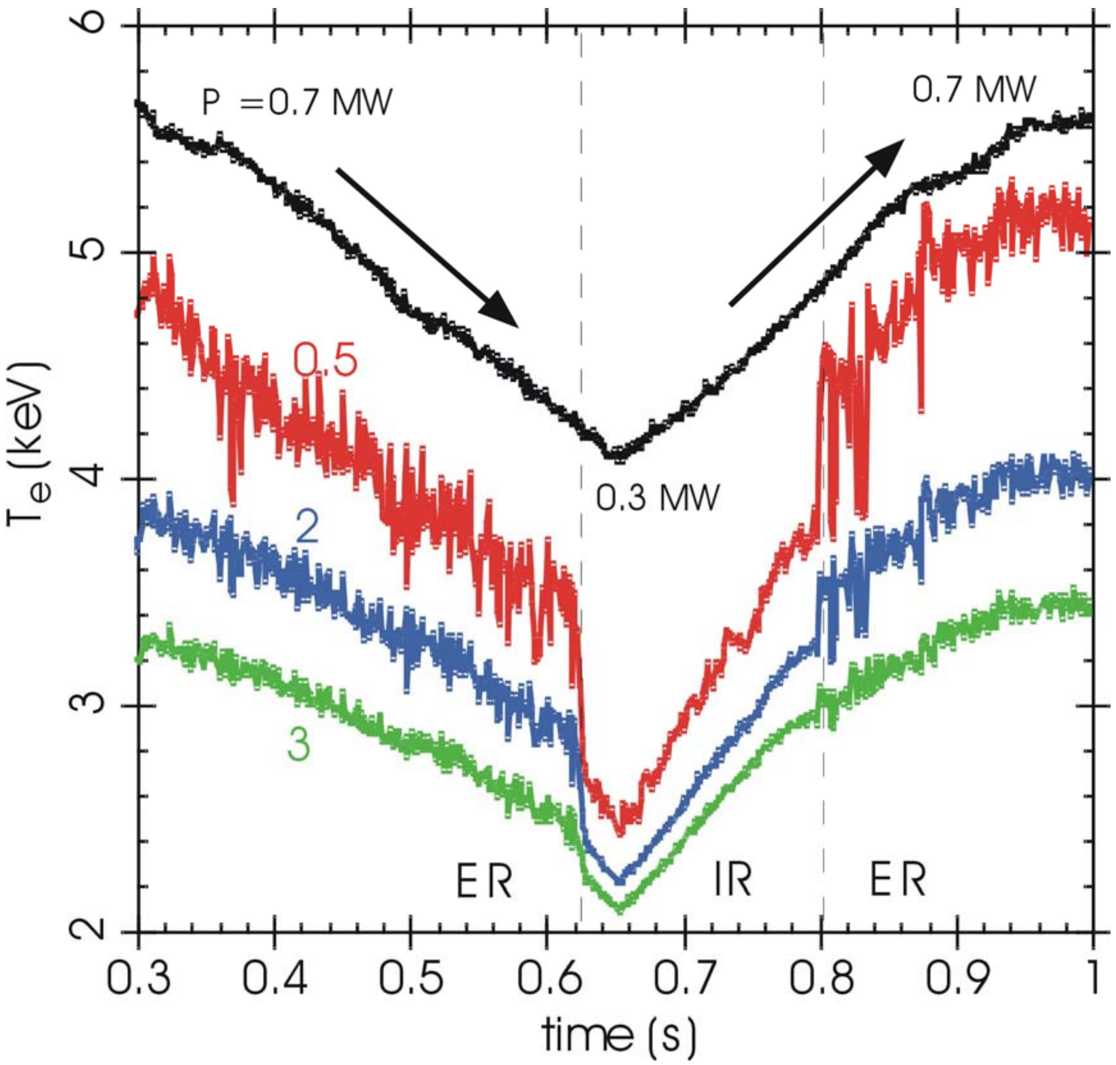


Neoclassical bifurcation in the W7-AS stellarator





Power-ramp experiments to investigate hysteresis



Conclusions

There exists a reasonable understanding of electro-static turbulence in toroidal plasmas.

Some turbulence control can be achieved by optimising the magnetic configuration.

Efficient reduction is due to sheared plasma flows which can be controlled by a number of different mechanisms