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Summer College on Plasma Physics

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Experiments on drift waves

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Experiments on drift waves

A selection of basic work

I. Observation of drift waves

II. Linear drift wave dynamics

III. Drift wave turbulence

IV. Control of drift waves

V. Summary

Observation of drift waves

Where?

- Magnetically confined plasmas
- Magnetized laboratory plasmas
- Plasmas in the magnetosphere

How?

- Local probes (n, φ)
- Fast optical cameras + beam or gas puff
- Microwave reflectometry
- Laser-induced flourescence

Varieties of drift waves

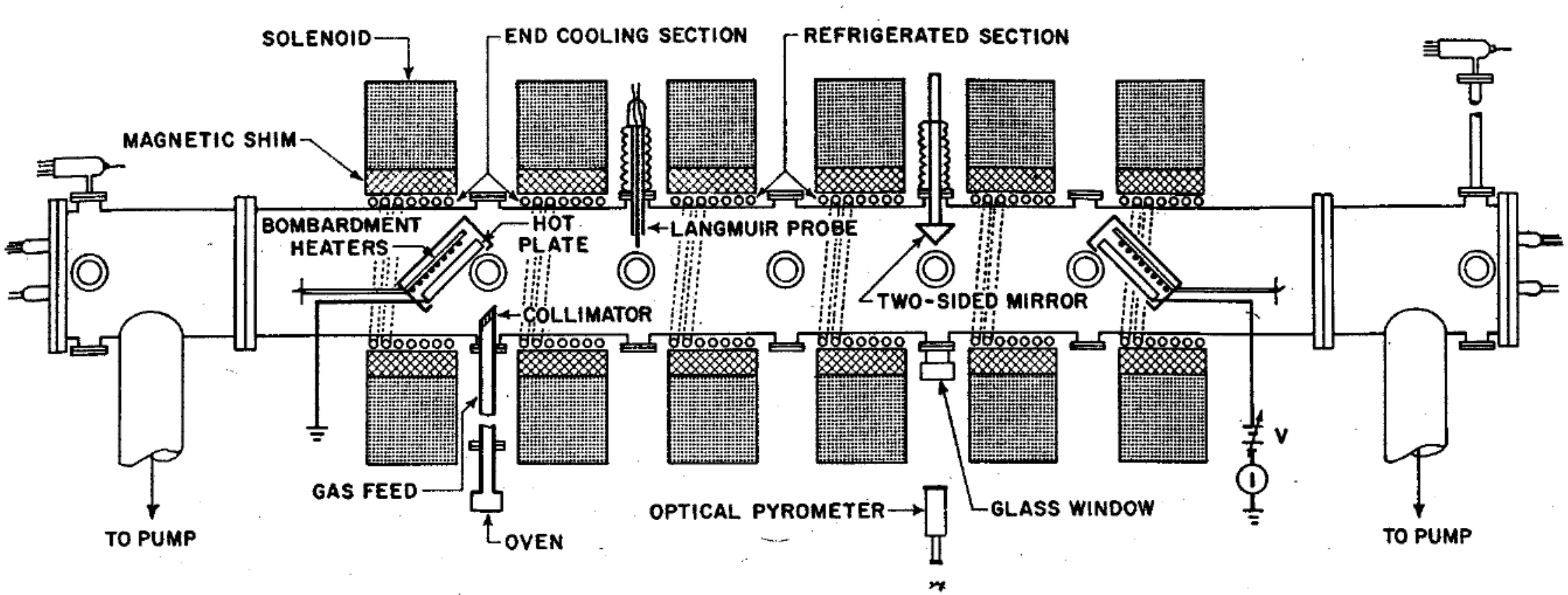
Common features:

- pressure gradient B_0 (density or temperature)
- finite wavelength along B_0 (usually $k_{\parallel} << k_{\perp}$)
- electron and ion motions different (2 - fluid)

Some variations:

- collisional drift wave (electron resistivity)
- collisionless drift wave (electron-wave resonance)
- current driven drift wave (includes δT_e)
- rotation shear (KH, Kelvin-Helmholtz instability)
- B-field curvature (resistive ballooning mode)
- ion and electron temperature gradient (ITG, ETG)
- trapped electron and ion modes (TEM, TIM, toroidal)
- drift-Alfven waves (DAW, finite magnetic perturbations)

Earlier work



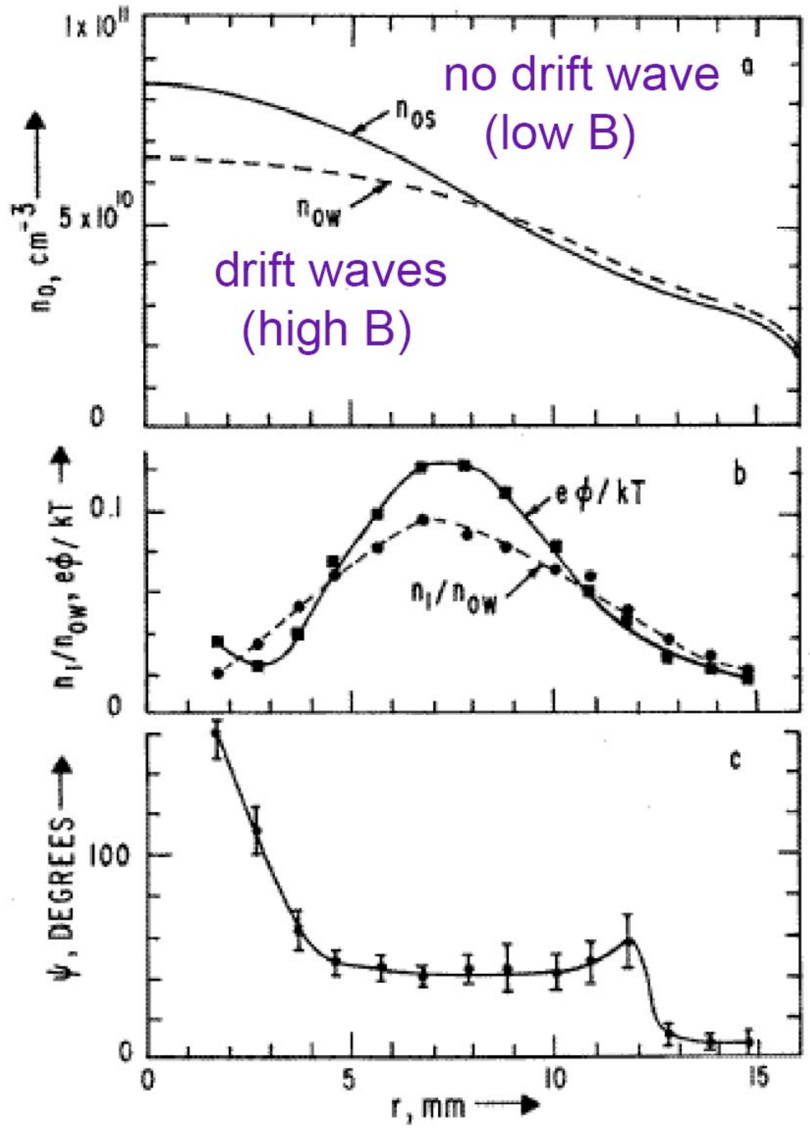
- **Q-machine with K or Cs plasma**
- **relatively low density n ~ $10^4 \ldots 10^7$ m^{-3}**
- **isothermal** $T_i = T_e = 0.25 eV$

Hendel et al. Phys. Rev. Lett. 18, 439 (1967) and Hendel et al. Phys. Fluids 11, 2426 (1968)

Earlier work

A few comments:

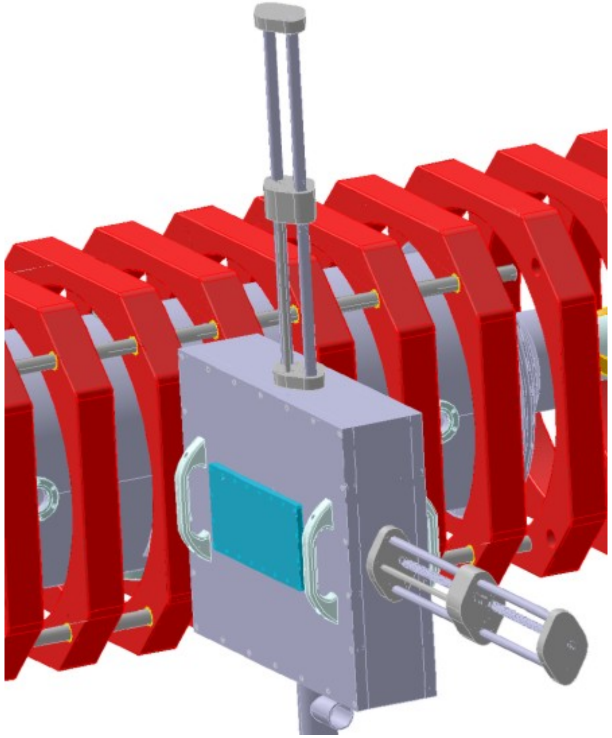
- nearly coherent drift mode
- localized in high ∇n region
- $e\delta\varphi/k_bT \approx \delta n/n$ Boltzmann satisfied
- δn leads $\delta\varphi$
- expected from linear theory
- collisional drift wave
- destabilized by electron resistivity
- stabilized by ion viscosity $\perp B$
- unstable when $k\cdot\rho_i \sim 0.5$
- saturated instability



Linear device: VINETA

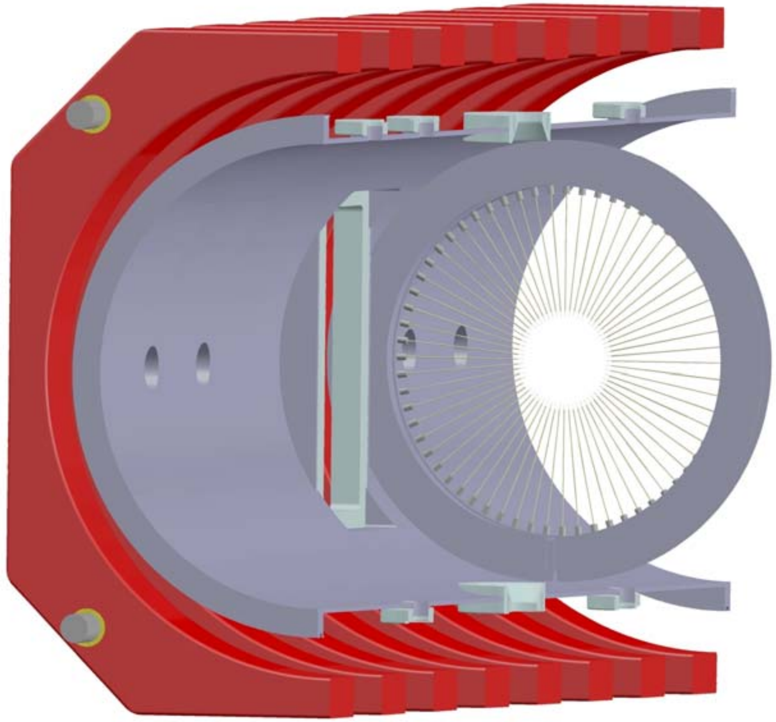
Advanced probe diagnostics

azimuthal single probe positioning system



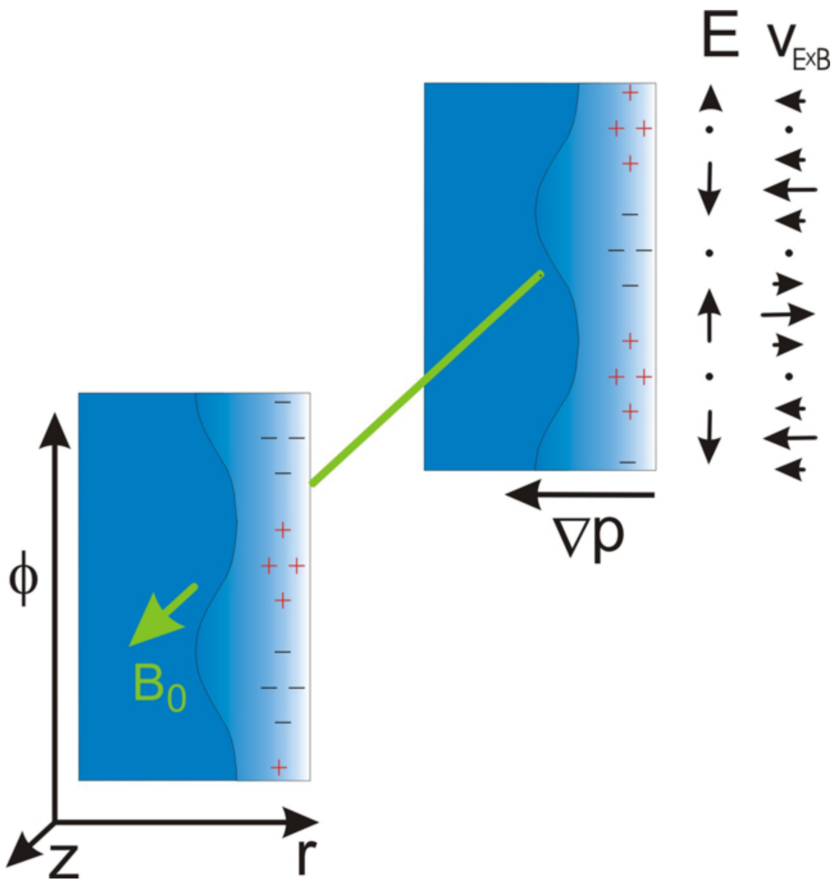
- **2D profiles**
- **2D correlation functions**

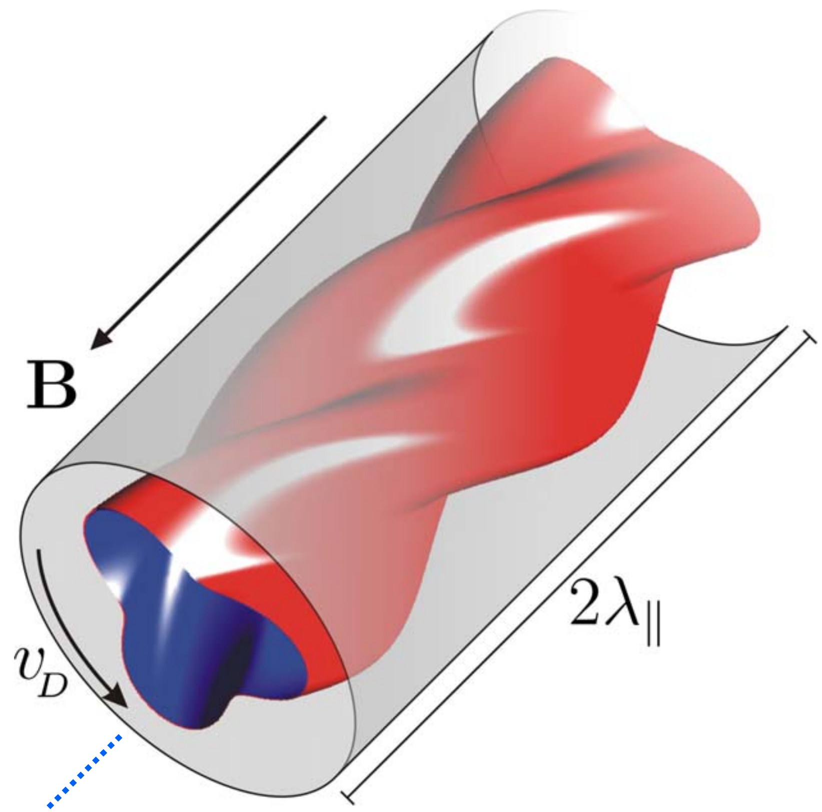
azimuthal 64 probe array



- **density fluctuations on azimuthal circumference**

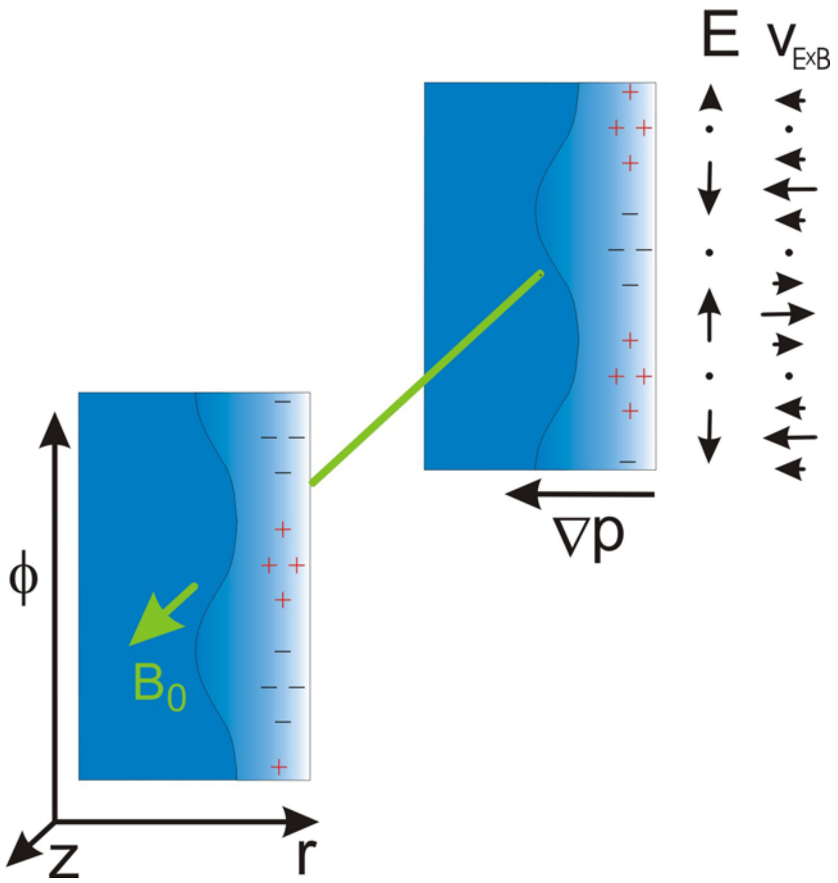
Probe array raw data

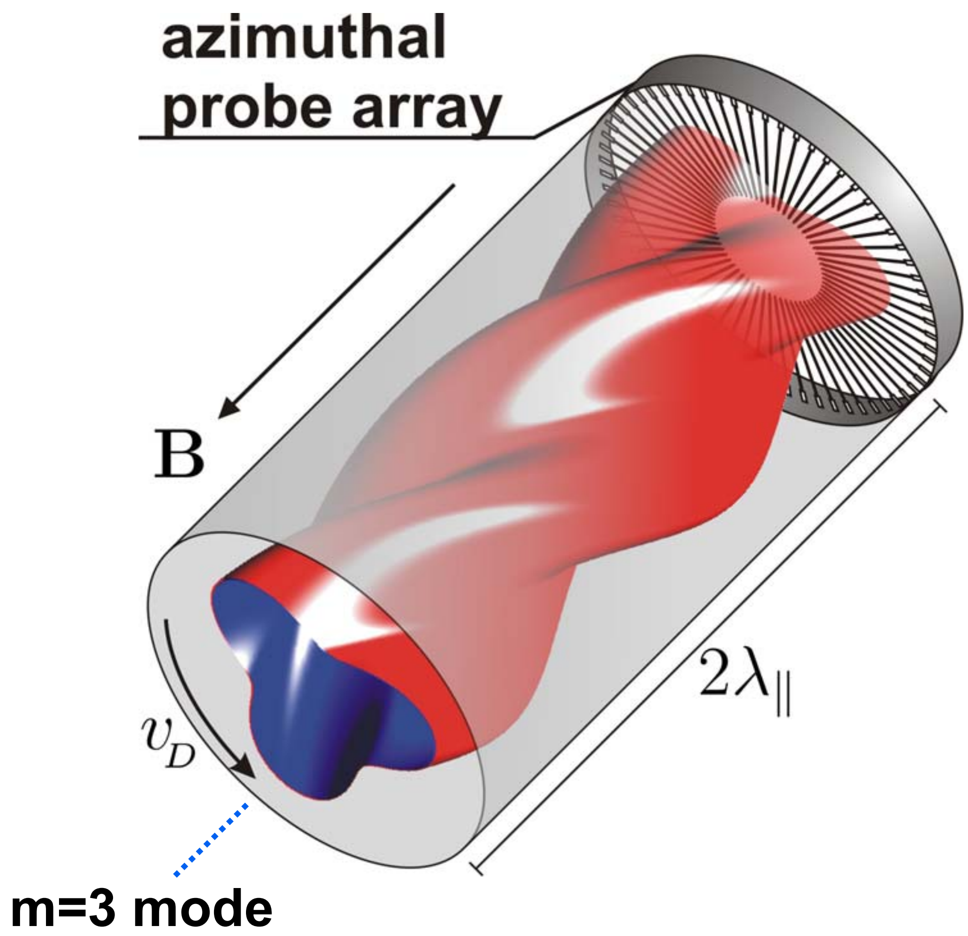




m=3 mode

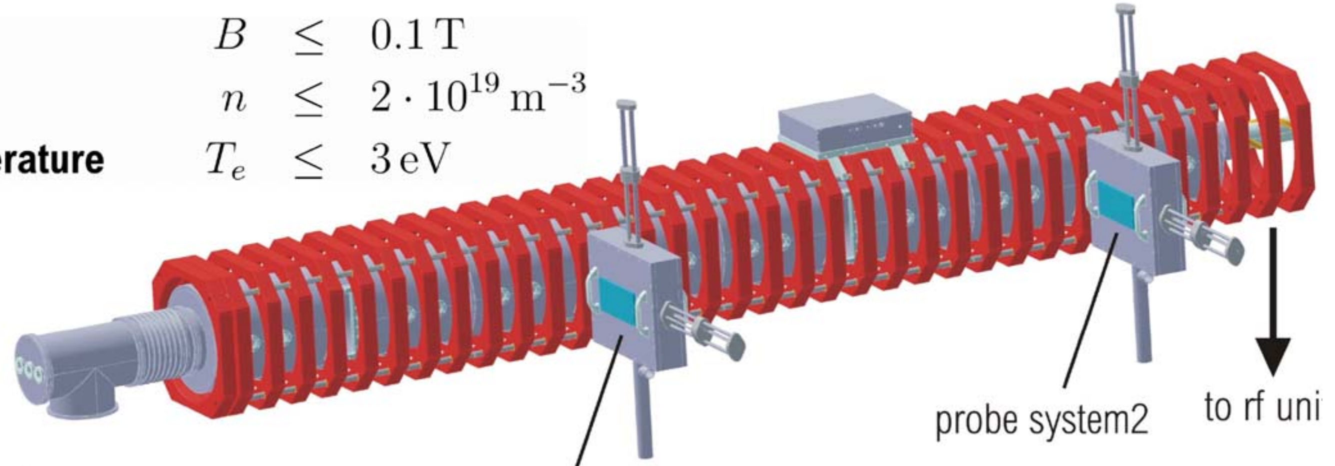
Probe array raw data

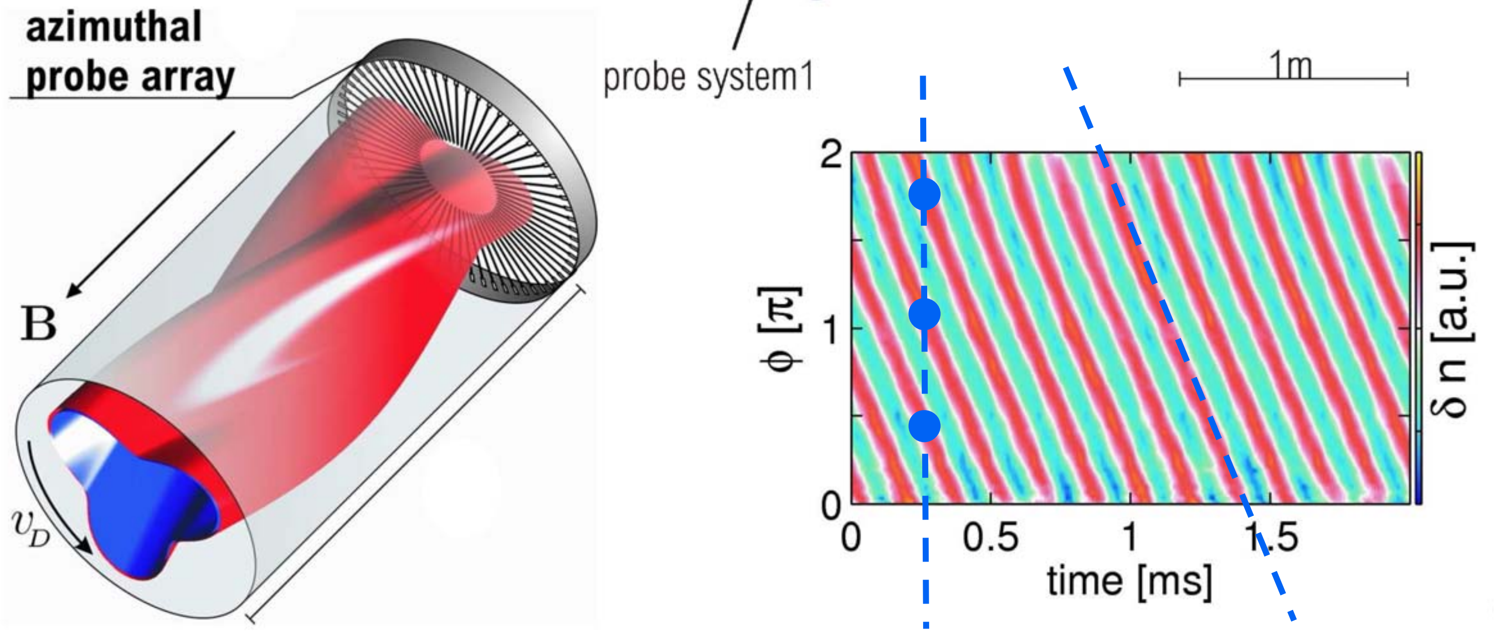




Space-time data - mode

magnetic field	B	$\leq$	$0.1\,\mathrm{T}$
density	n	$\leq$	$2 \cdot 10^{19}\,\mathrm{m}^{-3}$
electron temperature	T_e	$\leq$	$3\,\mathrm{eV}$

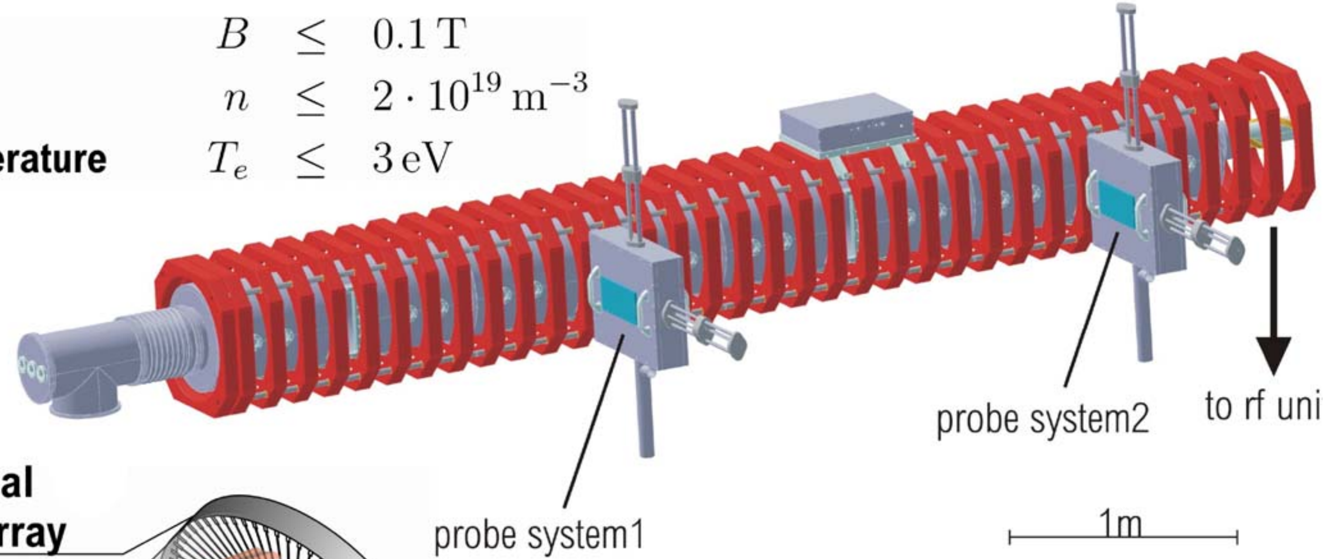


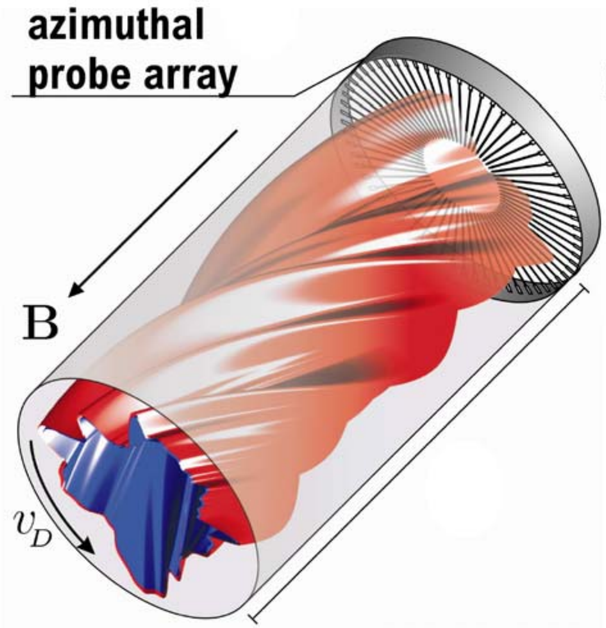


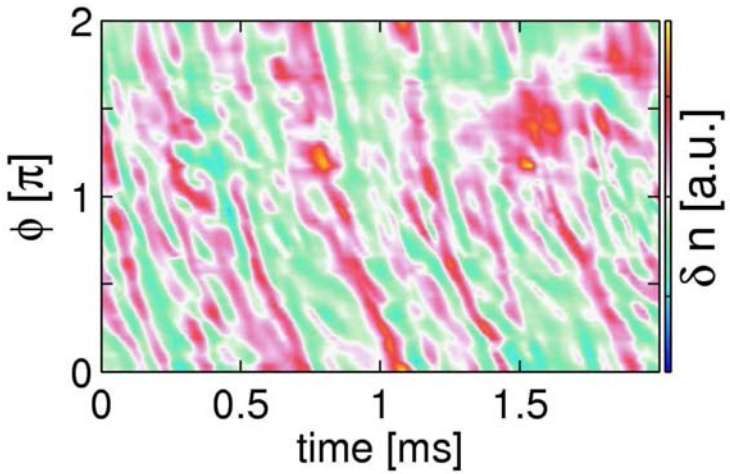
$\mathrm{FT}[\delta n(\phi,t)] \rightarrow S(m,\omega)$ m = 3 **pitch** $\propto v_{ph}$

Space-time data - turbulence

magnetic field	B	$\leq$	$0.1\,\mathrm{T}$
density	n	$\leq$	$2 \cdot 10^{19}\,\mathrm{m}^{-3}$
electron temperature	T_e	$\leq$	$3\,\mathrm{eV}$

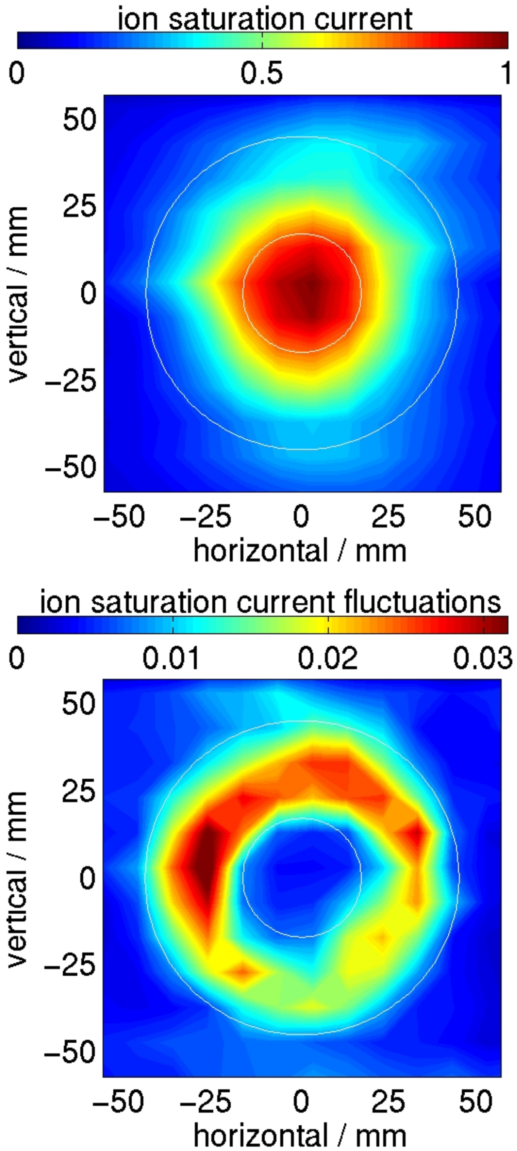


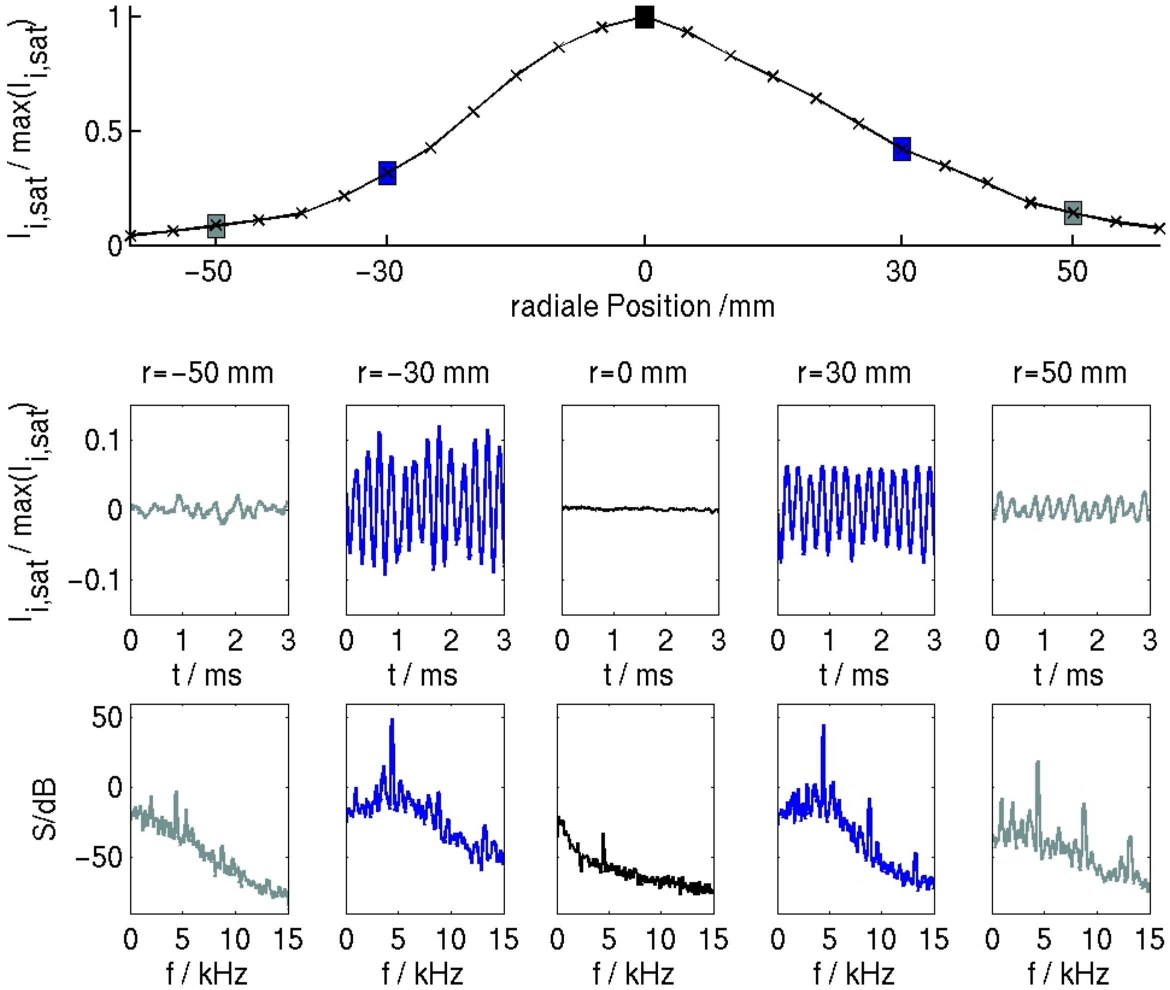




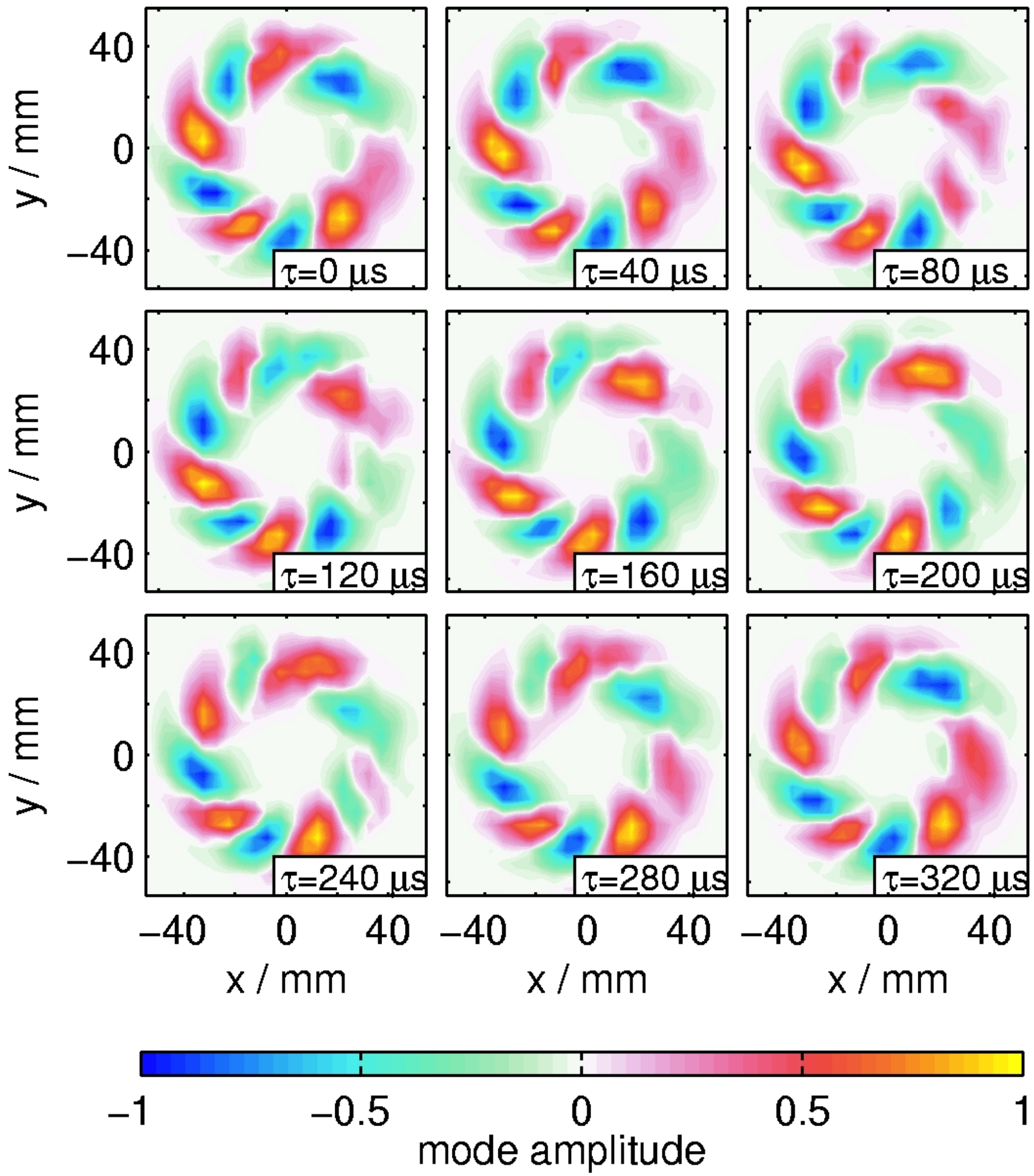
$$\mathrm{FT}[\delta n(\phi,t)] \rightarrow S(m,\omega)$$

Basic fluctuation characteristics

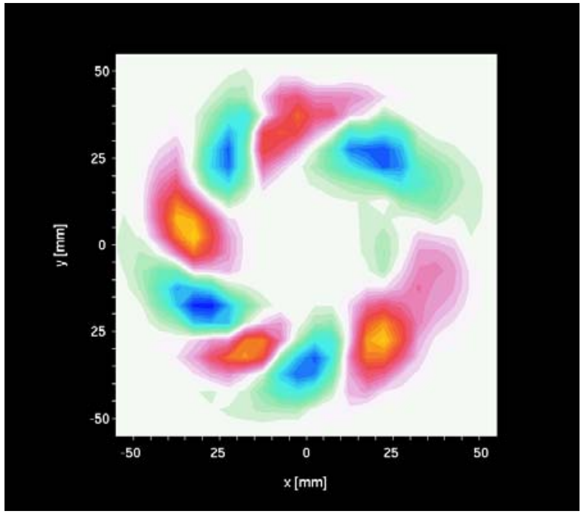




Azimuthal mode structure



- **propagation in** v_{ed}
- **fluctuation** $\tilde{n}/n \sim 10\%$
- **mode structure**
- **azimuthally sheared**



Linear global model

eigenvalue equation

*Ellis et al., Plasma Physics **22**, 1980*

$$\partial_{rr}\phi + \left(\frac{1}{r} - \kappa(r) + RD(r)\right)\partial_r\phi + \left(Q(r) - \frac{m^2}{r^2}\right)\phi = 0$$

with

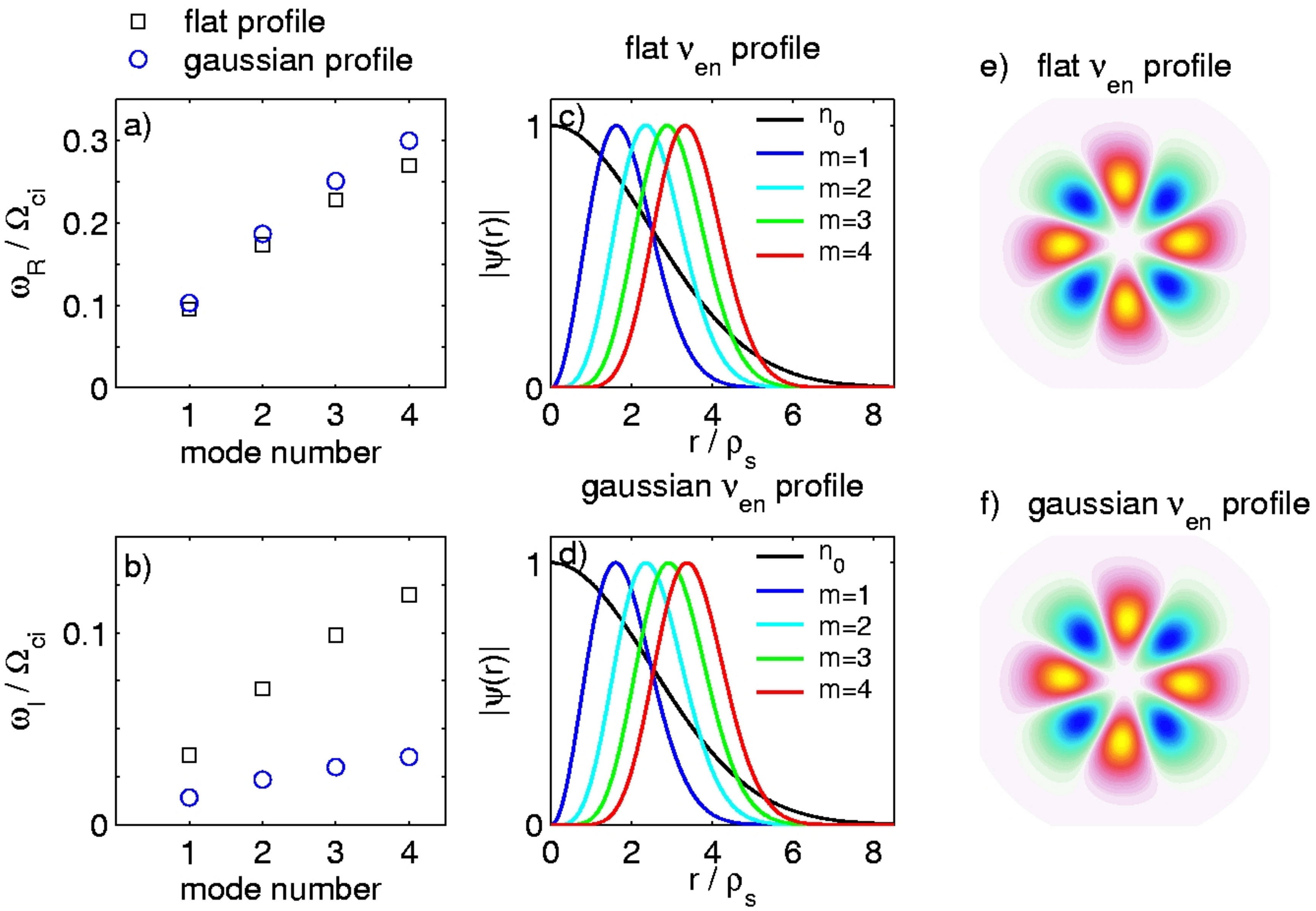
$$RD(r) := i\,\frac{1}{\tilde{\omega} + i\nu_{in}}\left(\frac{\omega^* + iP}{\tilde{\omega} - \omega_1 + iP}\right)\nu_{in}\, r\, V_p$$

$$Q(r) := \frac{1}{\tilde{\omega} + i\nu_{in}}\left[\omega^* + \frac{m}{r}S_p - \tilde{\omega}\,\frac{\omega^* + iP}{\tilde{\omega} - \omega_1 + iP}\right] ;\ P = P(\nu_e)$$

- **important:** $\nu = \nu(r)$
- **solve for eigenfrequencies & eigenmodes**

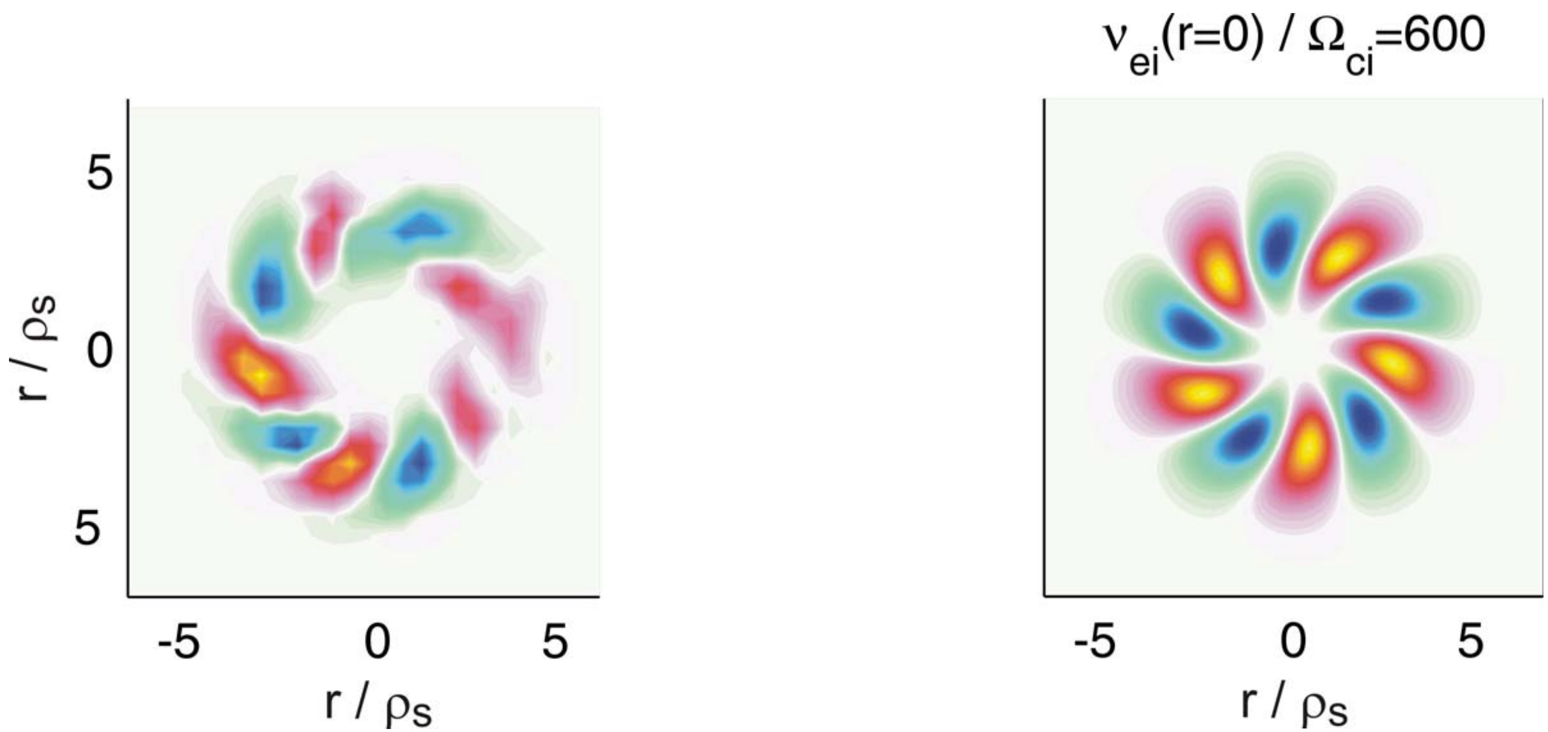
$$\omega = \omega_R + i\omega_I$$
$$\psi(r) = \psi_R(r) + i\psi_I(r)$$

Eigenvalue solutions



Detailed mode structure

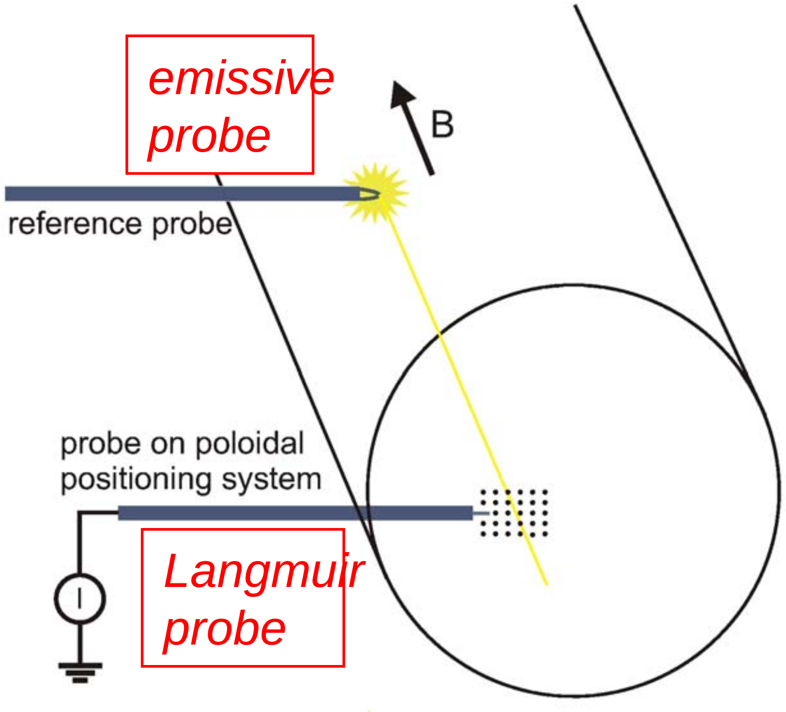
measurement ⟷ **model**



sheared mode structure owing to radial collisionality profile

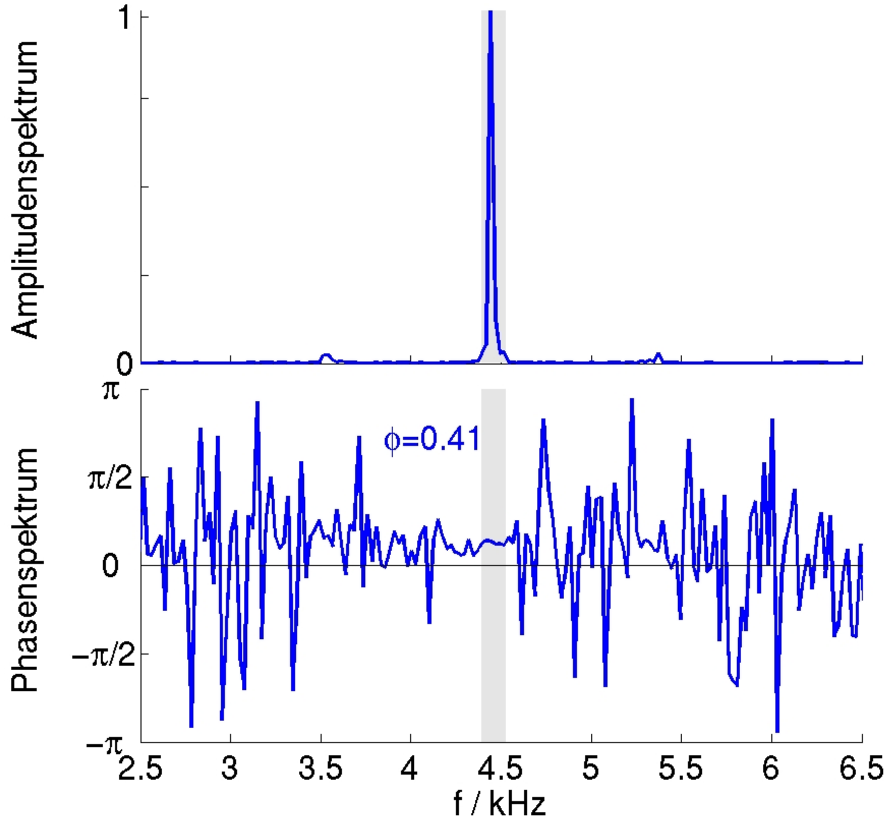
Parallel wavelength

alignment of probes along magnetic field

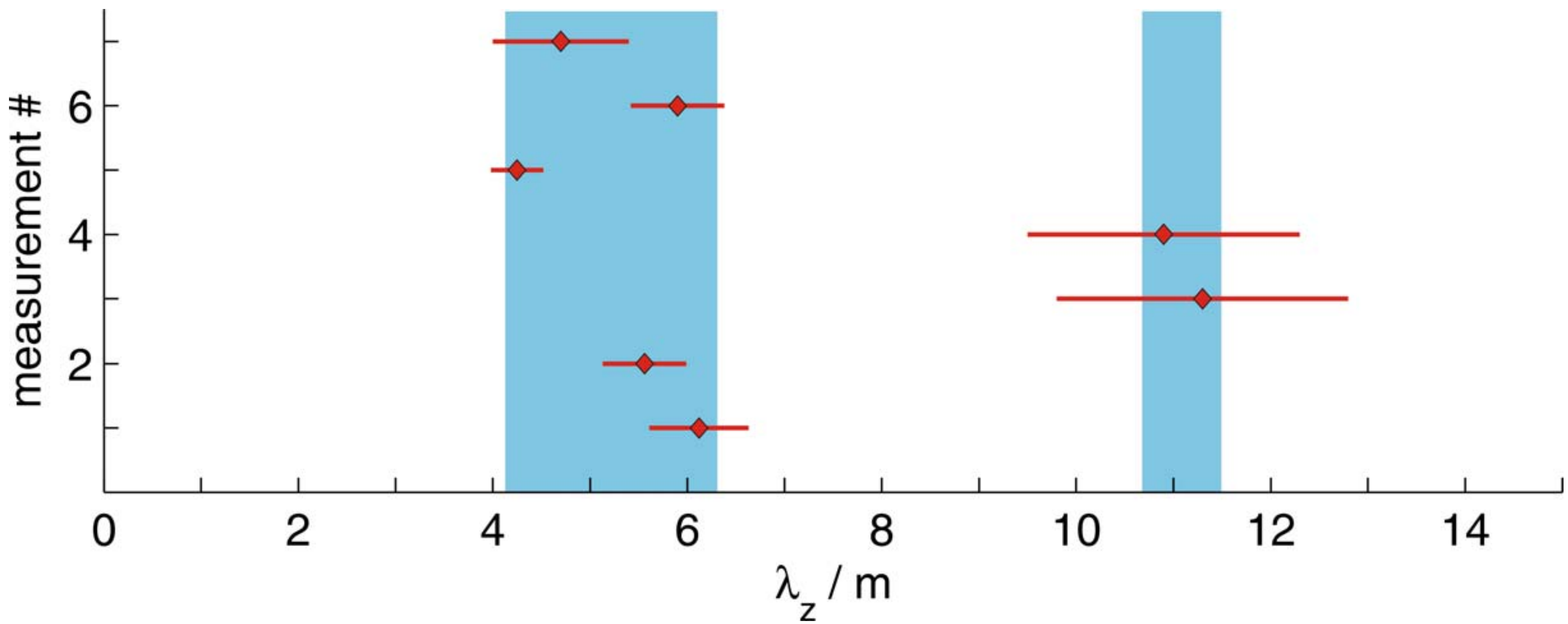


- **alignment accuracy ≤ 1mm**

phase shift along magnetic field



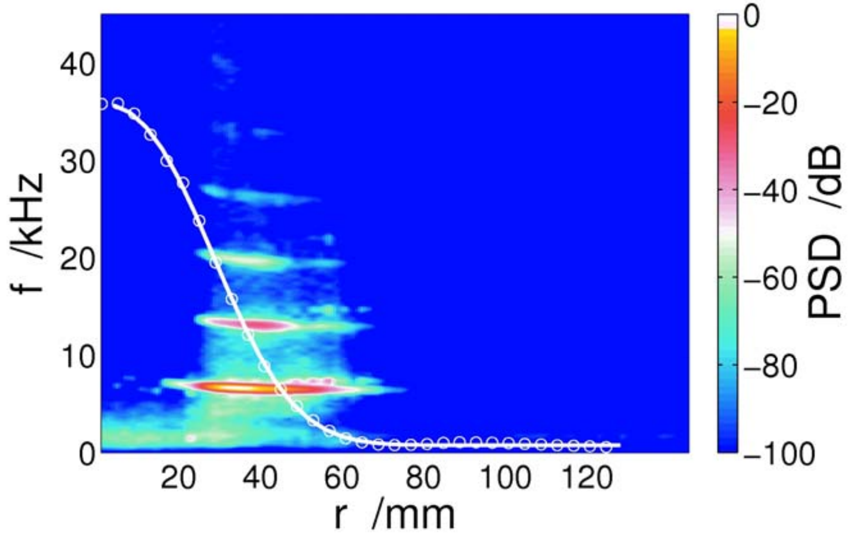
Parallel wavelength



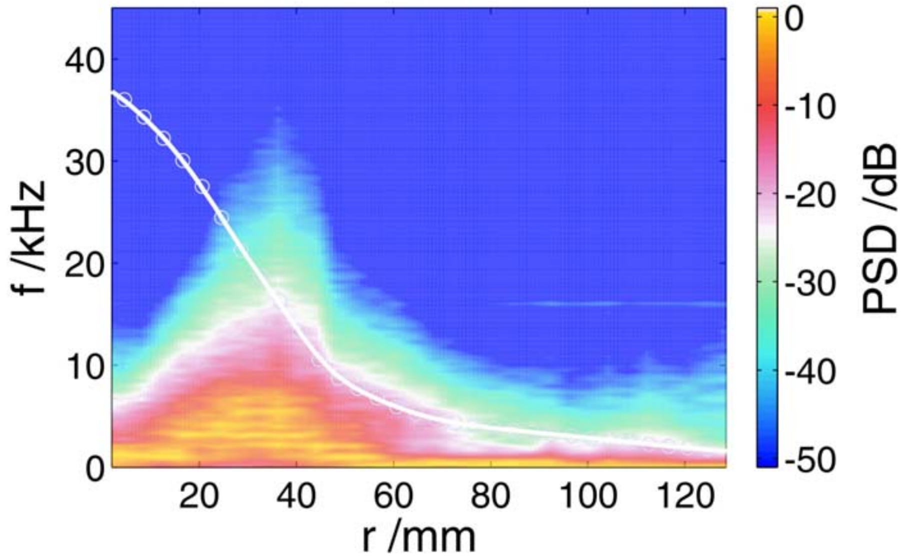
- $k_{||} \neq 0$
- **phase shift & axial separation provides parallel wavelength** λ_z
- **wavelengths group at** $L_{||}$ **and** $2L_{||}$
- **important proof to observe *really* drift waves**

Drift wave turbulence spectra

drift wave mode



drift wave turbulence



radially resolved power

spectra

- coherent fluctuations
- fluctuations well localized
- spectrum is peaked
- higher harmonics

- incoherent fluctuations
- fluctuations spread
- spectrum is broad
- power-law decrease

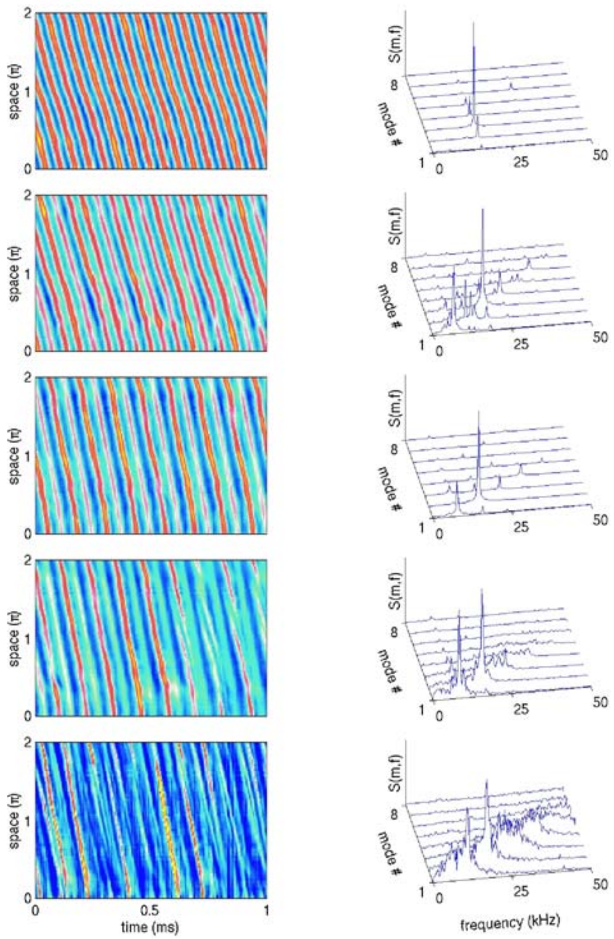
A transition to turbulence

control parameter

$$\epsilon = \frac{U_g - U_{gc}}{U_g}$$

separation grid bias

onset drift wave



⑧-t - diagram **spectrum**

increas of grid bias

increase of plasma current

A transition to turbulence

$\varepsilon = 0.13$

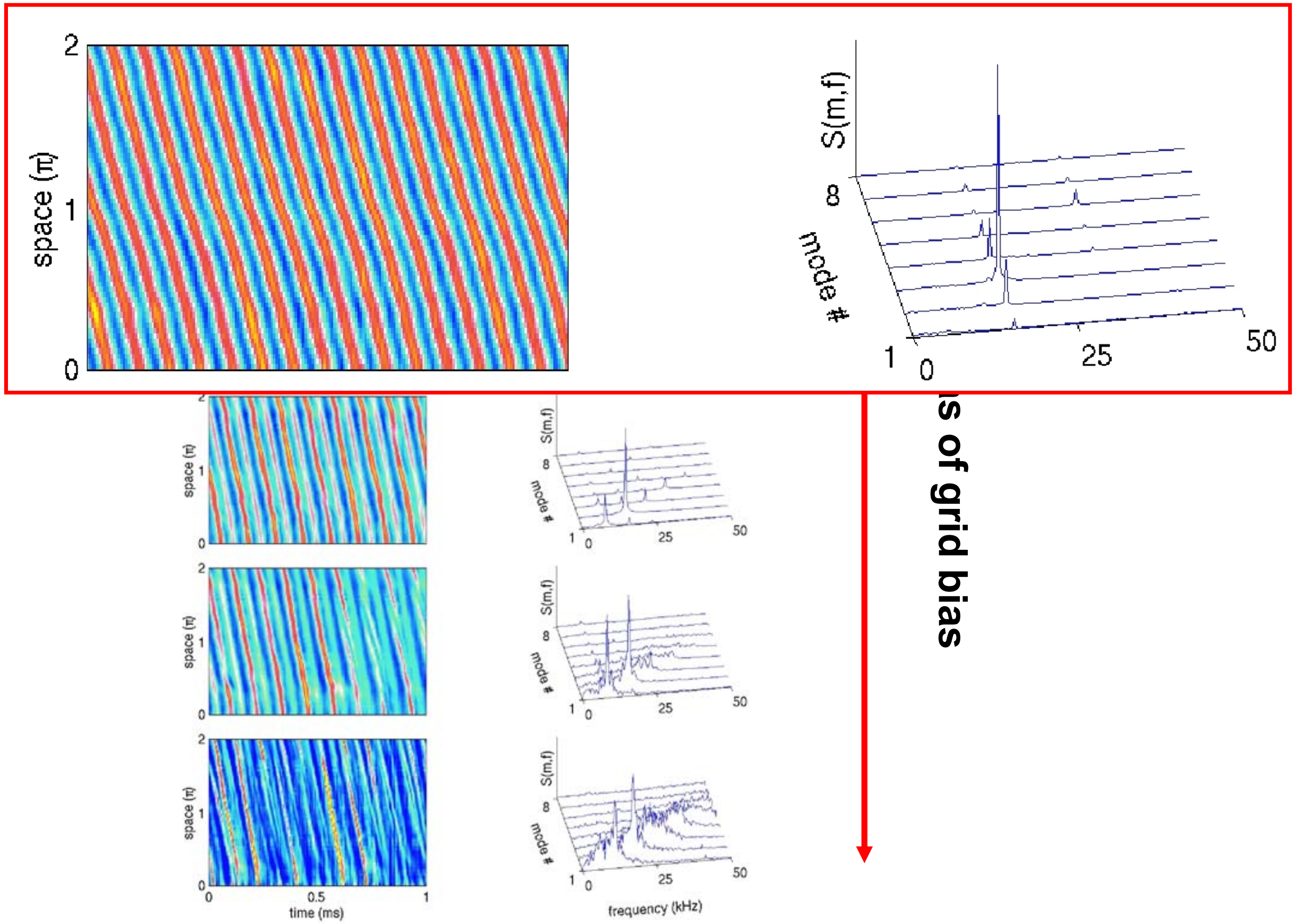
m=3 mode

$\varepsilon = 0.49$

$\varepsilon = 0.62$

$\varepsilon = 0.75$

$\varepsilon = 1.01$



ϑ-t - diagram

spectrum

A transition to turbulence

$\varepsilon = 0.13$

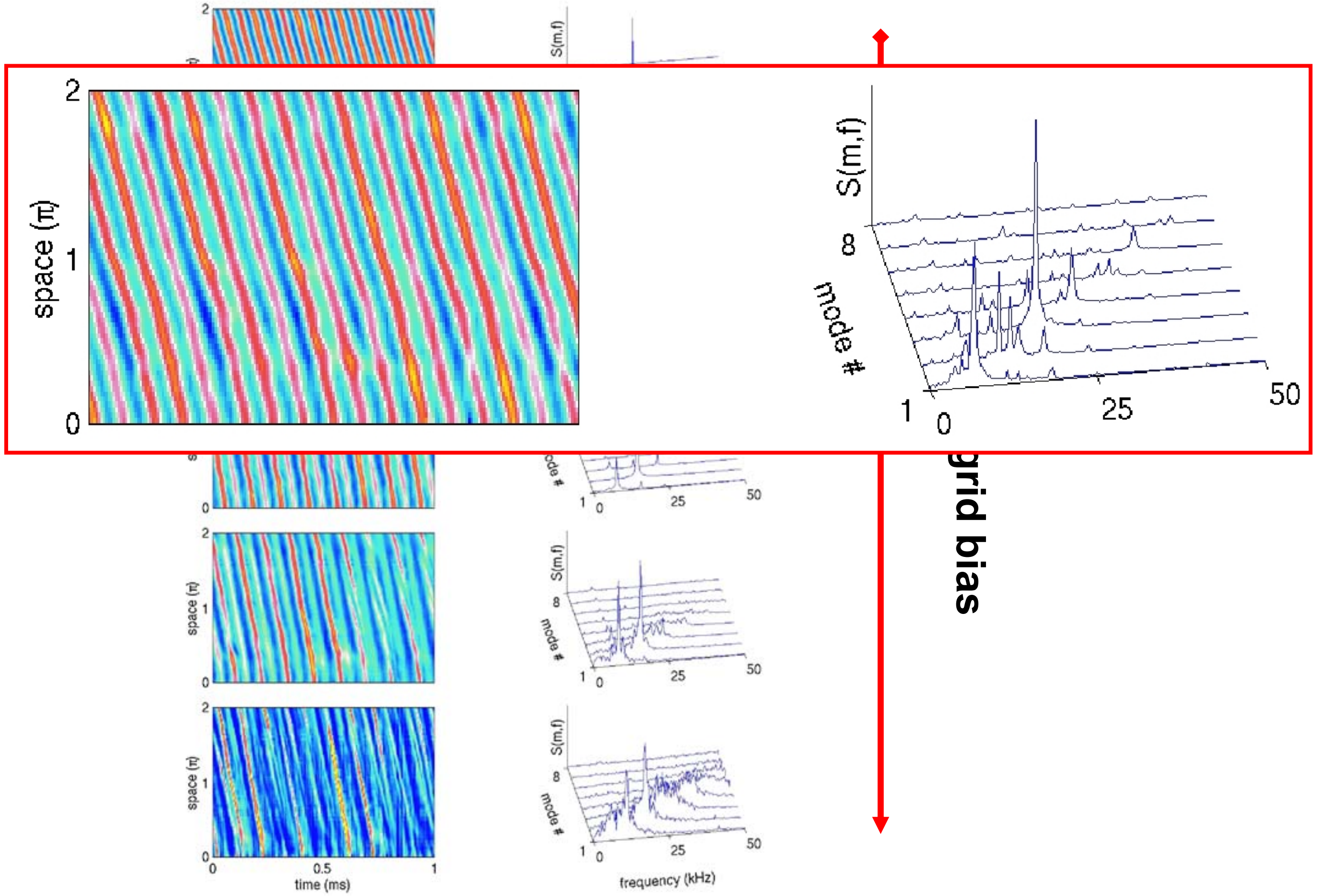
$\varepsilon = 0.49$

2 **modes**

$\varepsilon = 0.62$

$\varepsilon = 0.75$

$\varepsilon = 1.01$



⑧-t - **diagram** **spectrum**

A transition to turbulence

$\varepsilon = 0.13$

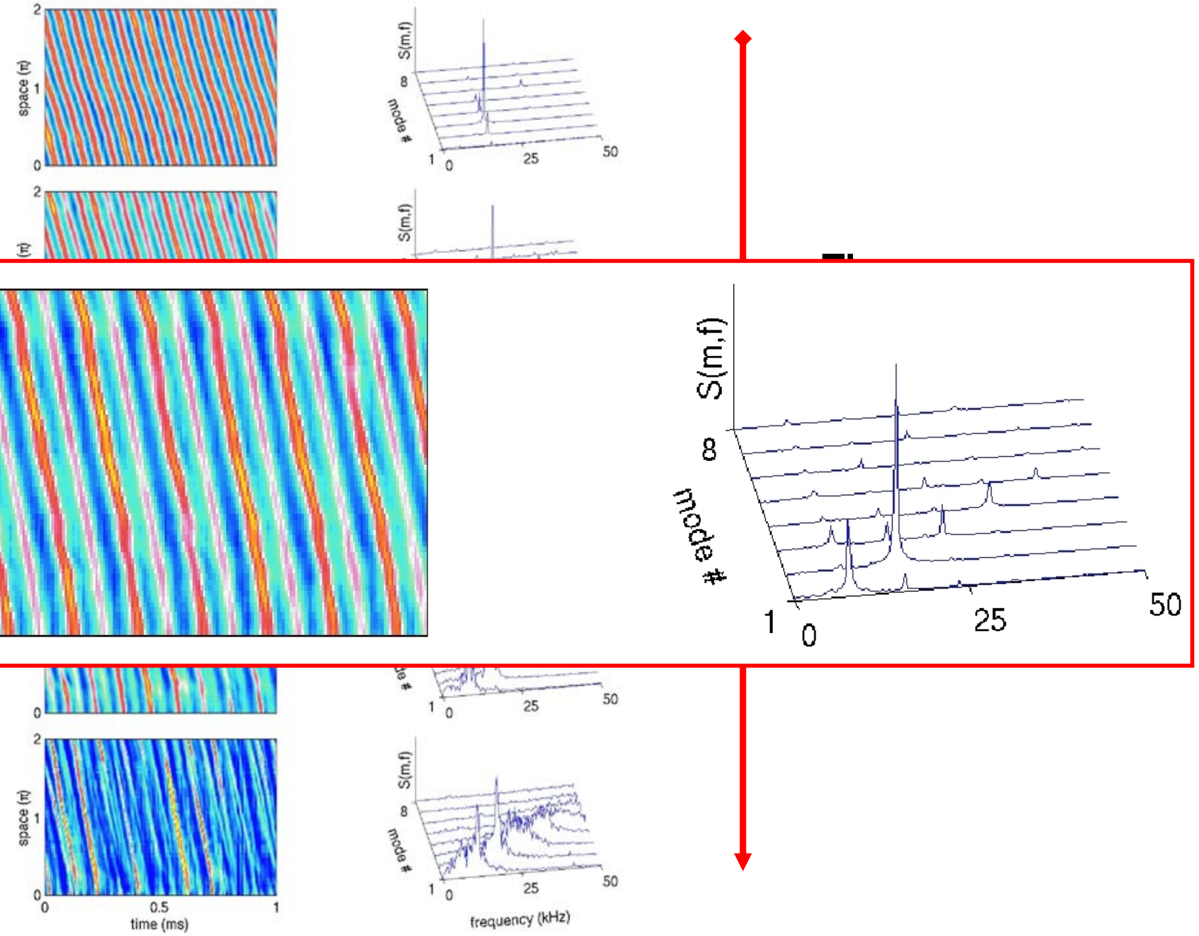
$\varepsilon = 0.49$

$\varepsilon = 0.62$

mode-lock

$\varepsilon = 0.75$

$\varepsilon = 1.01$



θ-t - **diagram** **spectrum**

A transition to turbulence

$\varepsilon = 0.13$

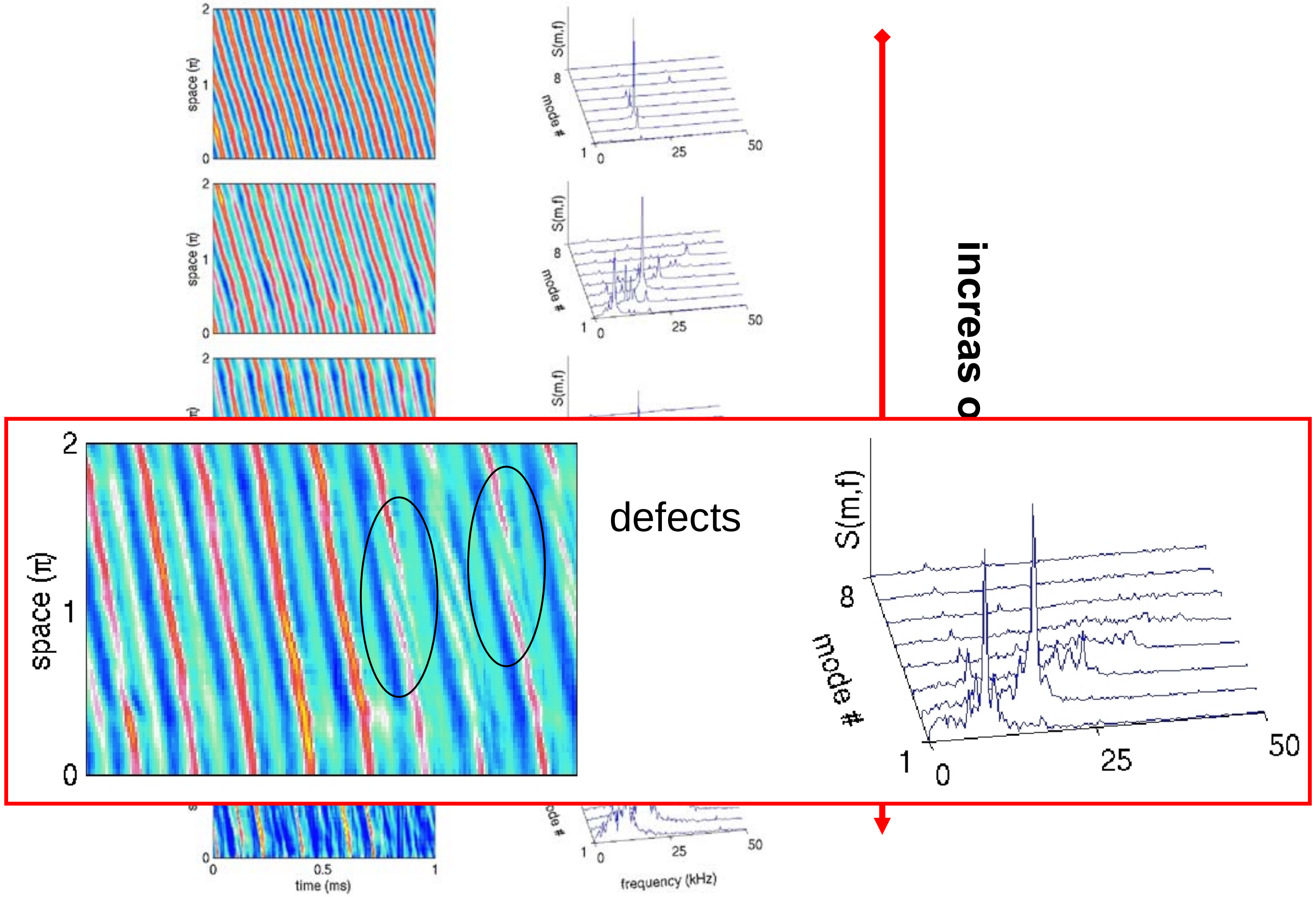
$\varepsilon = 0.49$

$\varepsilon = 0.62$

$\varepsilon = 0.75$

chaos

$\varepsilon = 1.01$



ϑ-t - diagram   spectrum

A transition to turbulence

$\varepsilon = 0.13$

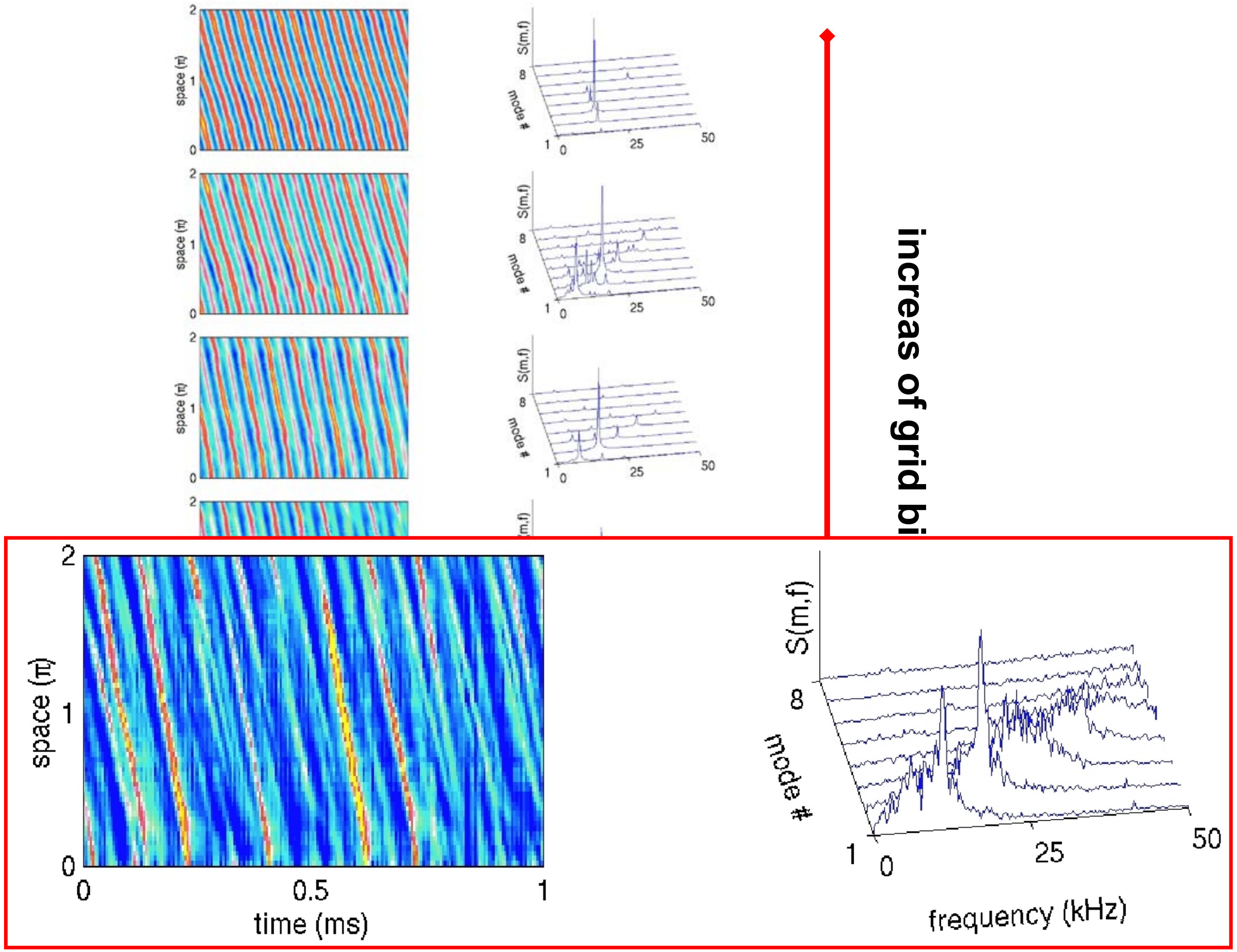
$\varepsilon = 0.49$

$\varepsilon = 0.62$

$\varepsilon = 0.75$

$\varepsilon = 1.01$

turbulence



„weak“ drift wave turbulence

- **Phase space analysis ◆ dimension, stability ✱ scenario**

  T.K. et al., PRL 79, 3913 (1997), Plasma Phys. Controlled Fusion 39, B145 (1997)

- **Ruelle-Takens-Newhouse (RTN) transition scenario**

  Newhouse, Ruelle, Takens, Commun. Math. Phys. 64, 35 (1978)

- **RTN was already found in earlier drift wave models**

  Wersinger, Finn, Ott, Phys. Fluids 23, 1142 (1980)
  Biskamp, He, Phys. Fluids 28, 2172 (1985)

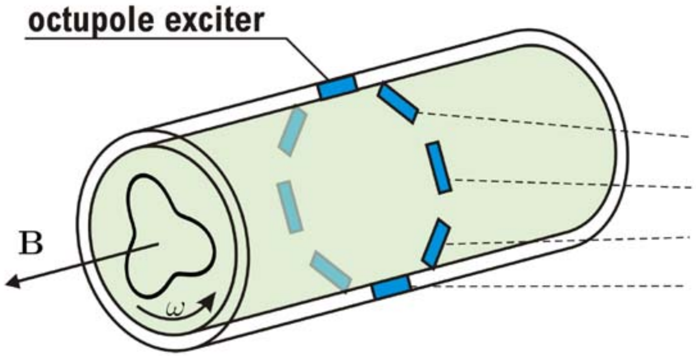
- **Drift wave chaos exists in transition regime only**

  - turbulence is high-dimensional D~100
  - phase space analysis impossible

- **Quick transition to weakly developed turbulence**

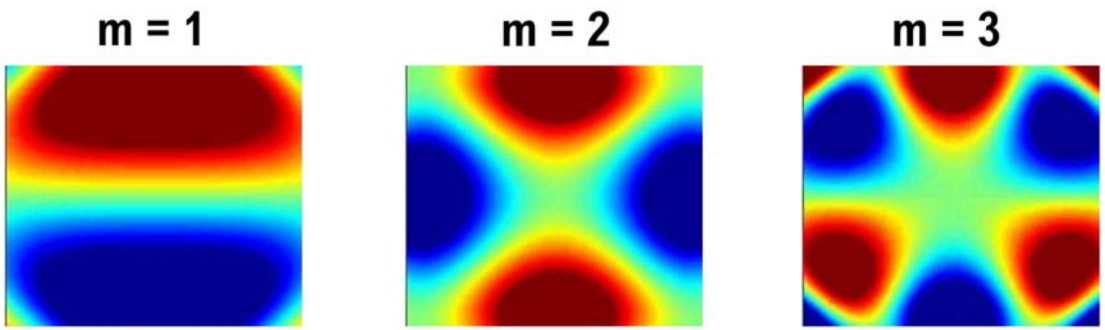
  Manneville, Dissipative Structures and Weak Turbulence, Academic Press 1990

Control of drift wave turbulence



$$
\begin{aligned}
U_1 &= A\sin(\omega t) \\
U_2 &= A\sin(\omega t + \delta) \\
U_3 &= A\sin(\omega t + 2\delta) \\
U_4 &= A\sin(\omega t + 3\delta) \\
&\dots
\end{aligned}
$$

- **mode control by phase shift:** $\delta = \pm \frac{2\pi \cdot m}{8}$
- **Nyquist limit:** $m_{ex} < 4$



T.K., Schröder, Block et al., Phys. Plasmas 8, 1961 (2001)

Schröder, T.K., Block, Piel, Bonhomme, Naulin, Phys. Rev. Lett. 86, 5711 (2001)

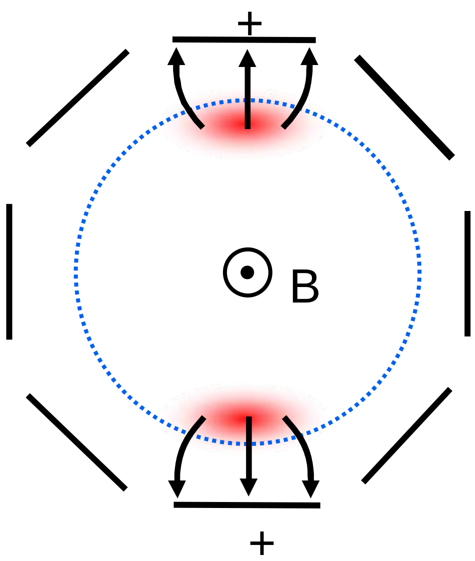
Model: rotating current profile

extended HW-model (2d)

$$\frac{\partial}{\partial t}\nabla_\perp^2\phi + \vec{V}_{E\times B}\cdot\nabla\nabla_\perp^2\phi = \tilde{\sigma}\left(\phi - n\right) - S + \mu_w\nabla_\perp^4\phi$$

$$\frac{\partial}{\partial t}n + \vec{V}_{E\times B}\cdot\nabla\left(N_0 + n\right) = \tilde{\sigma}\left(\phi - n\right) - S + \mu_n\nabla_\perp^2 n$$

$$S = A\sin(\pi r/r_0)\sin(m_d\Theta - \omega_d t)$$



- **rotating electron current profile** $|| B$
- **azimuthal mode structure (m=2)**
- **radial localisation**

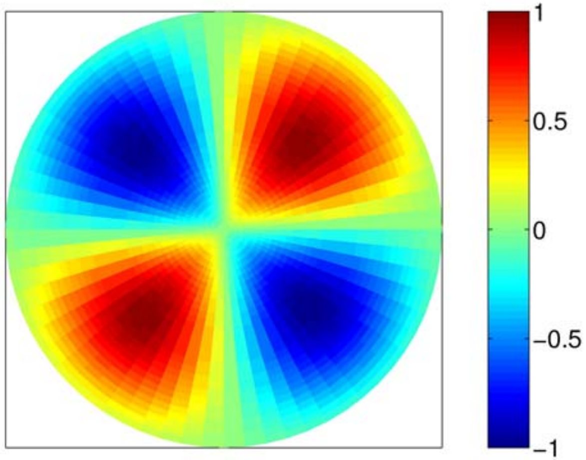
Model: rotating current profile

extended HW-model (2d)

$$\frac{\partial}{\partial t}\nabla_\perp^2\phi + \vec{V}_{E\times B}\cdot\nabla\nabla_\perp^2\phi = \tilde{\sigma}\,(\phi - n) - S + \mu_w\nabla_\perp^4\phi$$

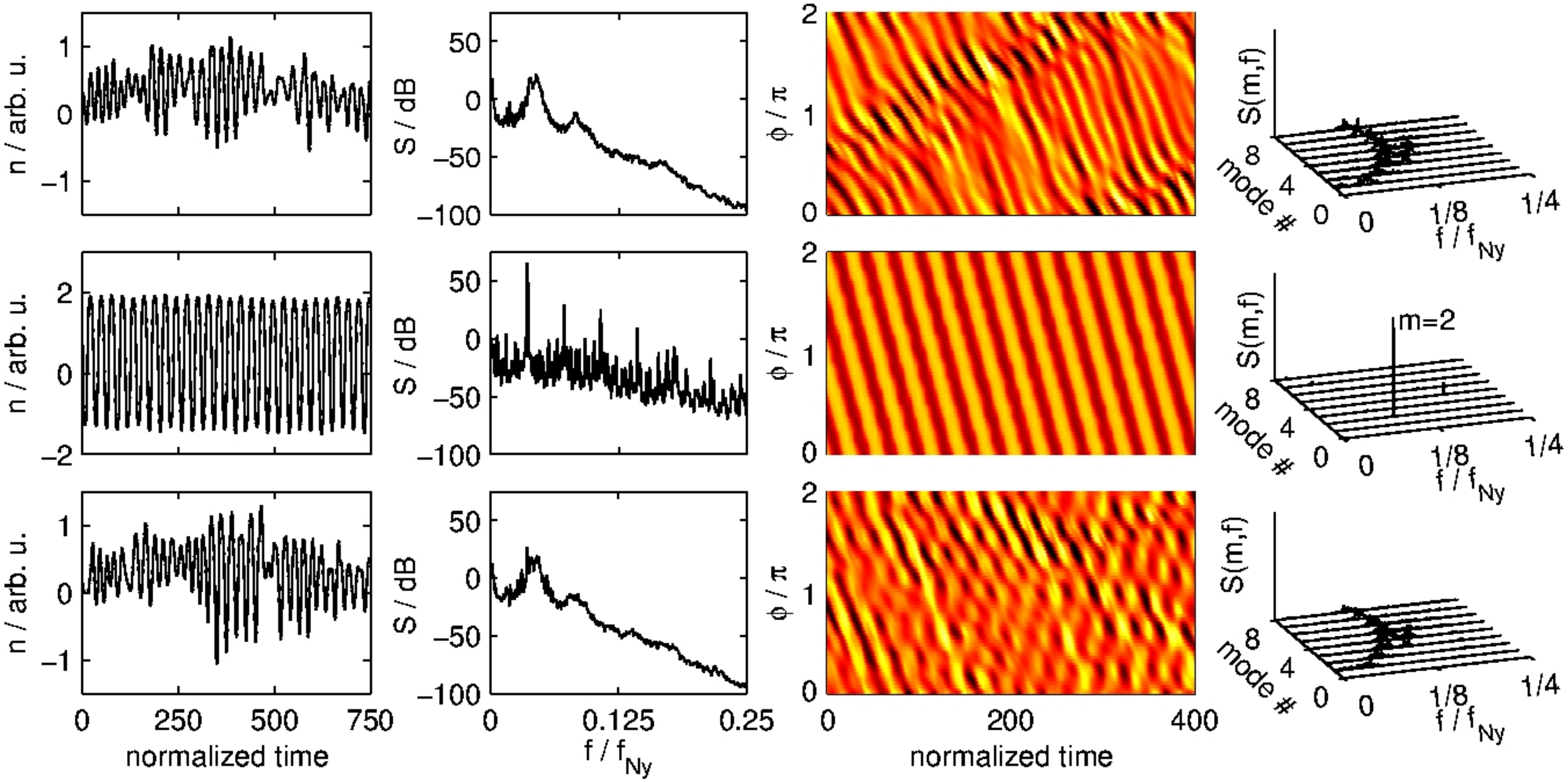
$$\frac{\partial}{\partial t}n + \vec{V}_{E\times B}\cdot\nabla\,(N_0 + n) = \tilde{\sigma}\,(\phi - n) - S + \mu_n\nabla_\perp^2 n$$

$$S = A\sin(\pi r/r_0)\sin(m_d\Theta - \omega_d t)$$



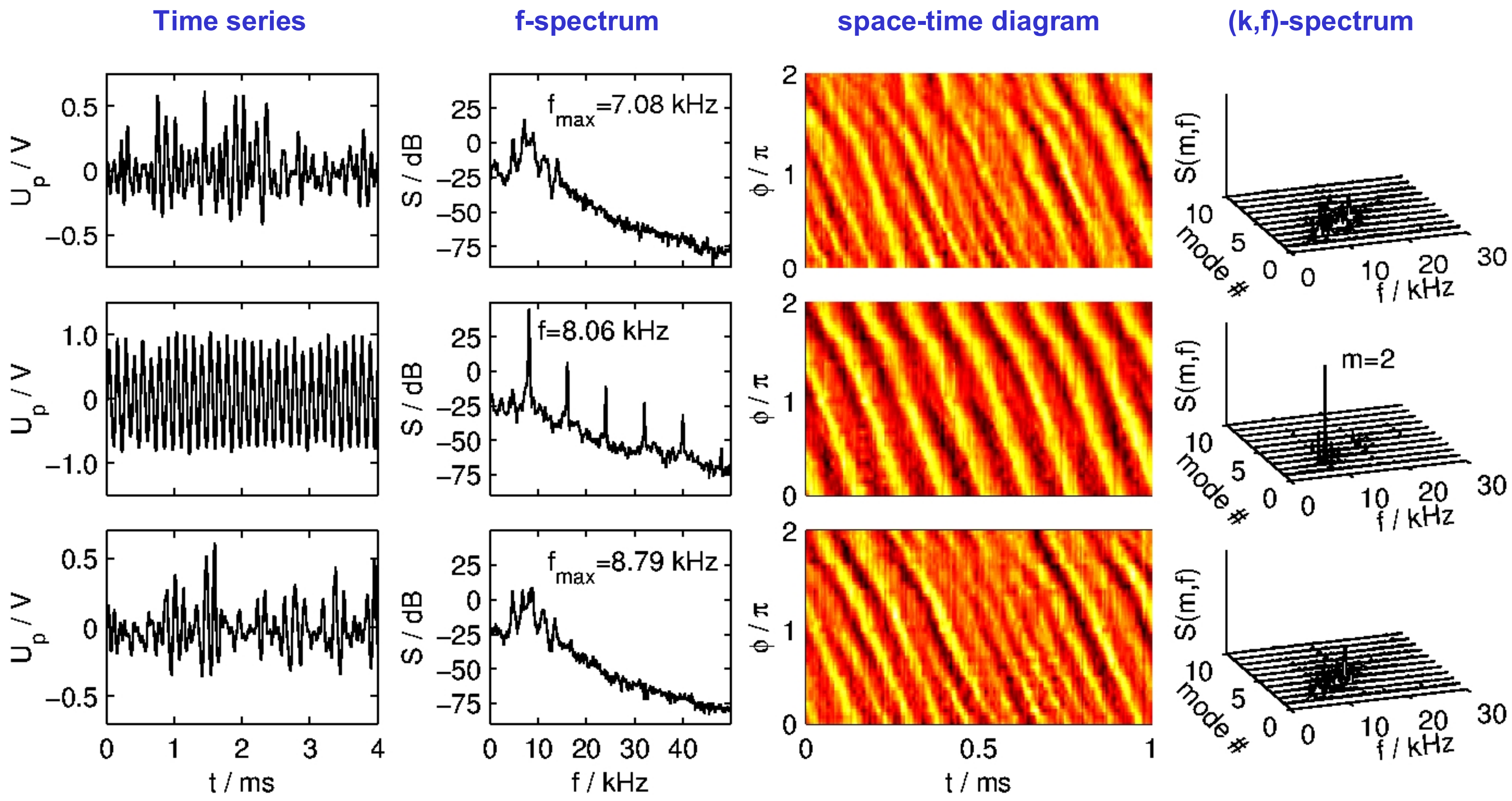
- **rotating electron current profile** $||\, B$
- **azimuthal mode structure (m=2)**
- **radial localisation**

Drift wave sync' - model



- no external field
- co-rotating field
- counter-rotating field

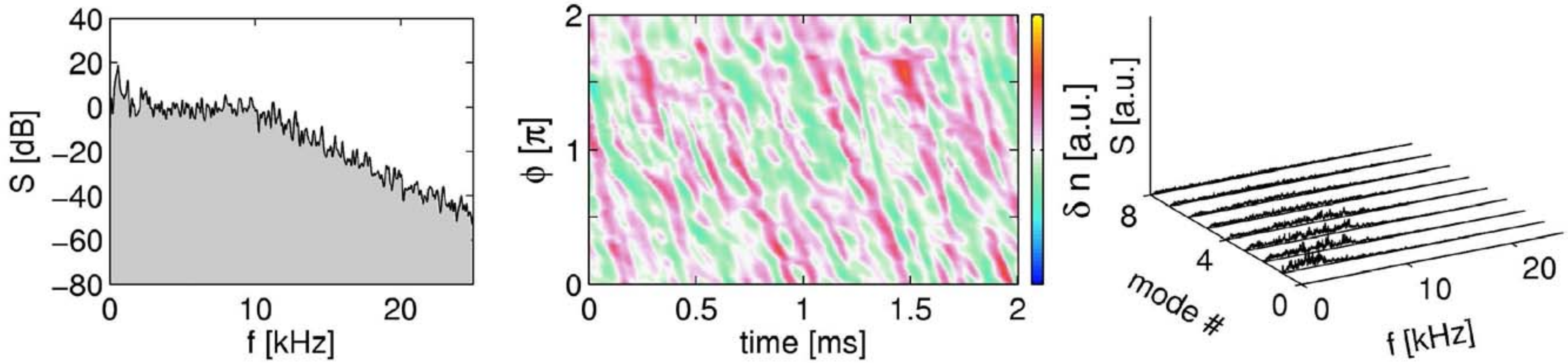
Drift wave sync' - experiment



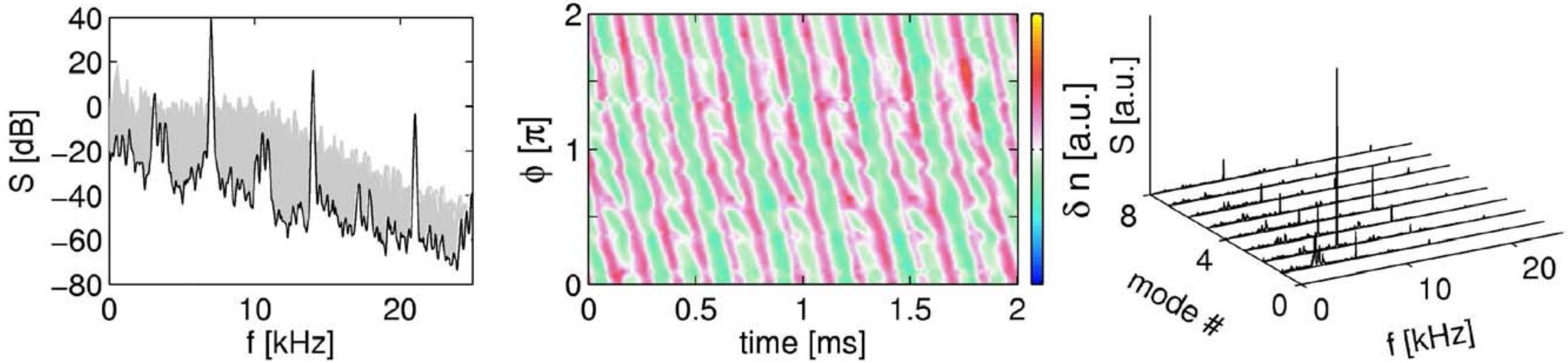
- no external field
- co-rotating field
- counter-rotating field

Synchronising turbulence

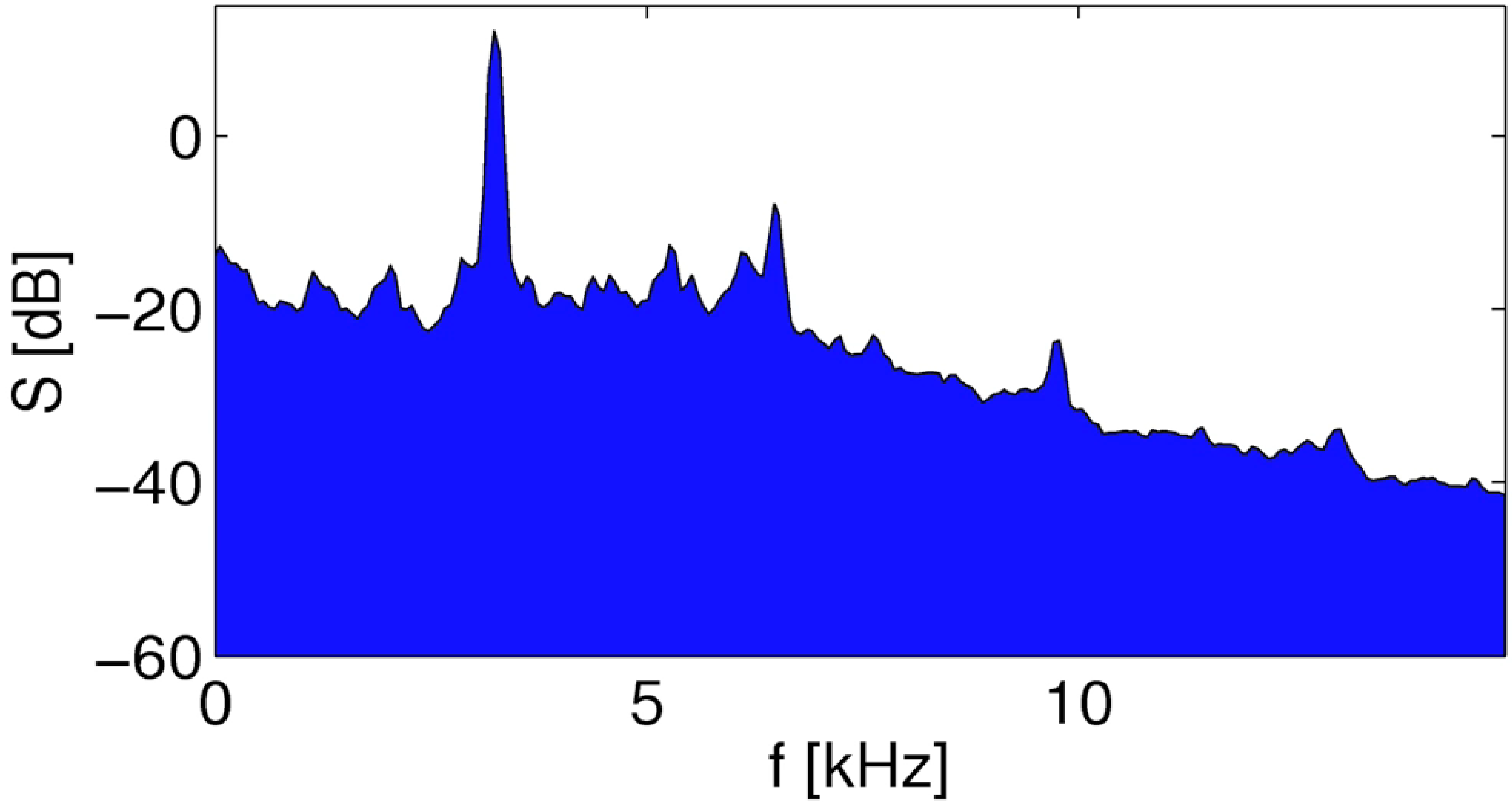
f-spectrum **spatiotemporal plot** **mode-f-spectrum**



V_{ex} = 20 V **f_{ex} = 8.4 kHz** **m_{ex} = 2**



Single mode synchronisation

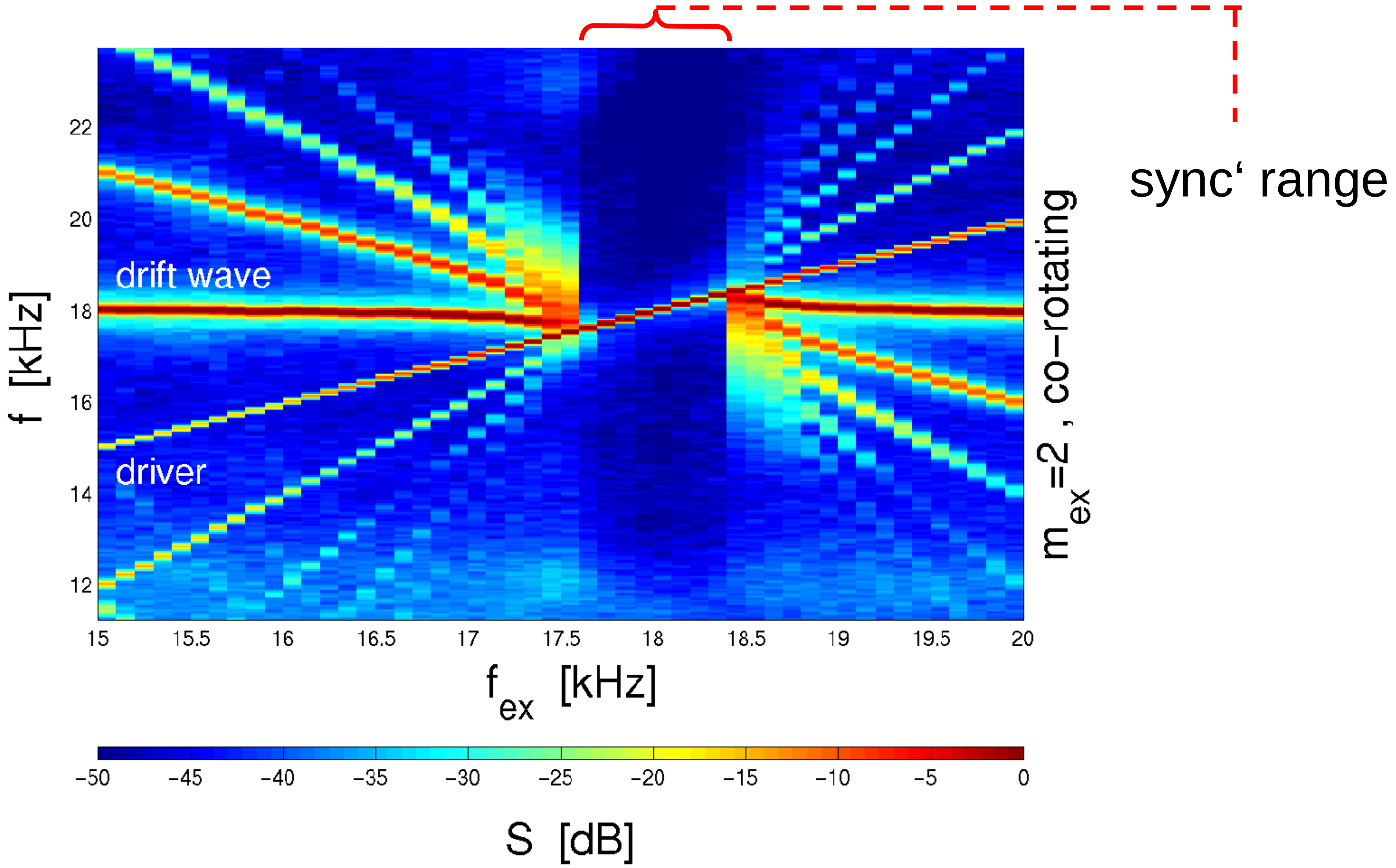


without external drive

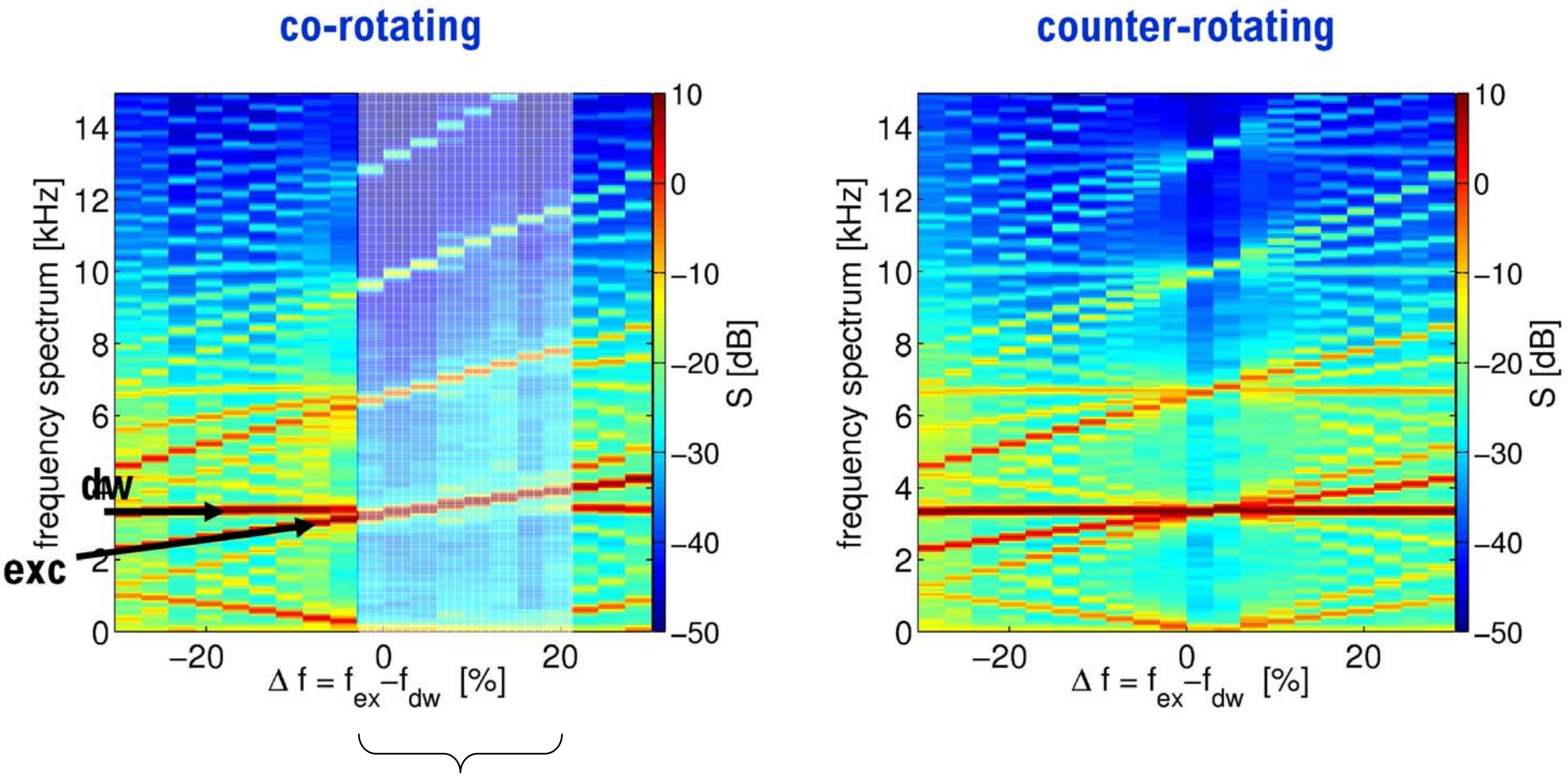
with external drive

movie

Single mode synchronisation

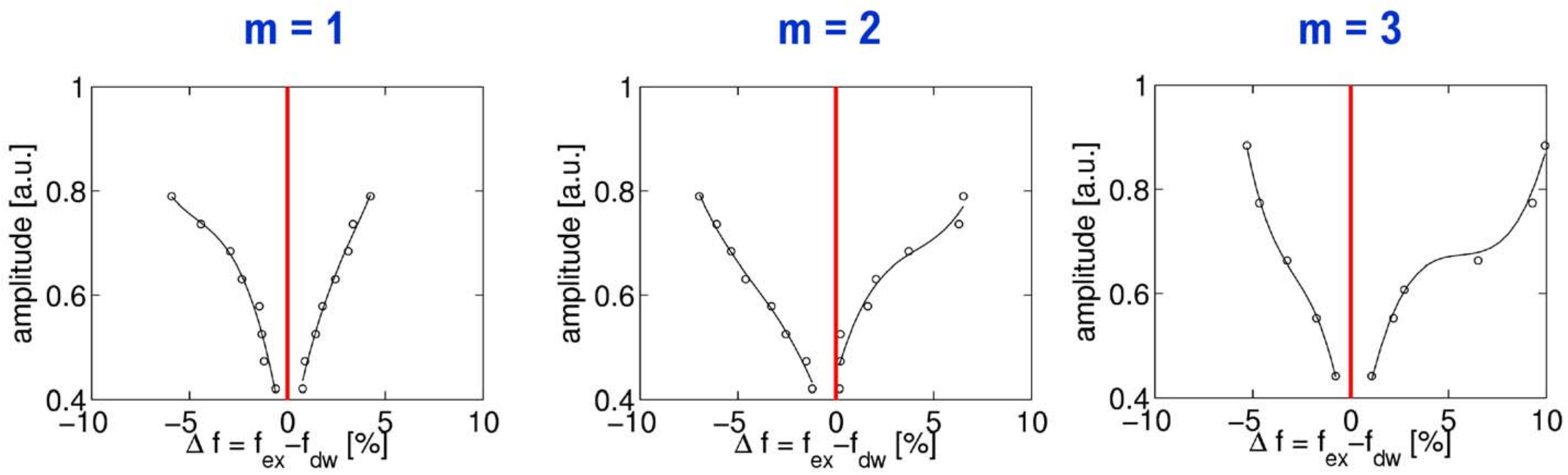


Single mode synchronisation



synchronisation range

Arnold‘d tongues



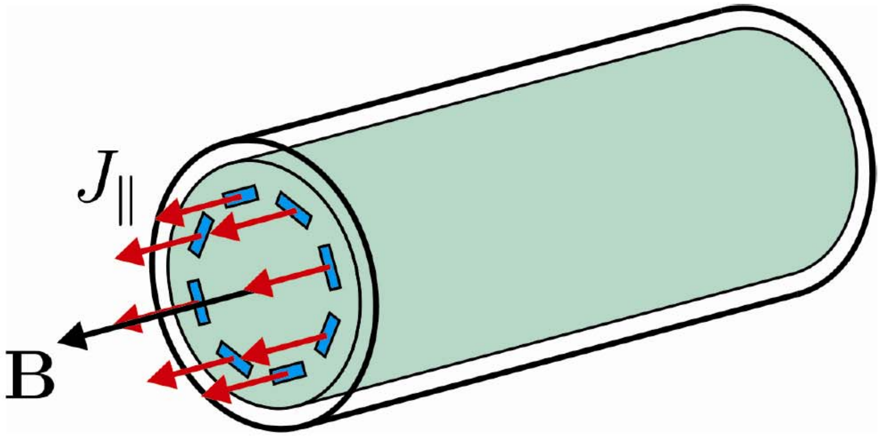
Summary of findings:

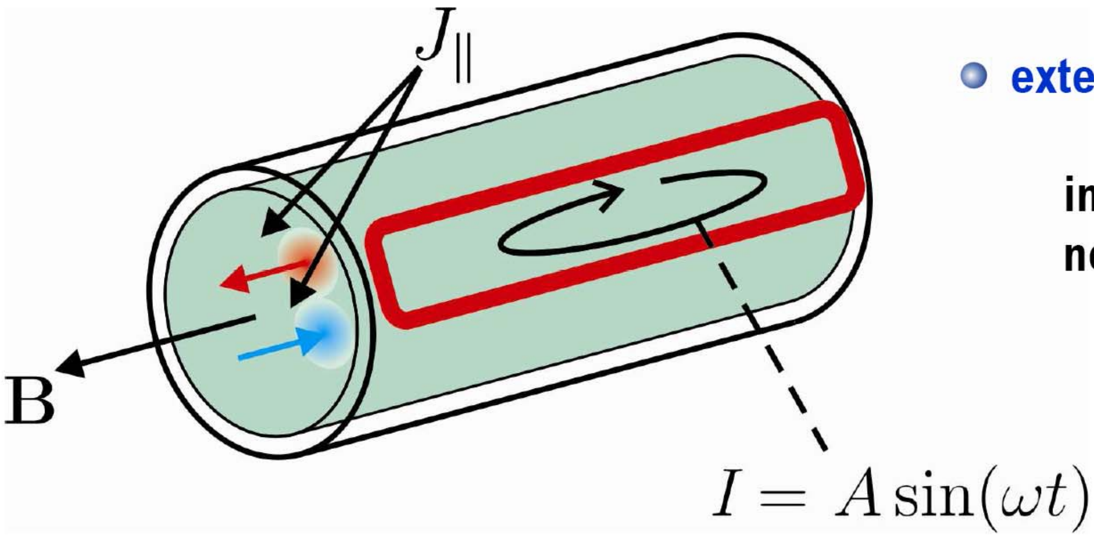
- **drift modes can be synchronised**
- **features very much like driven non-linear oscillator**
- **space-time modulation required**
- **mechanism: rotating || B current profile – at rest in wave frame**

Exciter schemes

- **electric exciter:**

  electrodes draw current
  direct contact with plasma





- **external magnetic field:**

  induction of parallel currents
  no contact with plasma

Conclusions

- **Drift waves are universal instabilities in magnetized plasmas**
- **Magnetic field geometry plays a significant role (not discussed)**
- **Linear space-time dynamics is well understood**
- **Non-linear models usually prodict fully developed turbulence**
- **Spatio-temporal chaos plays a role in the transition to turbulence**
- **Taming turbulence:**
  - **rotating electric (magnetic?) fields**
  - **synchronised drift mode on expense of turbulence**
  - **space-time oscillator behavior**

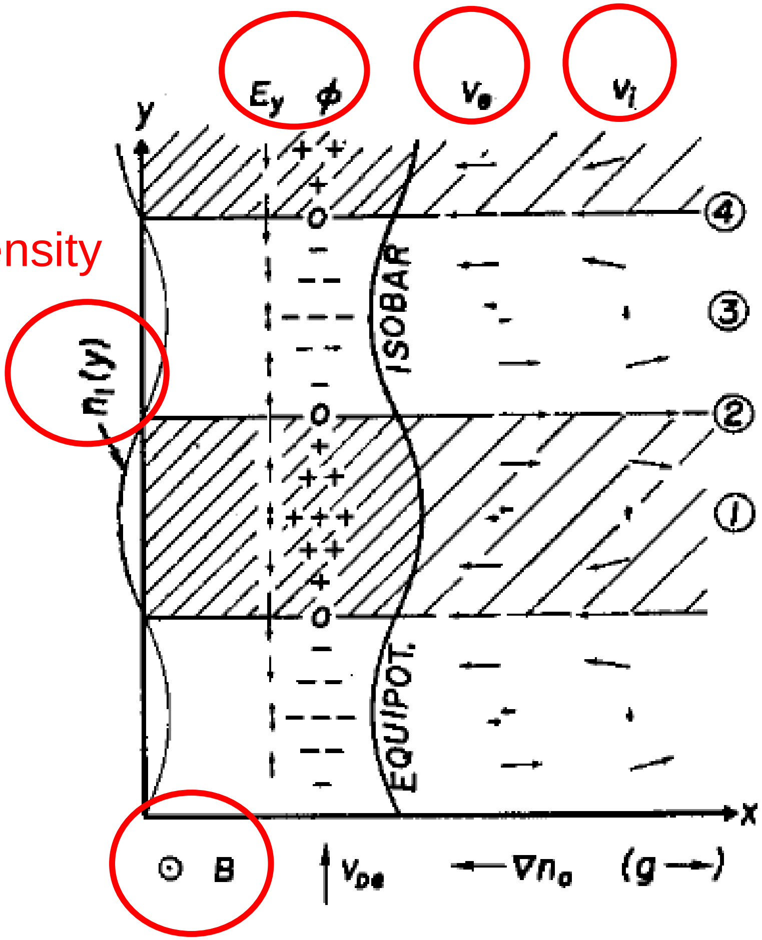
Credits to: O. Grulke, C. Schröder (MPI Greifswald); D. Block, A. Piel (U Kiel); G. Bonhomme (U Nancy); V. Naulin (Risoe); T. Dudok de Wit (U Orleans)

Drift wave basic elements

electric field
plasma potential

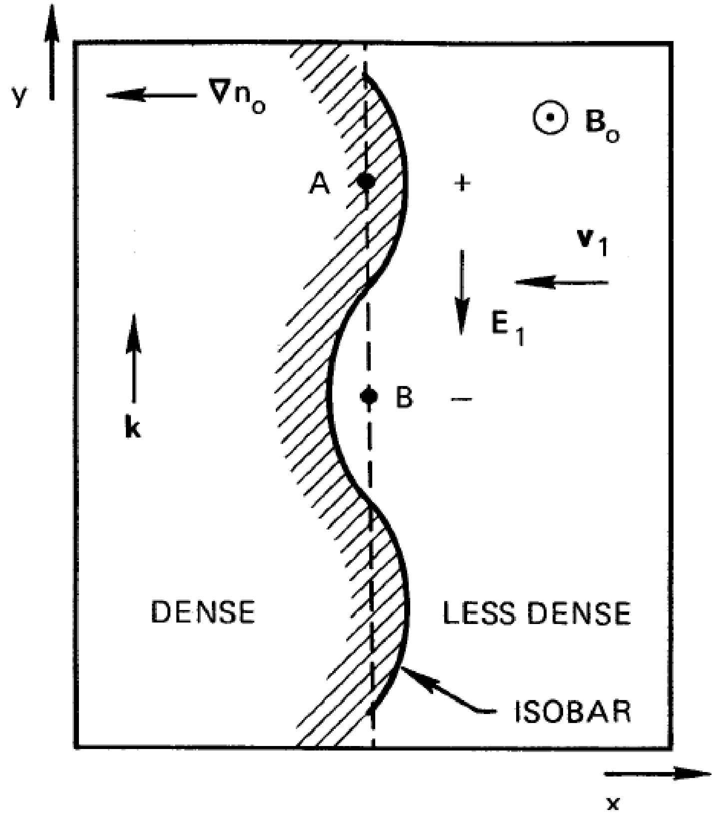
electron drift
ion drift

density



ambient magnetic field

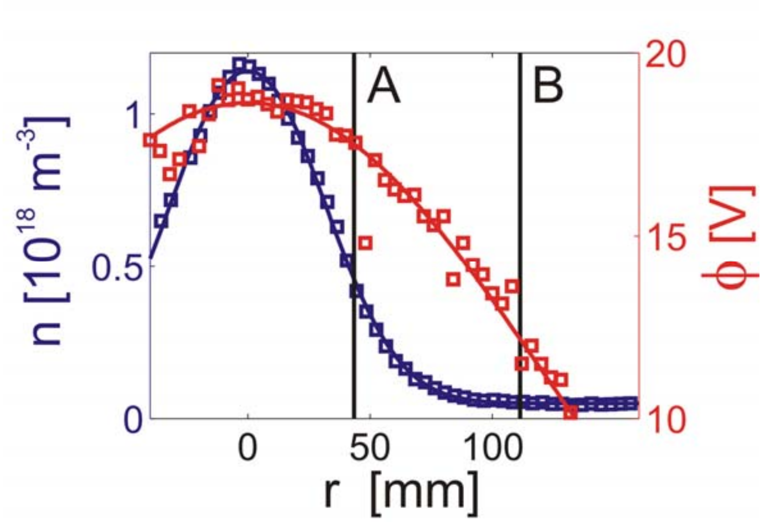
Chen, Phys. Fluids 8(5), 912 (1965)



simplified diagram

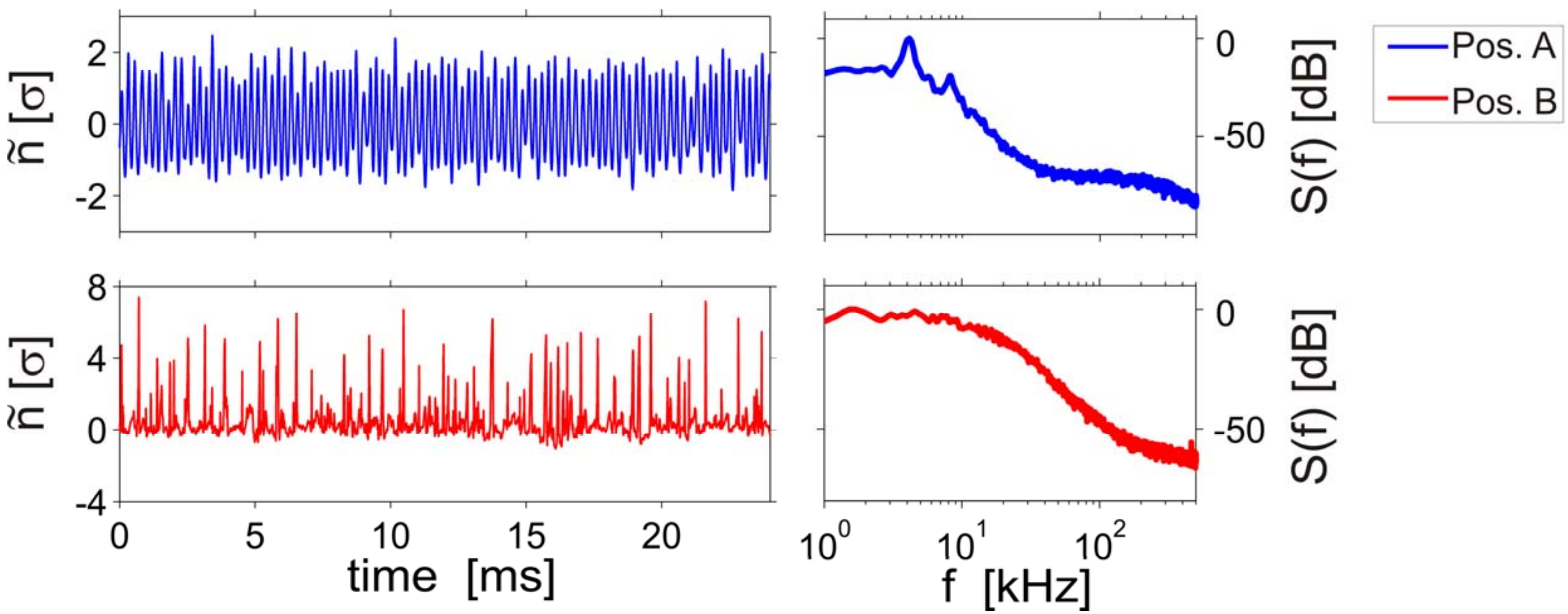
Chen, *Introduction to Plasma Physics*

Intermittency

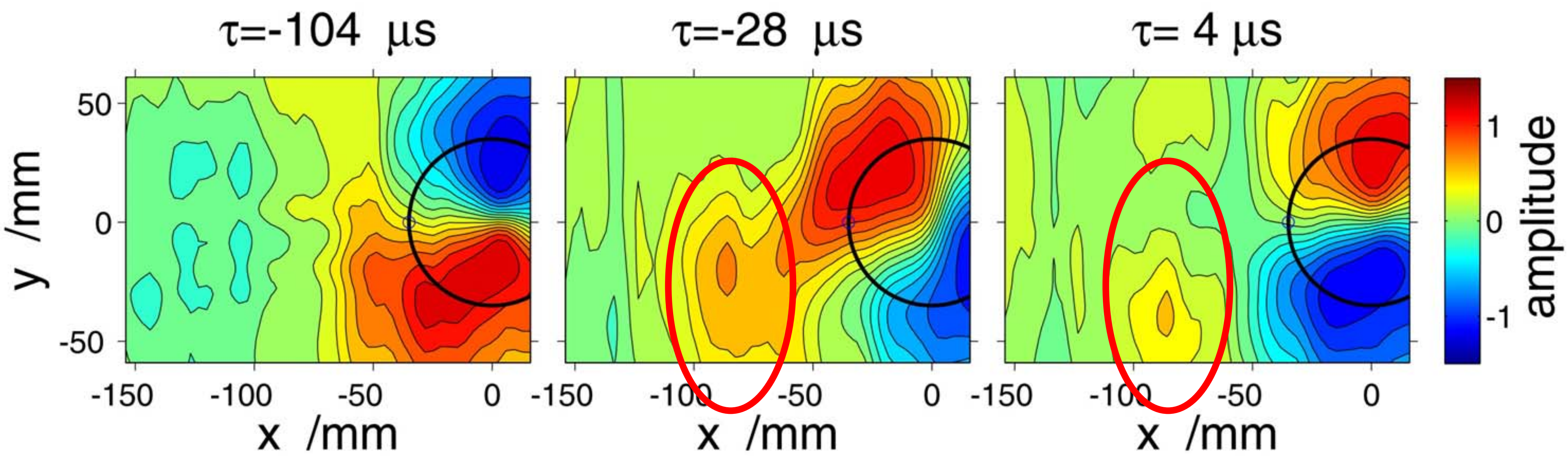


Observation:

- **quasi-coherent fluctuations in the gradient region**
- **strongly intermittent fluctuations in the far plasma edge**

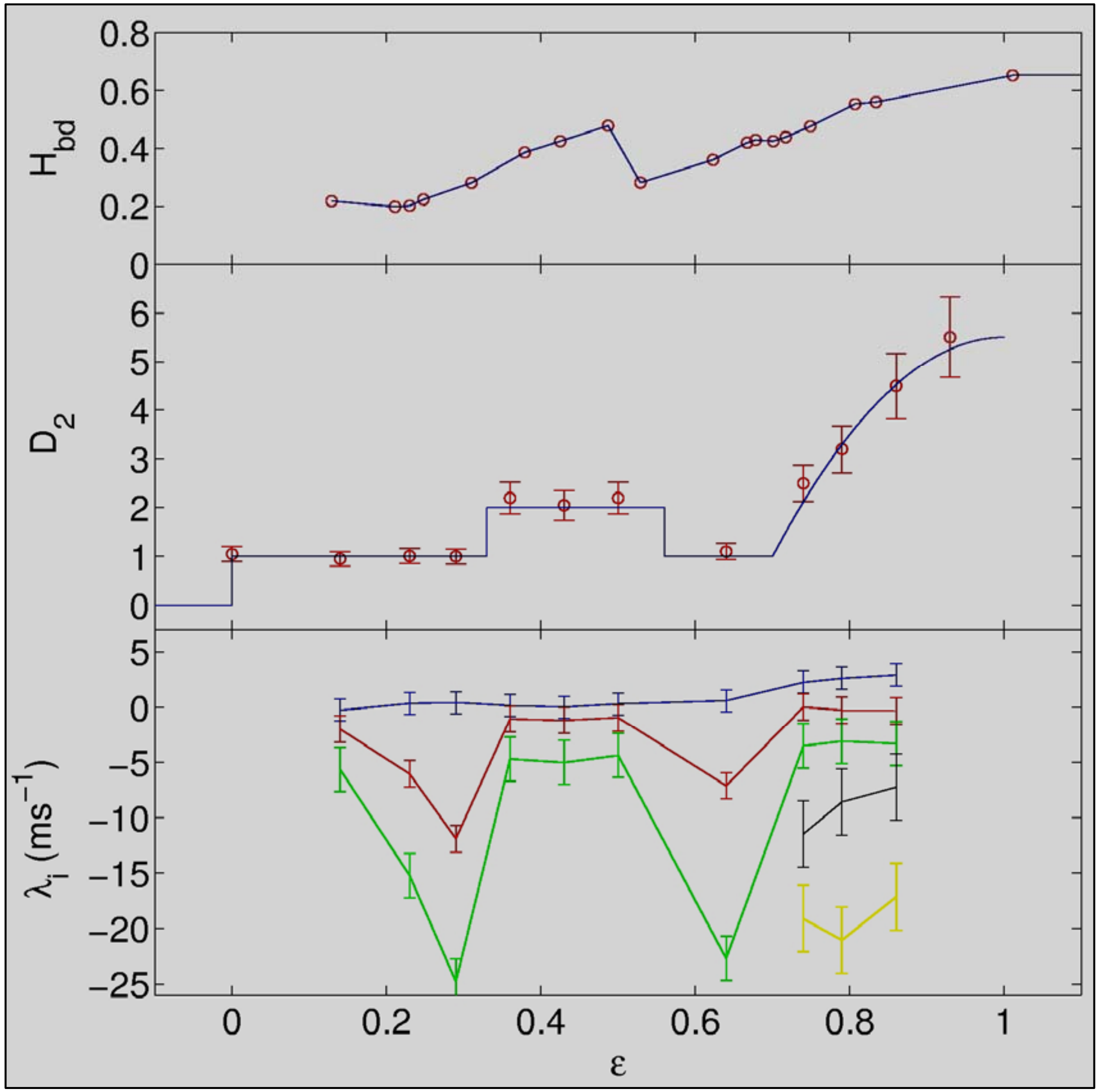


Intermittency



- conditional correlation analysis used to reconstruct spatiotemporal dynamics
- quasi-coherent m=1 mode pattern dominates
- mode-coupling analysis (bicoherence) suggests inverse energy transfer
- plasma peels-off and is transported into edge region

Phase space analysis



SVD entropy

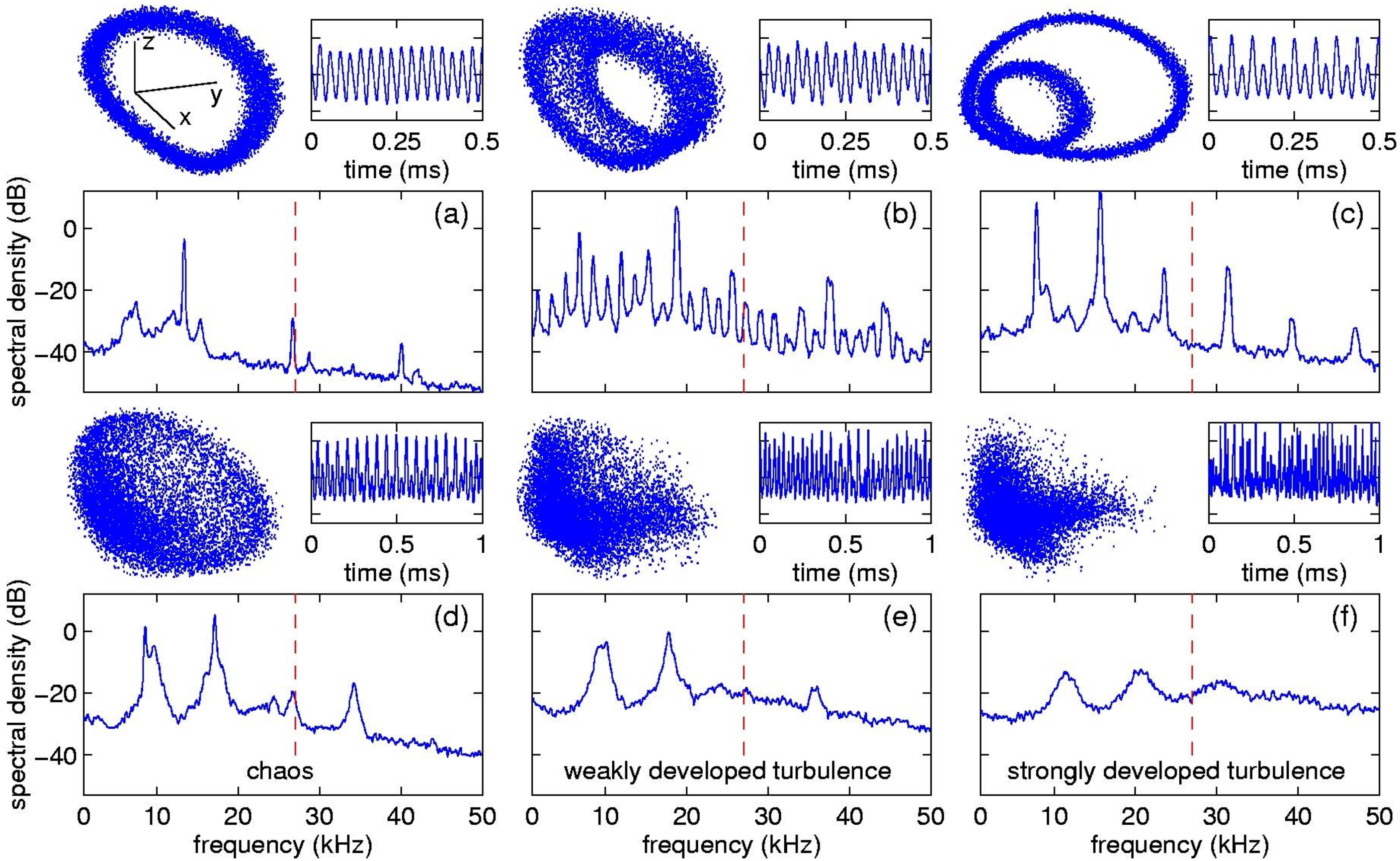
+

correlation dimension

+

Lyapunov exponents

Phase space



z
y
x
0
0.25
0.5
time (ms)
spectral density (dB)
0
−20
−40
(a)
(b)
(c)
0
0.5
1
time (ms)
(d)
(e)
(f)
chaos
weakly developed turbulence
strongly developed turbulence
0
10
20
30
40
50
frequency (kHz)