dynamics control in plasmas

the experimentalist‘s „point de vue“

I. Controlling chaos

II. Controlling noise

III. Controlling turbulence

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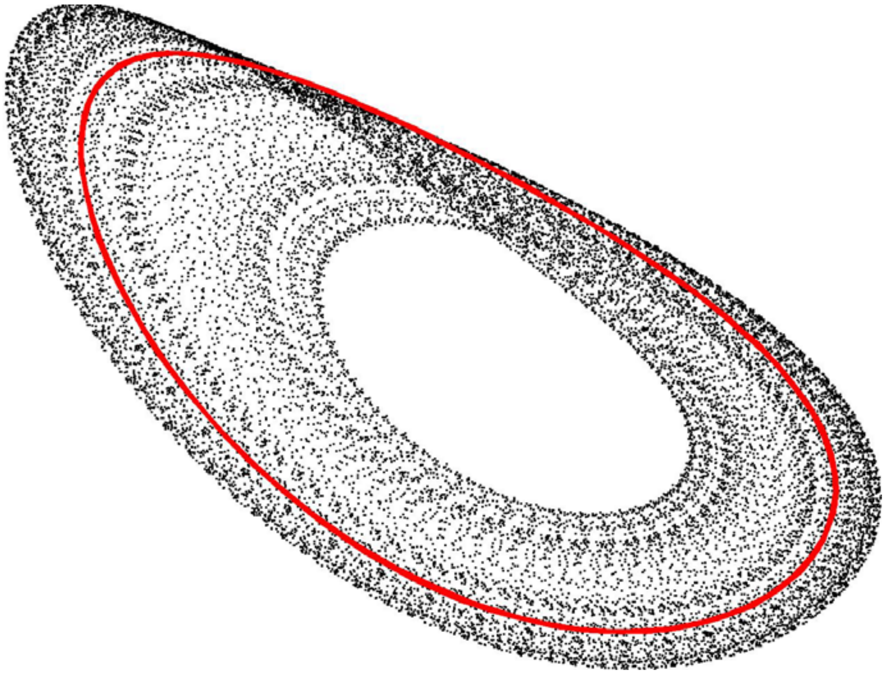
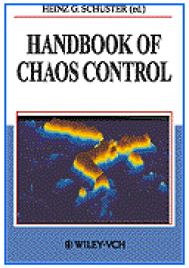
controlling chaos in plasmas



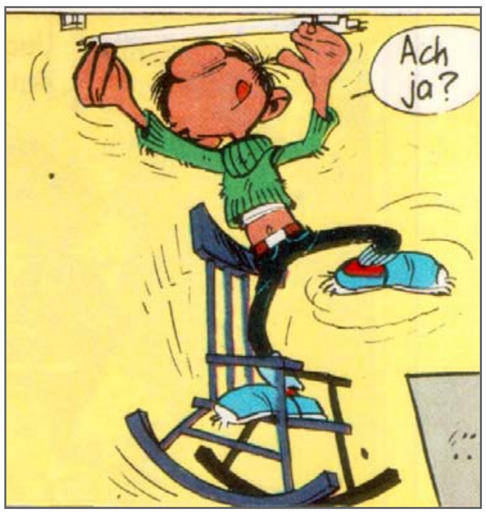
control of chaos - idea

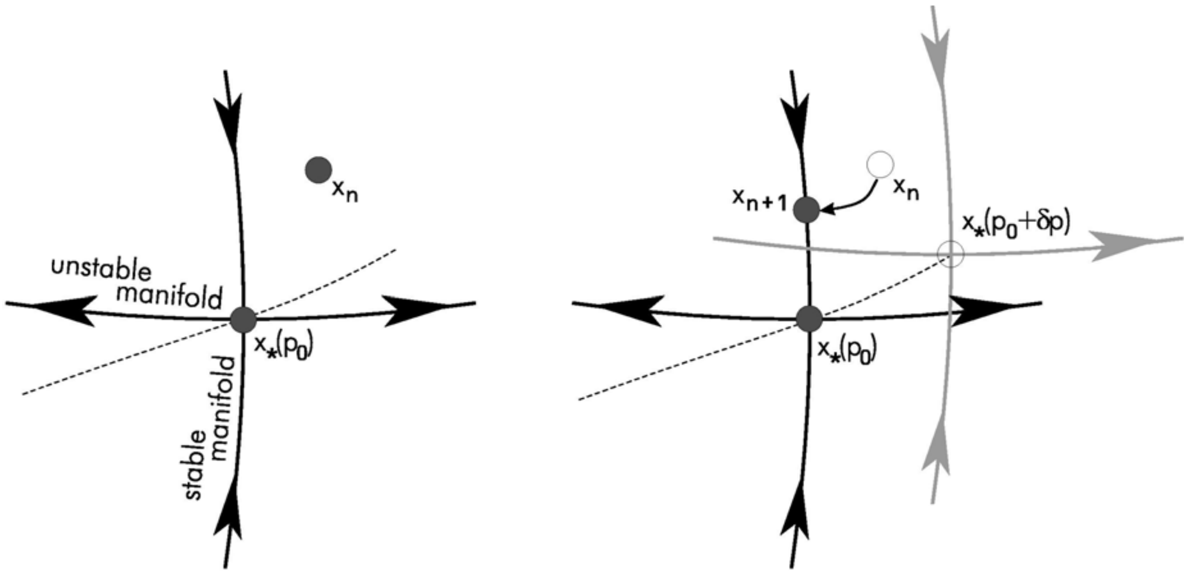


chaos = existence of unstable directions in phase space

control = stabilising unstable periodic orbits (UPOs)

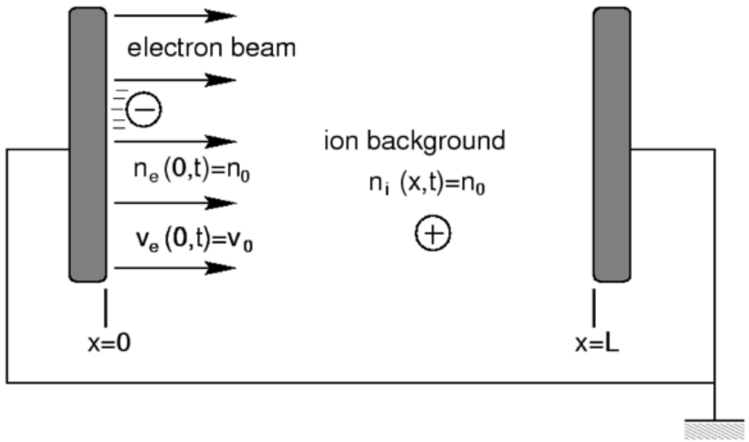
H. G. Schuster (Ed)
Handbook of Chaos Control
(VCH-Wiley 1999)





Ott, Grebogi, Yorke, *PRL* 64, 1196 (1990)

Pierce diode



toy model for plasma diode

- monoenergetic electron beam
- neutralising ion background
- surface charges on electrodes
- external circuit

1d electron fluid model

$$
\begin{aligned}
\partial_t n_e + \partial_x (n_e v_e) &= 0 \\
\partial_t v_e + v_e \partial_x v_e &= qE \\
\partial_x E &= \alpha^2 (n_i - n_e)
\end{aligned}
$$

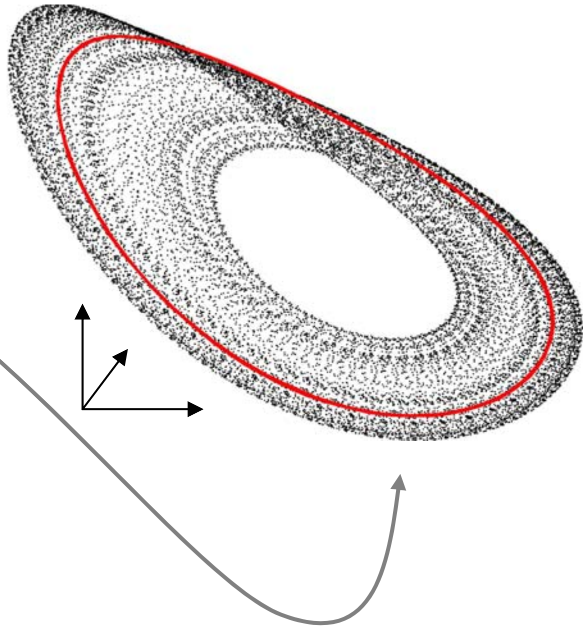
1d PIC simulation

- use XPDP1 (UC Berkeley)
- bounded plasmas code
- O(10000) particles

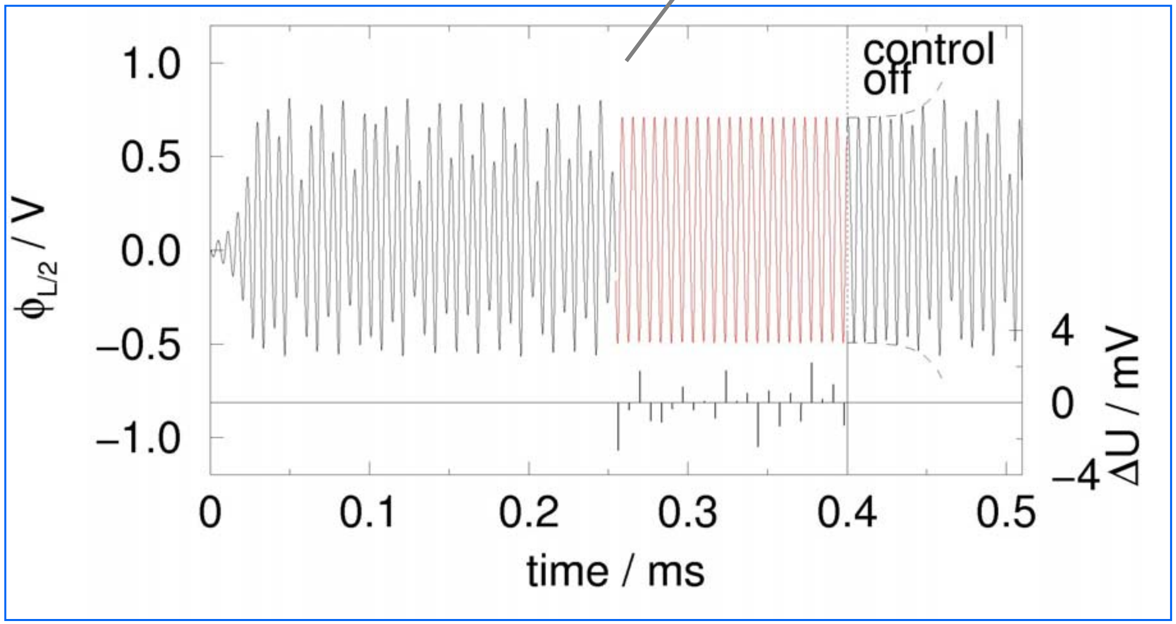
Pierce parameter $\alpha = \omega_{pe} L / v_0$ **control parameter**

chaos control

phase space contour



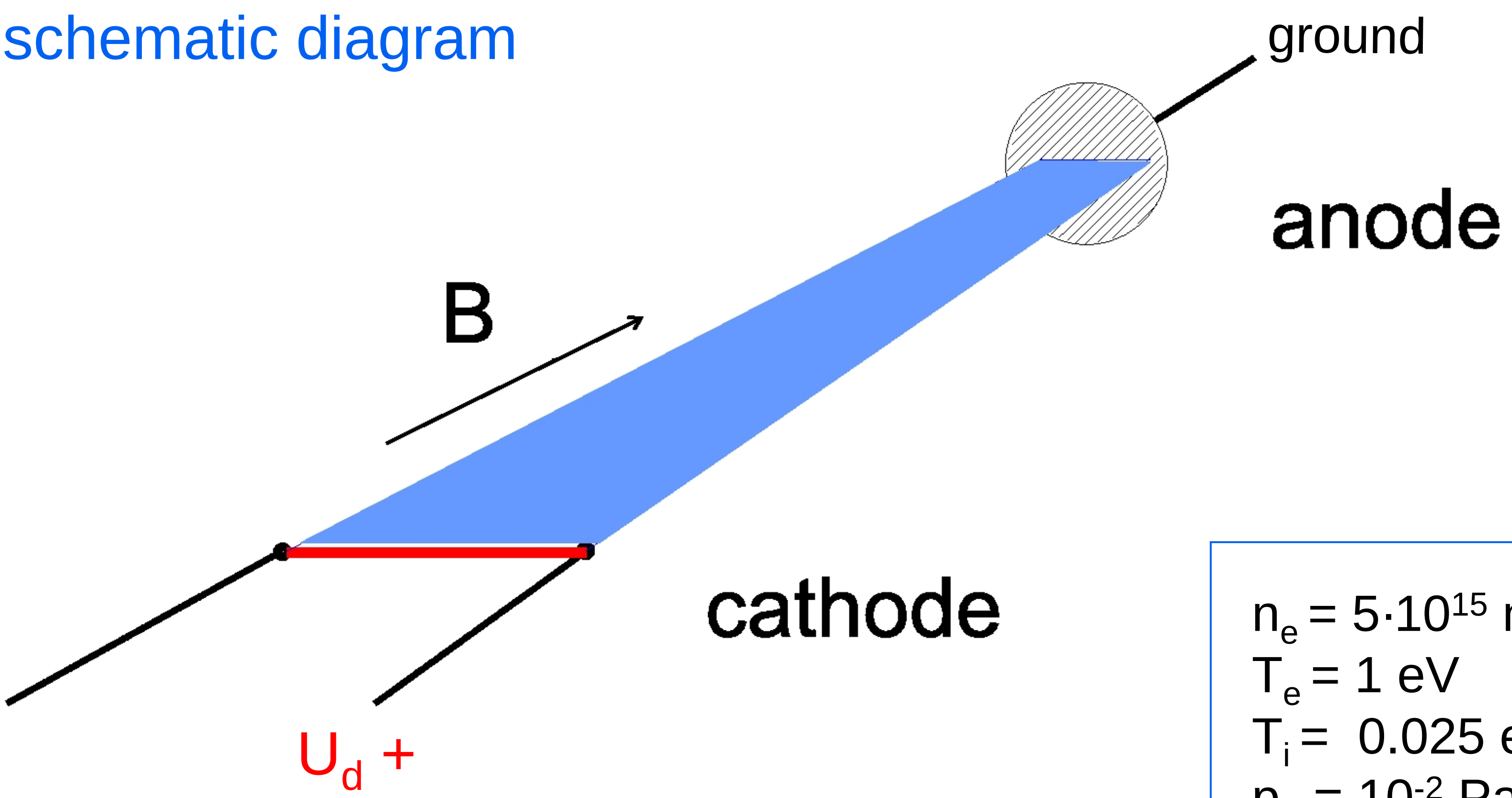
time series



Krahnstöver et al., *PLA* **239**, 103 (1998)

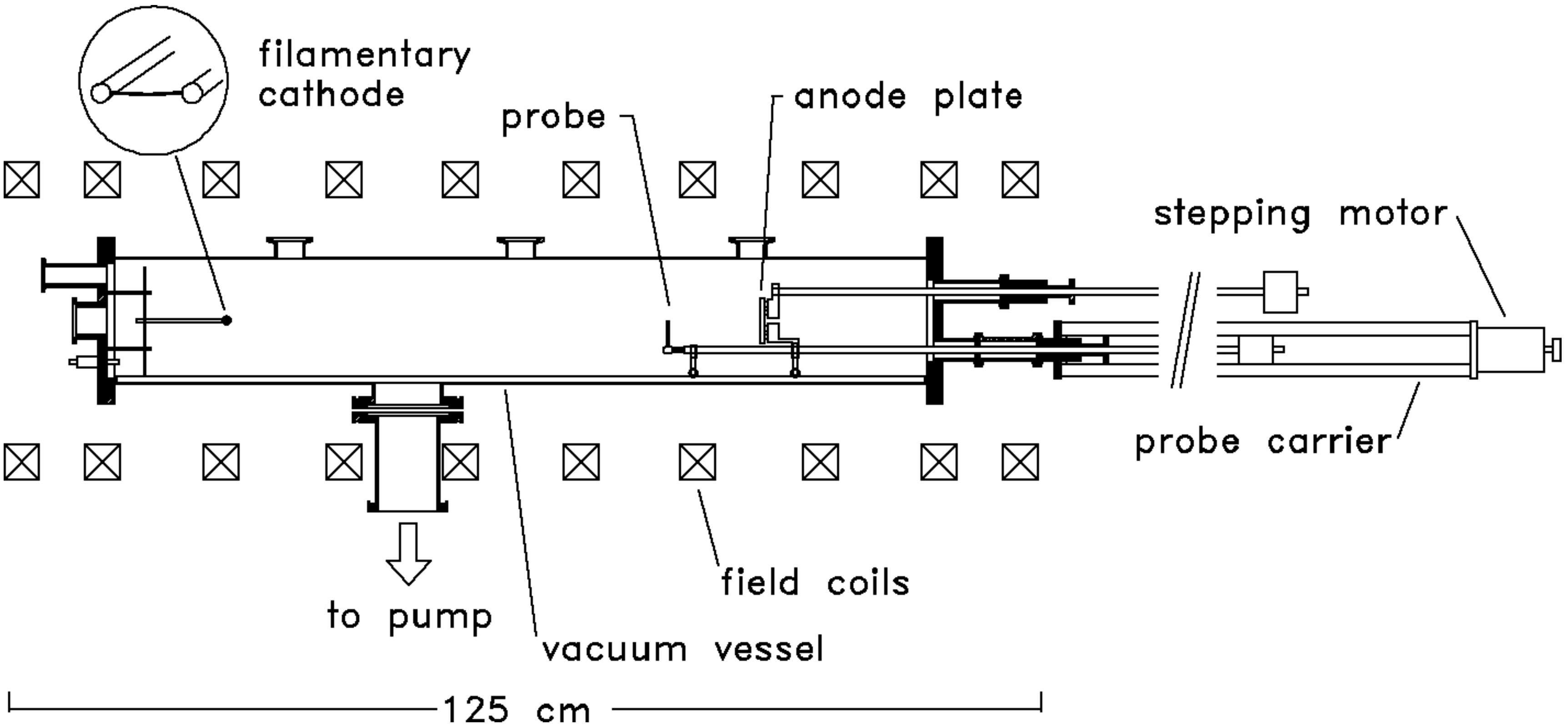
thermionic discharge

schematic diagram



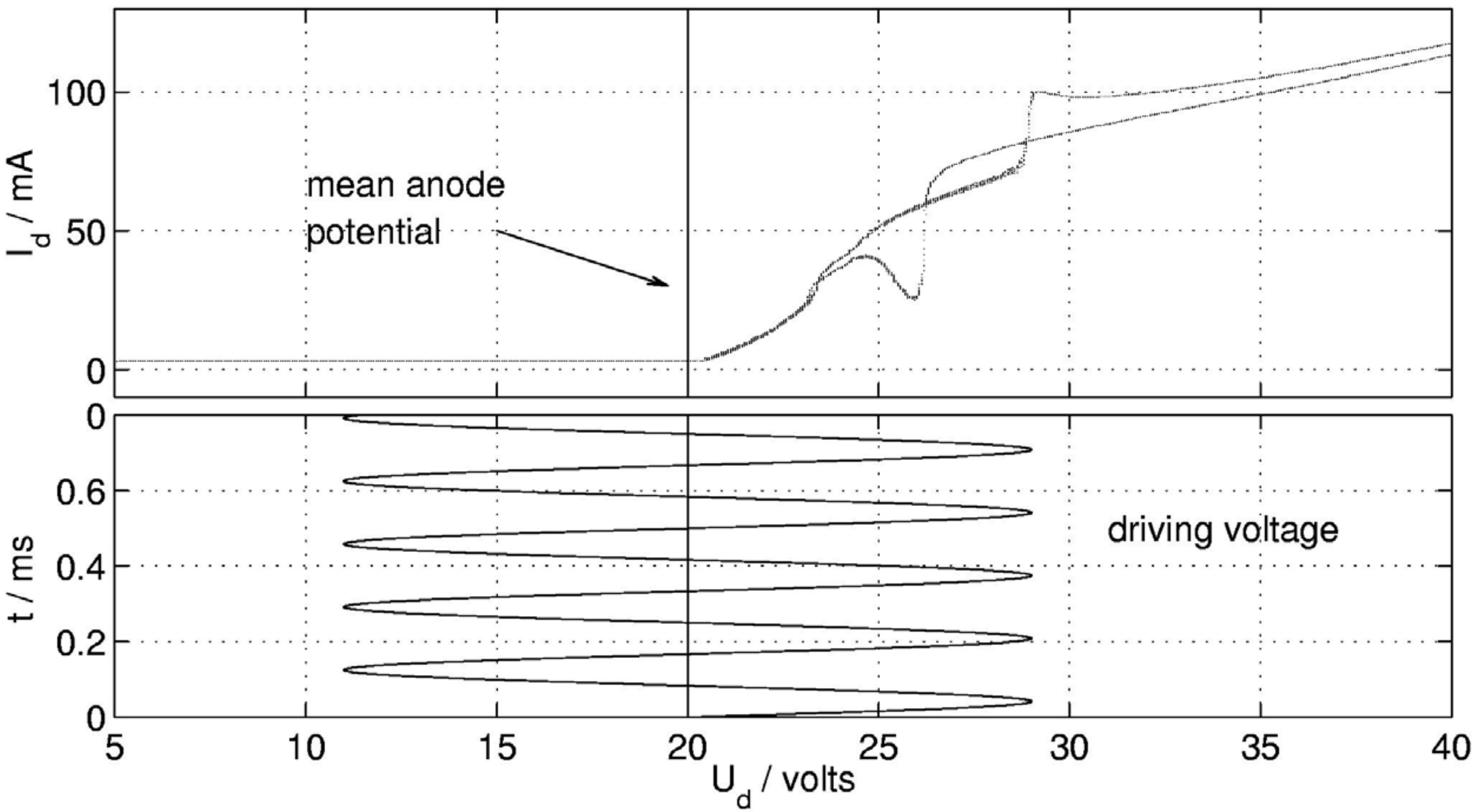
$n_e = 5 \cdot 10^{15}\ m^{-3}$
$T_e = 1$ eV
$T_i = 0.025$ eV
$p_{Ar} = 10^{-2}$ Pa
$\eta \leq 0.2\%$

the MATILDA device



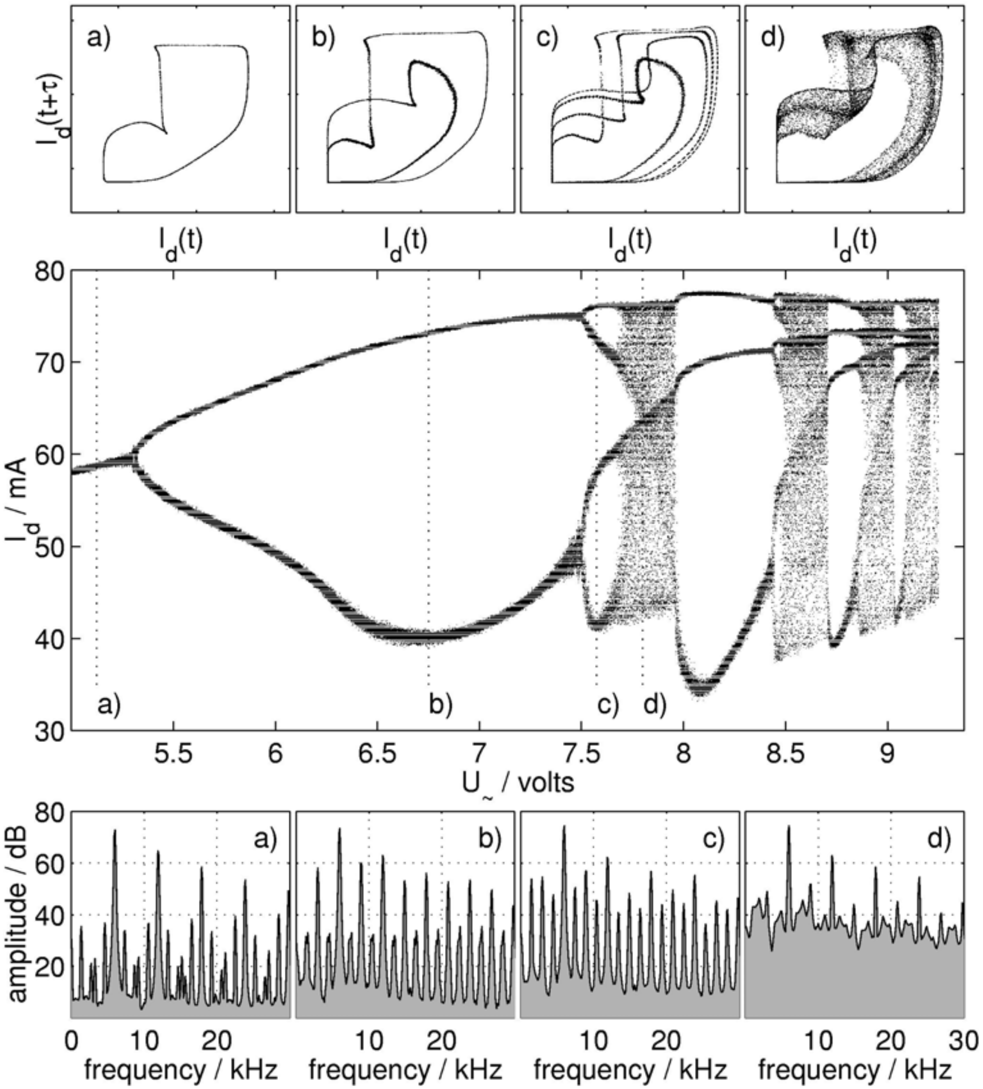
device located until recently at IEAP Kiel University

strong external drive



dynamical response of plasma current to periodic voltage drive

period doubling and chaos

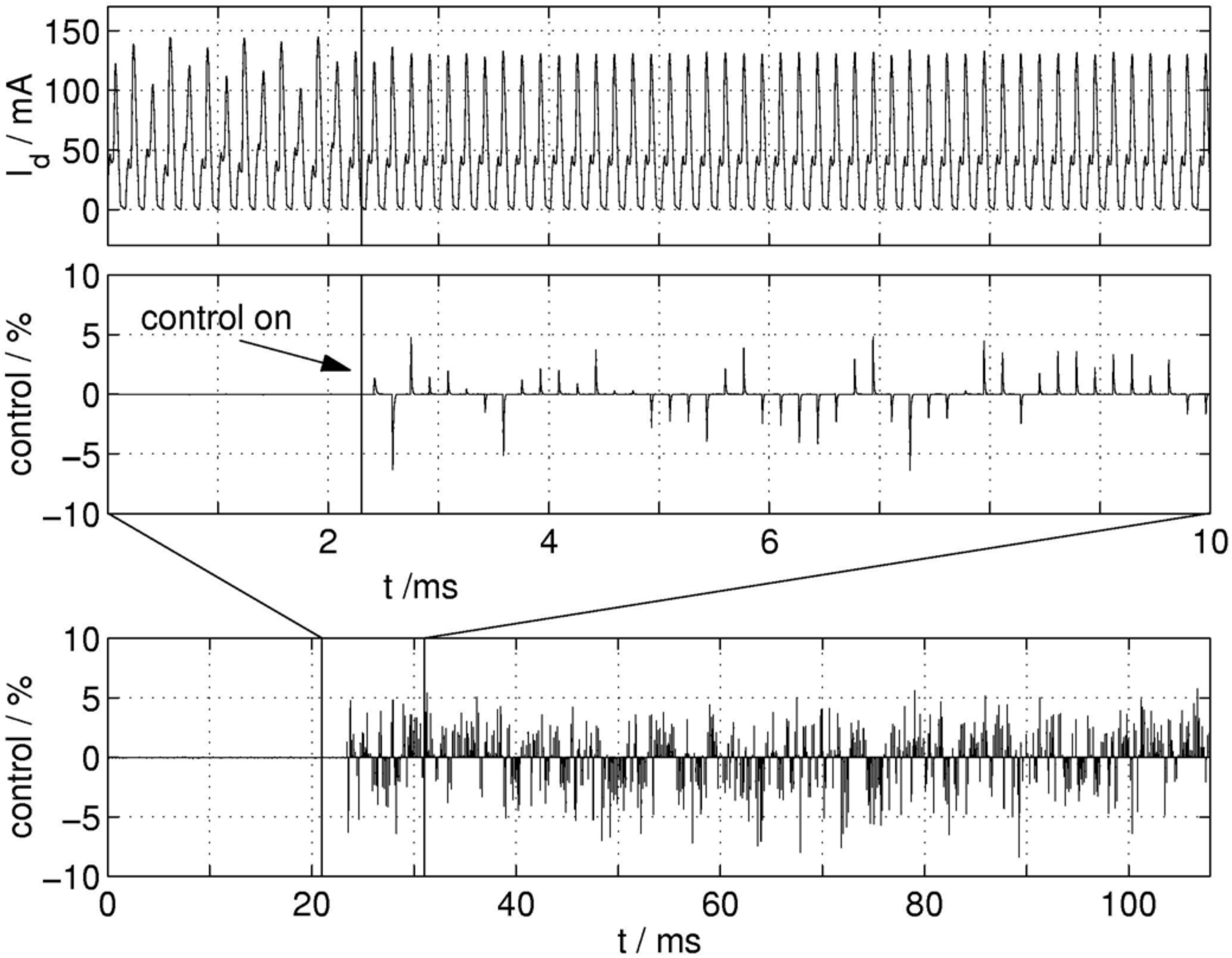


phase space portraits

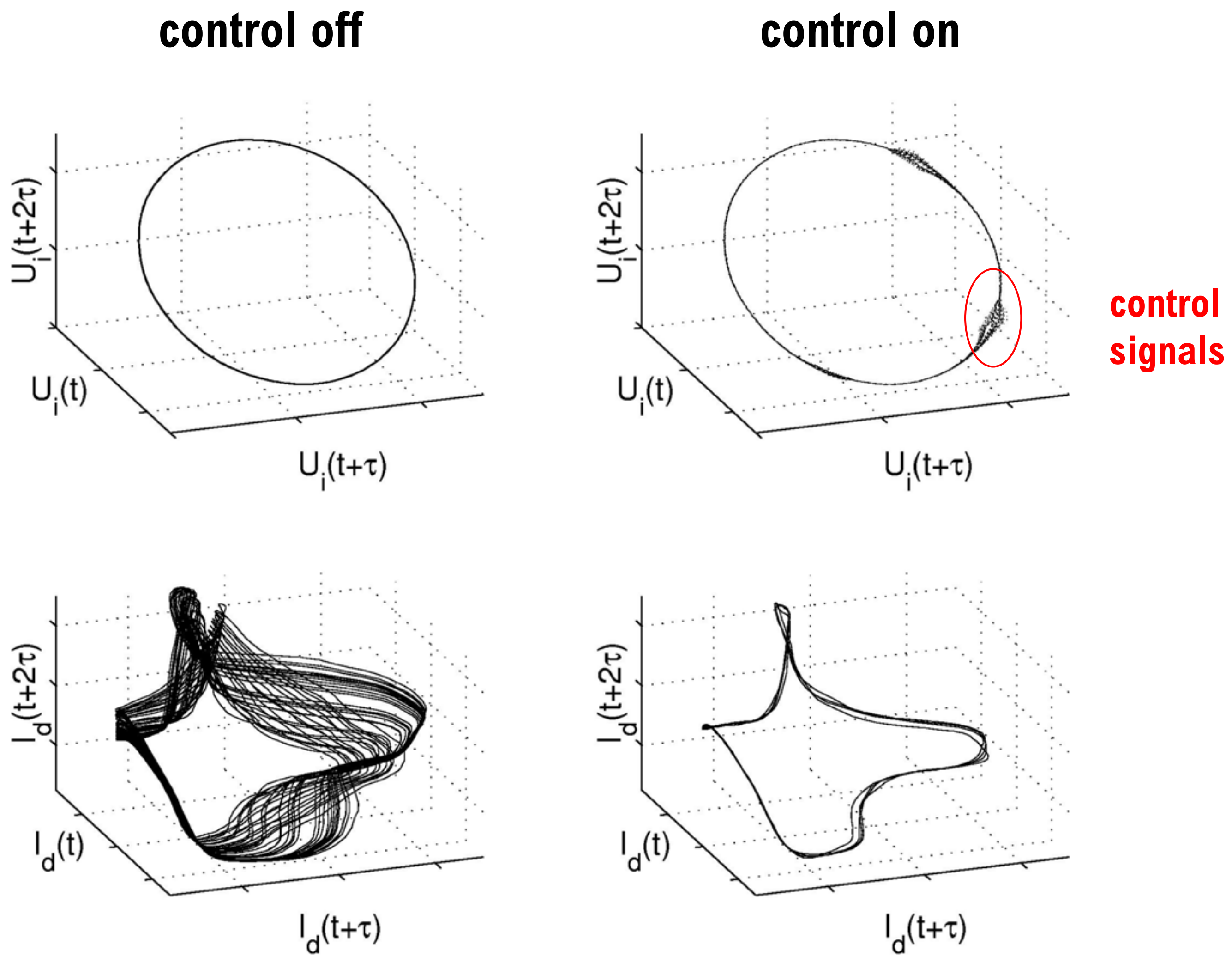
Poincaré sections ⇒

bifurcation diagram

power spectra

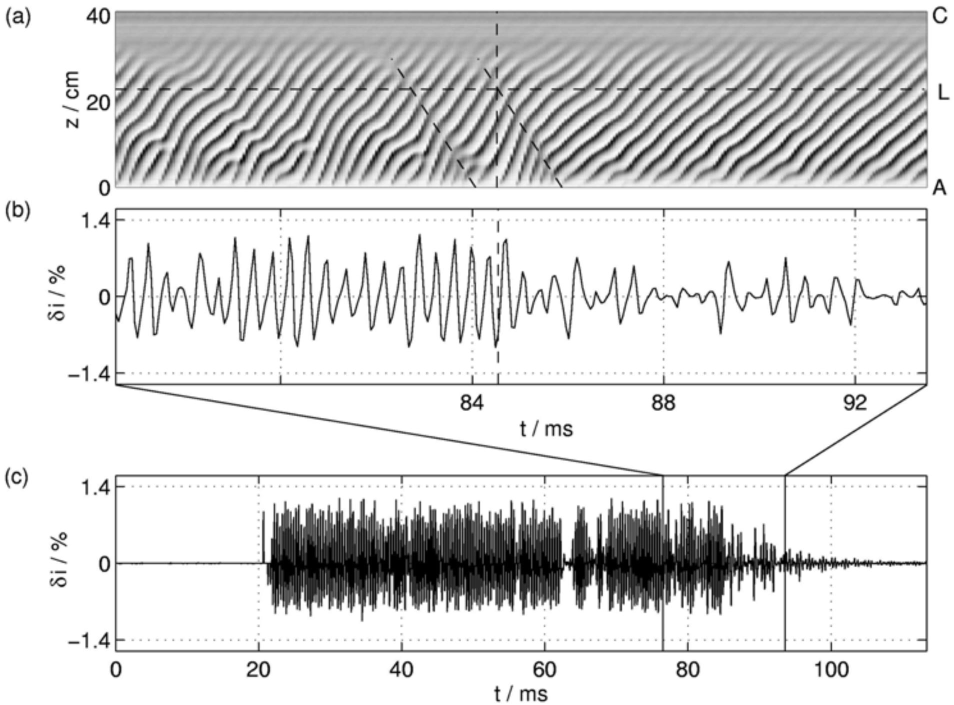

150
100
50
0
I_d / mA
10
5
0
–5
–10
control on
control / %
2
4
6
10
t /ms
10
5
0
–5
–10
control / %
0
20
40
60
80
100
t / ms

OPF control - phase space



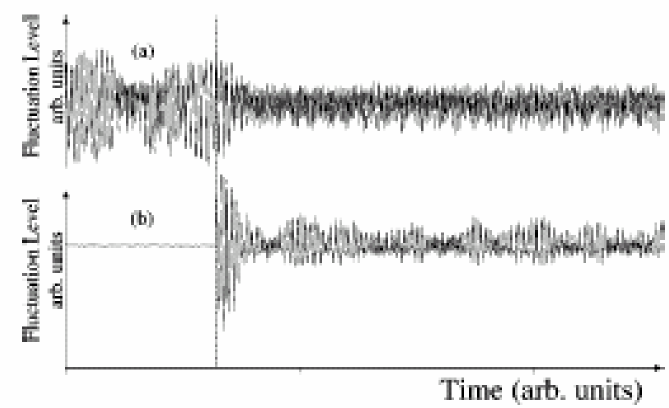
Mausbach, Klinger, Piel, *Phys. Plasmas* **6**, 3816 (1999)

wave chaos



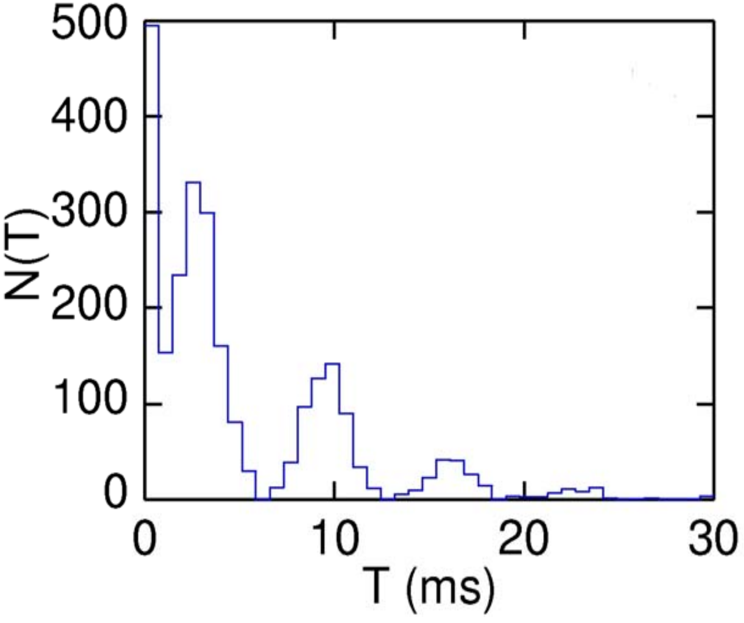
Mausbach et al. *PLA* **228**, 373 (1997)

time-delayed
auto synchronisation (TDAS)



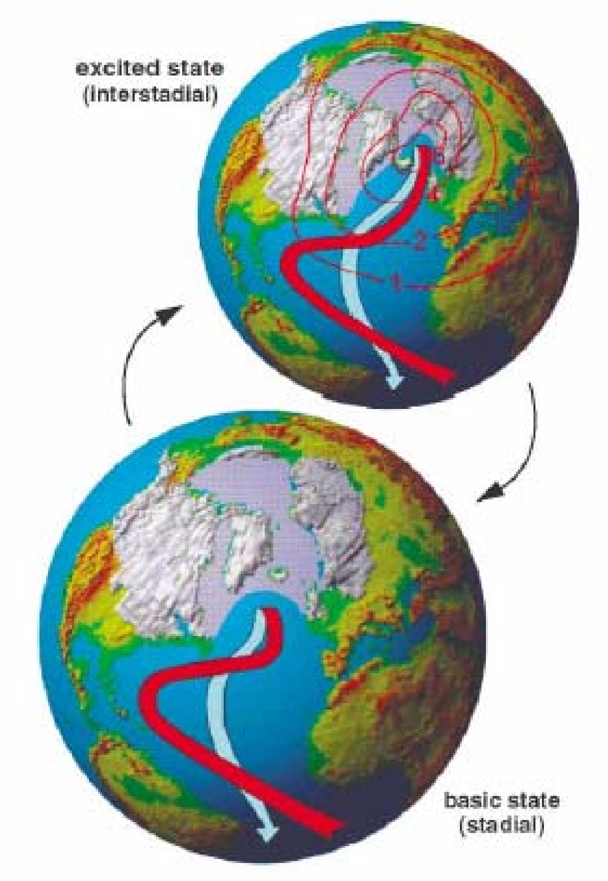
Gravier et al. *PoP* **6**, 1670 (1999)

controlling noise in plasmas



stochastic resonance

stochastic resonance = SR : first proposed by Benzi et. al, *Tellus* (1982)



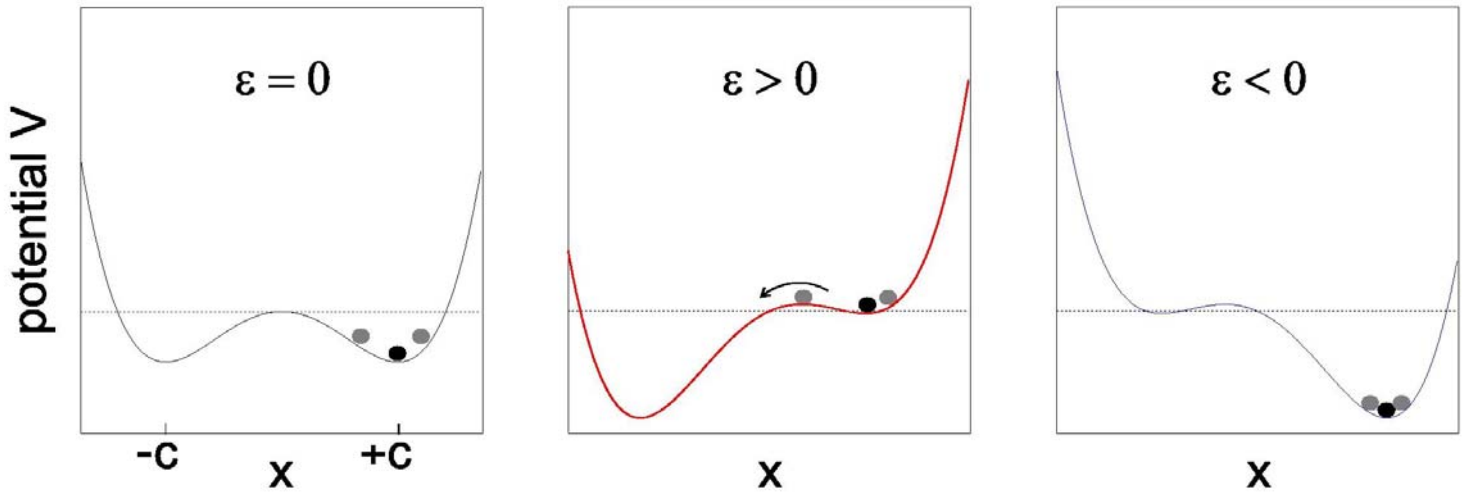
explain the 100 000 yr periodicity of glacial cycles

- stochastical systems theory
- optical systems
- electric and magnetic systems
- neuronal systems
- geoscience

Ganopolski and Rahmstorf, *PRL* **88**, 038501 (2002)

Gammaitoni et al., *RMP* **70**, 223 (1998)

SR principle



bistability: double well potential $V(x) = -\alpha x^2 + \beta x^4 + \epsilon x$

IDEA

$$\epsilon \rightarrow \underbrace{A\cos\omega_i t}_{\text{modulation}} + \underbrace{\sqrt{2\sigma}\eta(t)}_{\text{noise}}$$

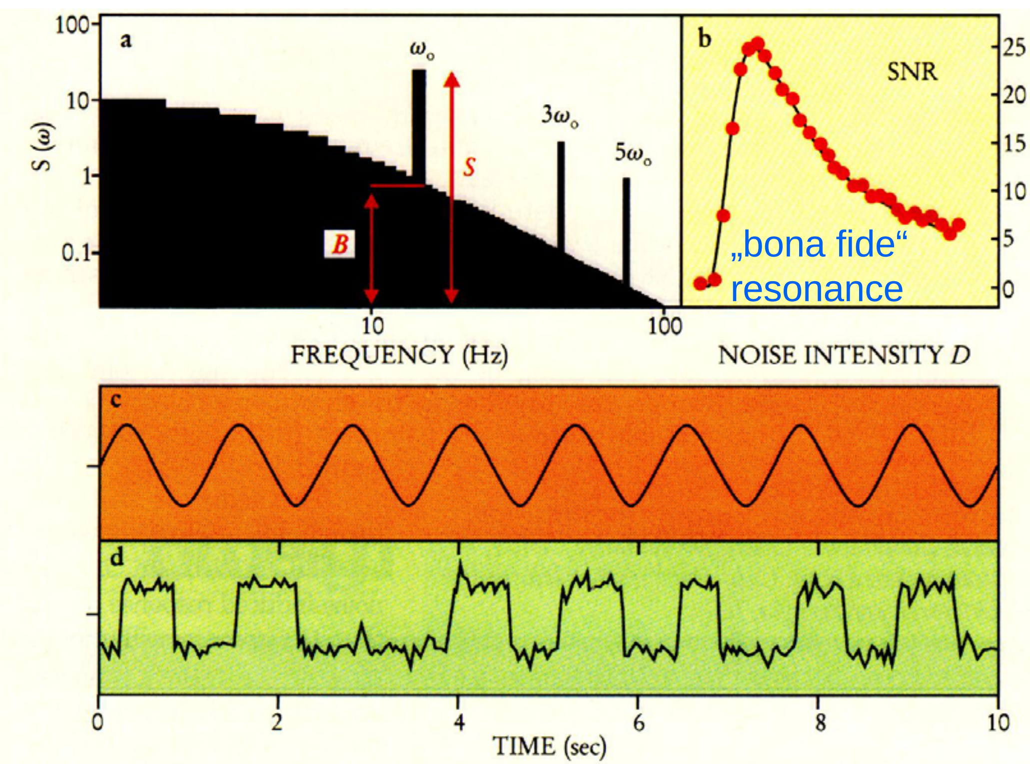
3 ingredients

apparent paradox: increase noise level → improved signal-to-noise ratio

some theory & simulation

$$\frac{dx}{dt} = -\frac{dV_0}{dx} + A\cos(\omega_d t) + \sqrt{2\sigma}\eta(t)$$
$$V_0 = -\alpha x^2 + \beta x^4$$

- Langevin stochastic ODE
- valid for large damping



signal-to-noise ratio

$$\mathrm{SNR} = 10\log_{10}(S/B)$$

Kramer‘s time

$$T_k \propto \frac{1}{\alpha}\mathrm{e}^{-U_0/\sigma} \quad \text{at } A = 0$$
$$\mathrm{SNR} \propto (A/\sigma)^2\,\mathrm{e}^{-U_0/\sigma}$$
$$S(\omega) = \frac{\alpha\beta}{\beta+\omega^2} + \gamma\delta(\omega-\omega_d)$$

McNamara and Wiesenfeld, *PRA* **39**, 4854 (1989)

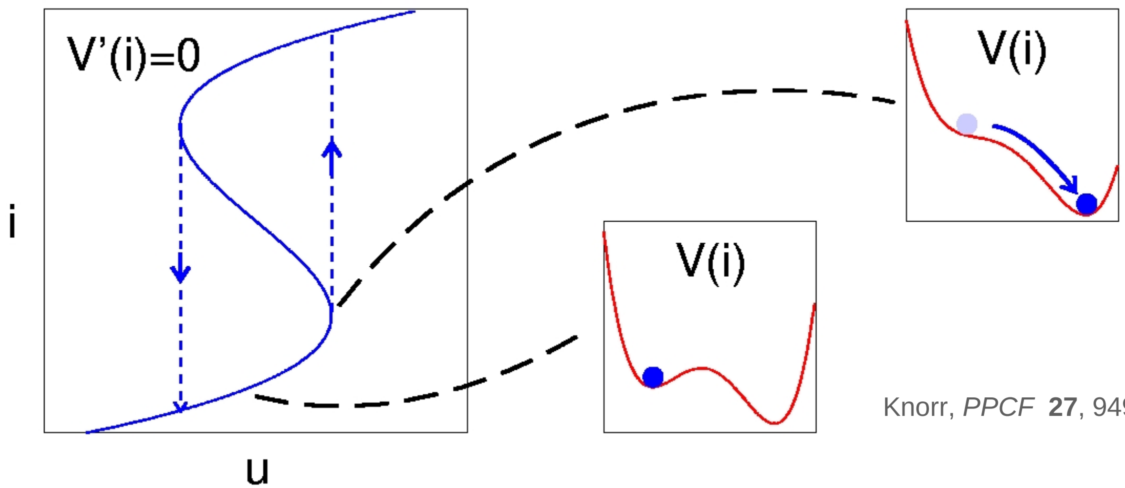
hysteresis models

heuristic pseudo potential

$$V(i) = i^4 + \mu i^2 + ui$$

equilibrium condition: potential minimum

$$V'(i) = 0$$



double well

Knorr, *PPCF* **27**, 949 (1984)

energy balance equation (Ohmic heating vs. surface loss)

$$f(\theta) = \alpha \exp(-1/\theta) - (\theta - \theta_0) = 0 \quad \text{with} \quad \theta = k_B T_e / E_i$$

similar conclusion!

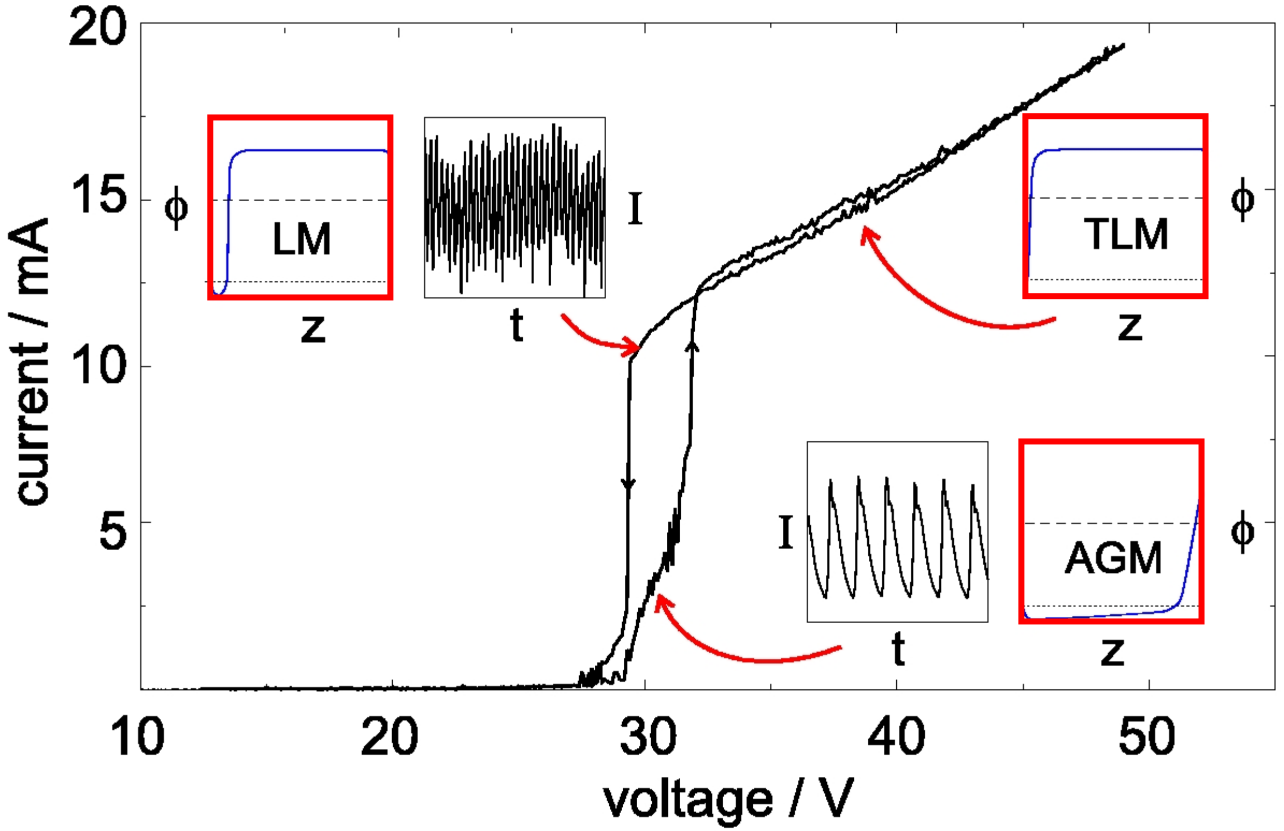
Matsunaga and Kato, *JPSJ* **66**, 115 (1997)

discharge modes

AGM = anode glow mode

TLM = temperature limited mode

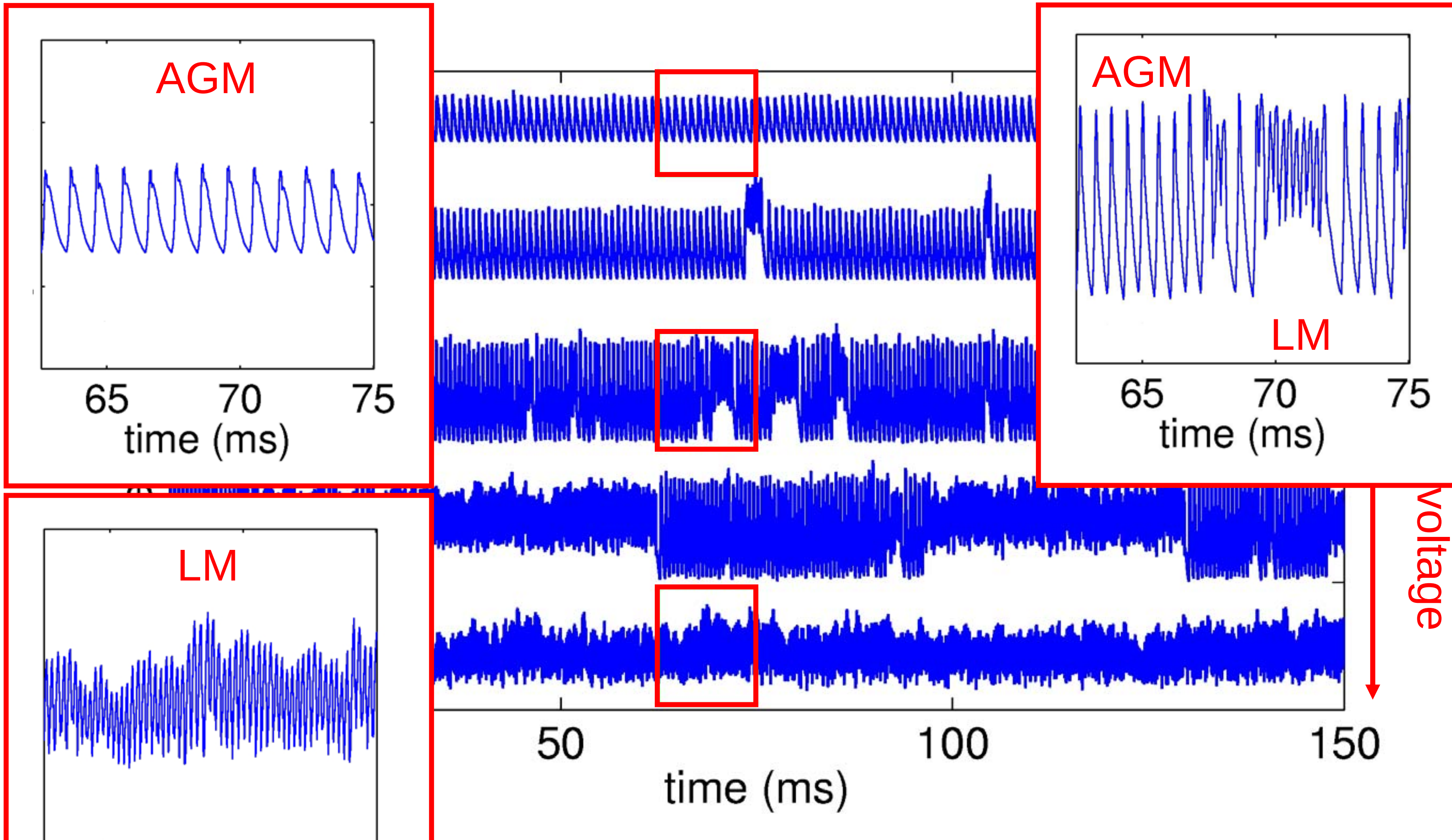
LM = Langmuir mode



- **bistability**
- **U_d-I_d-hysteresis**
- **I_d oscillations**
- **discharge modes**

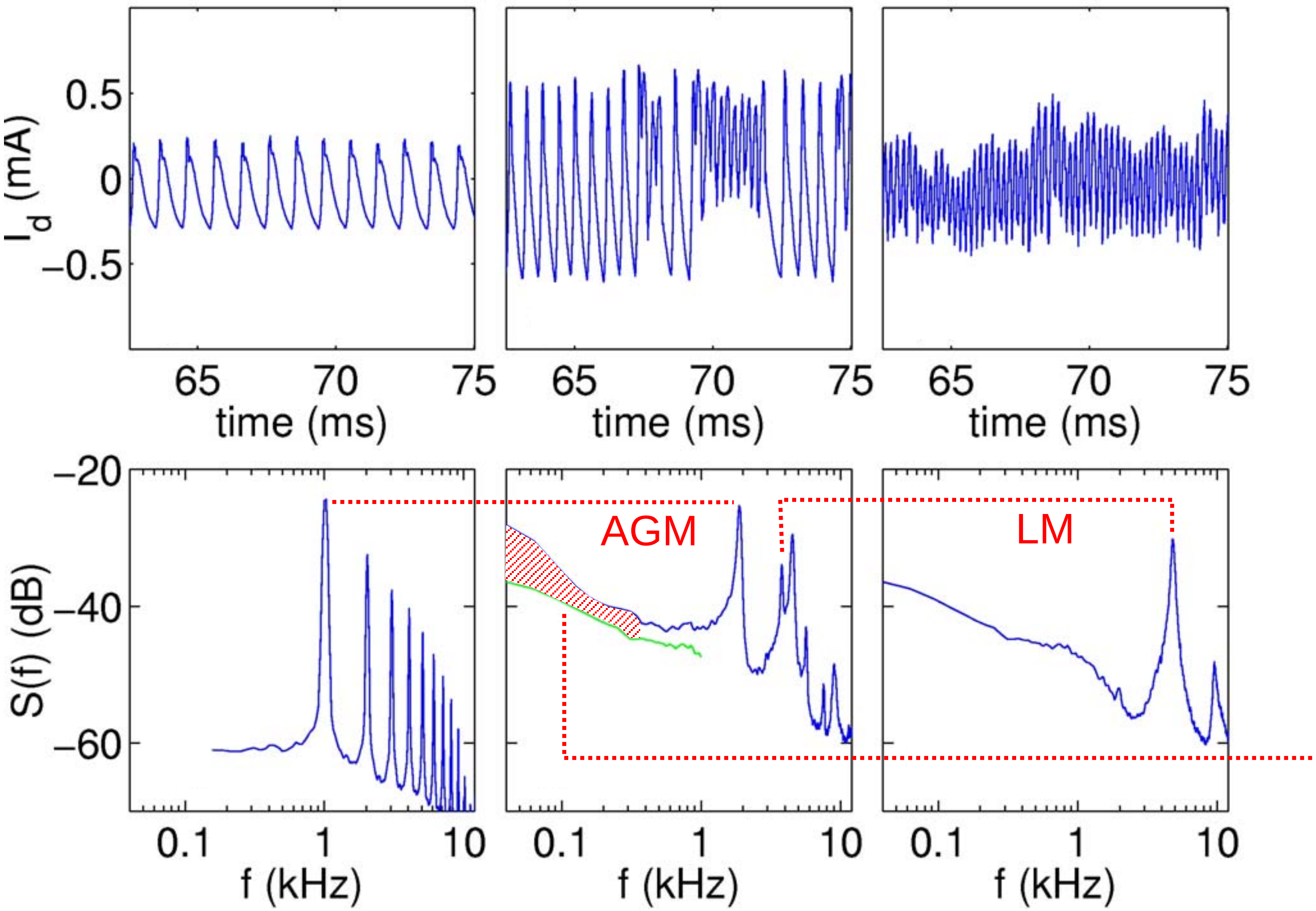
Greiner, Klinger, Klostermann, Piel, *PRL* **70**, 3071 (1993)

stochastic behaviour



I… rge current time series AGM → LM transition regime

stochastic behaviour



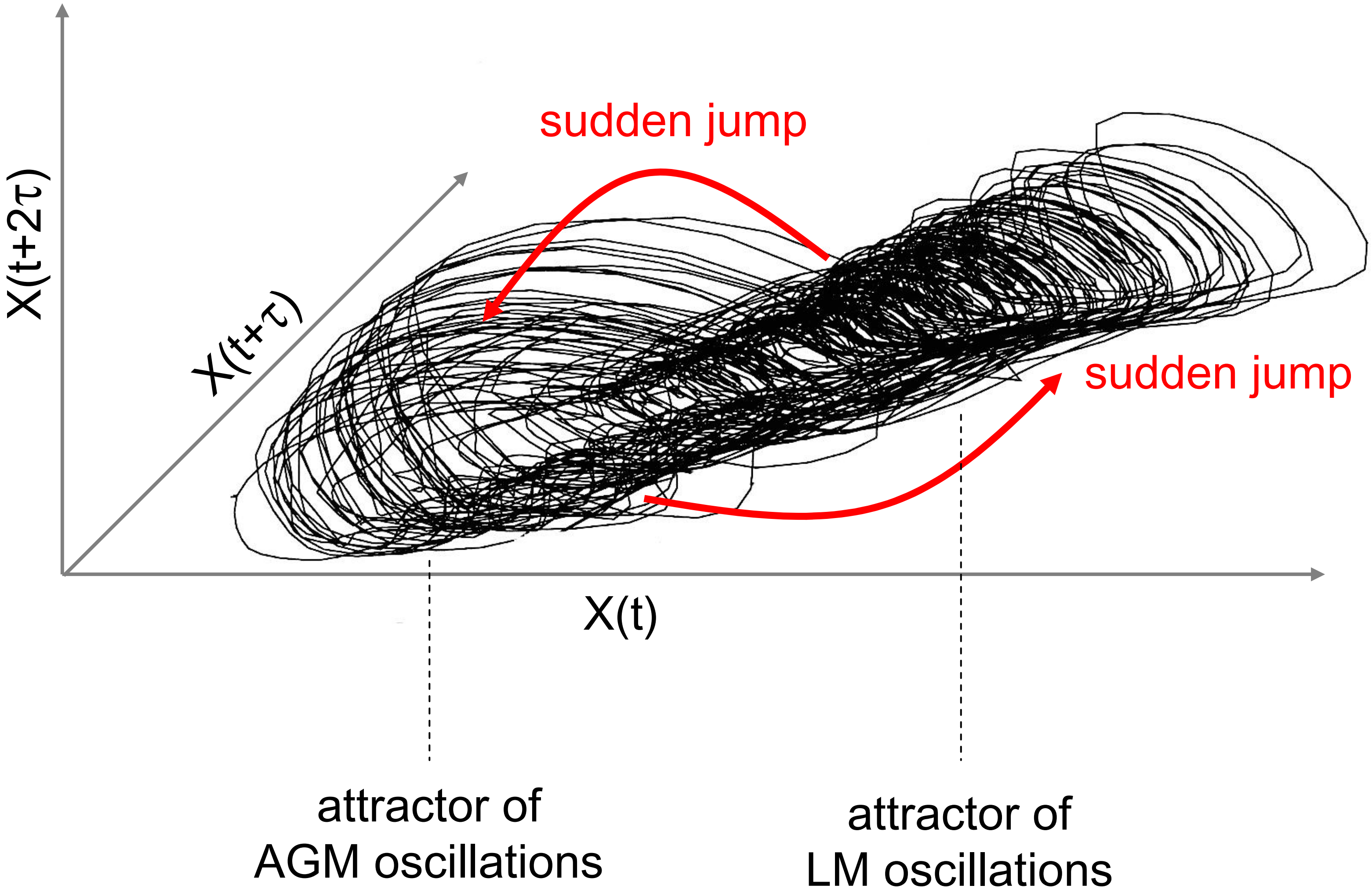
time series

power spectra

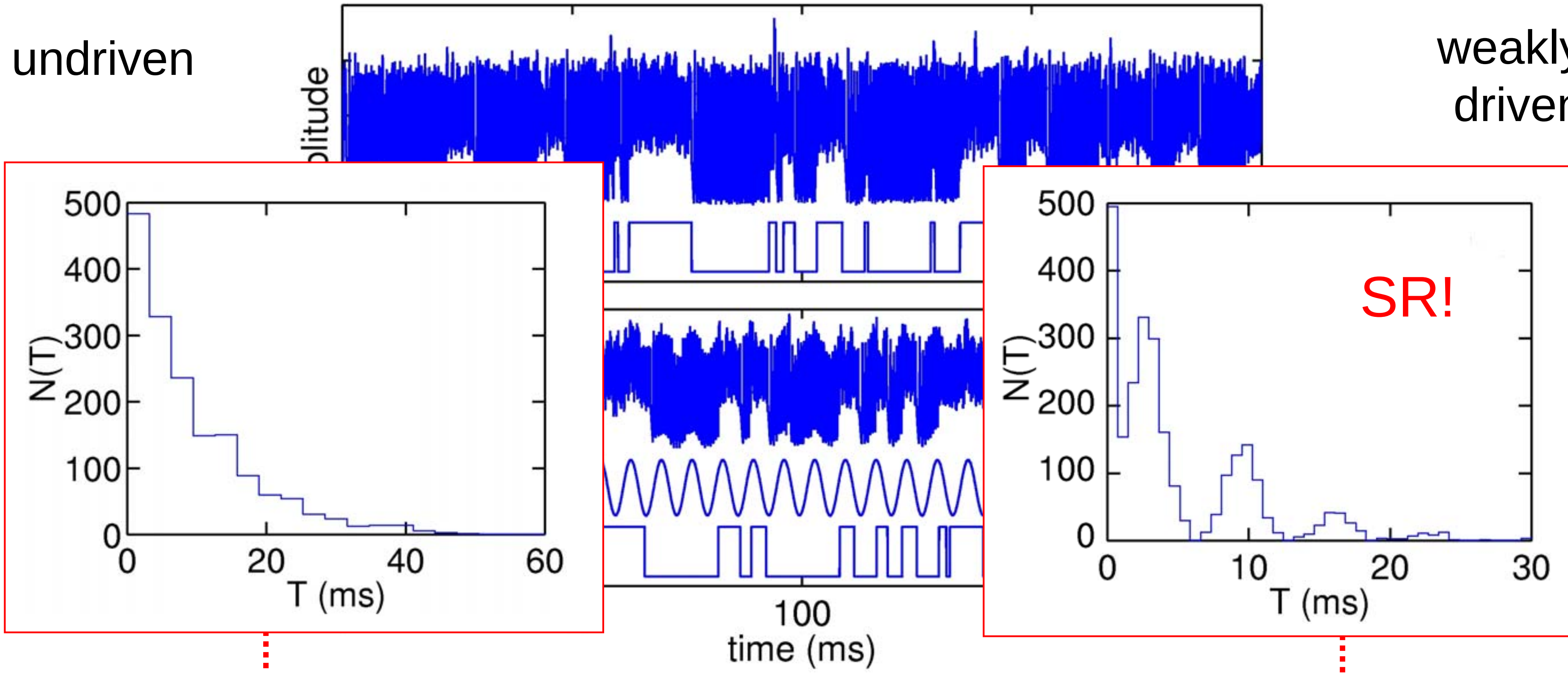
low-frequency noise ⇔ jumps

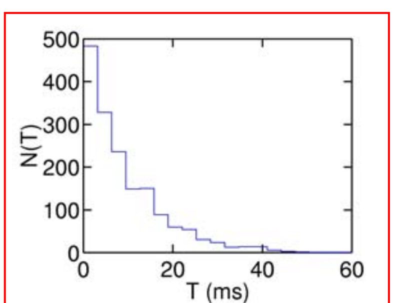
$T_k \approx 30$ms

phase space structure



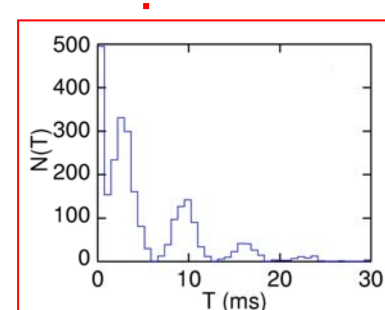
weak periodic drive





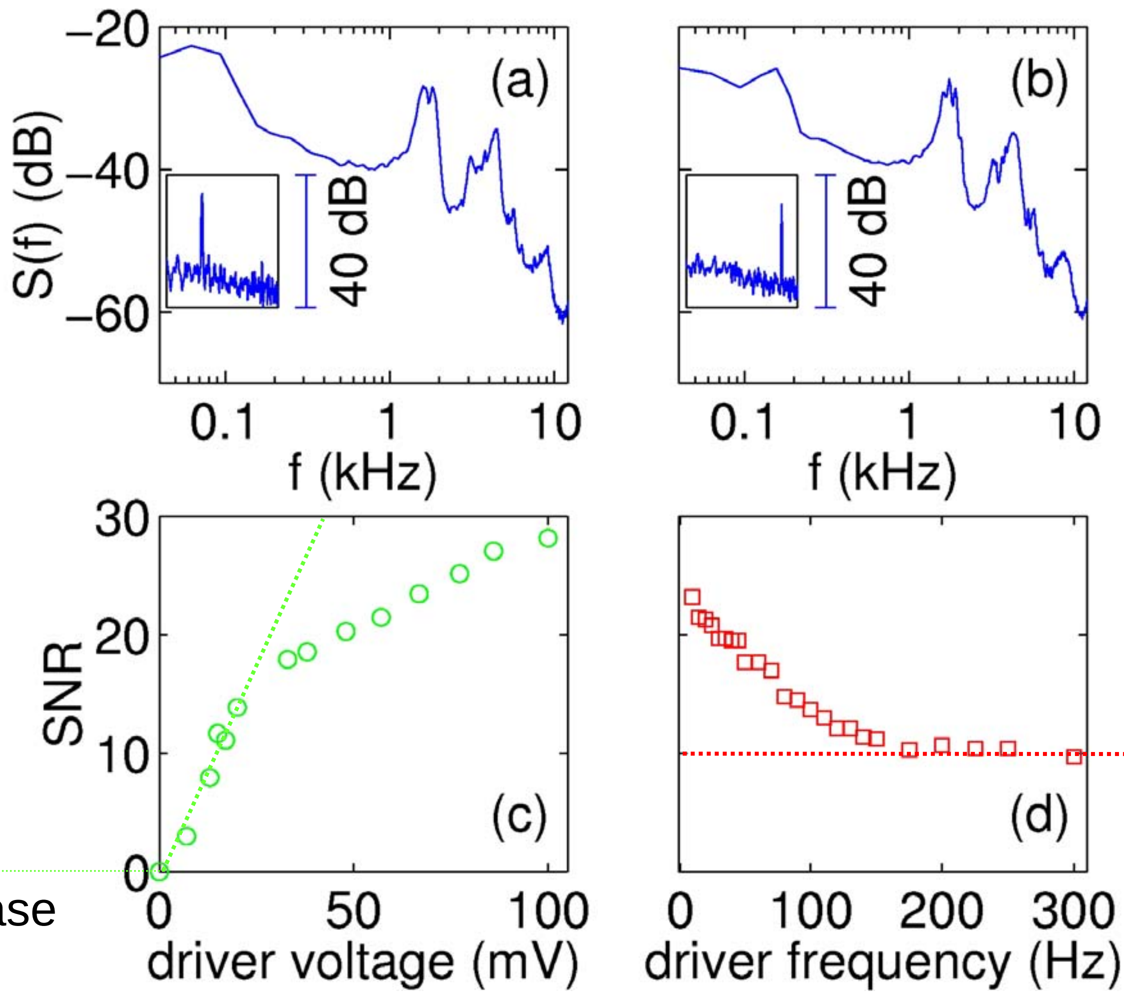
$$\mathrm{Prop}(T : [t, t+T] \rightarrow \mathrm{AGM})$$

residence time distribution



signal-to-noise

power spectra



frequency tune

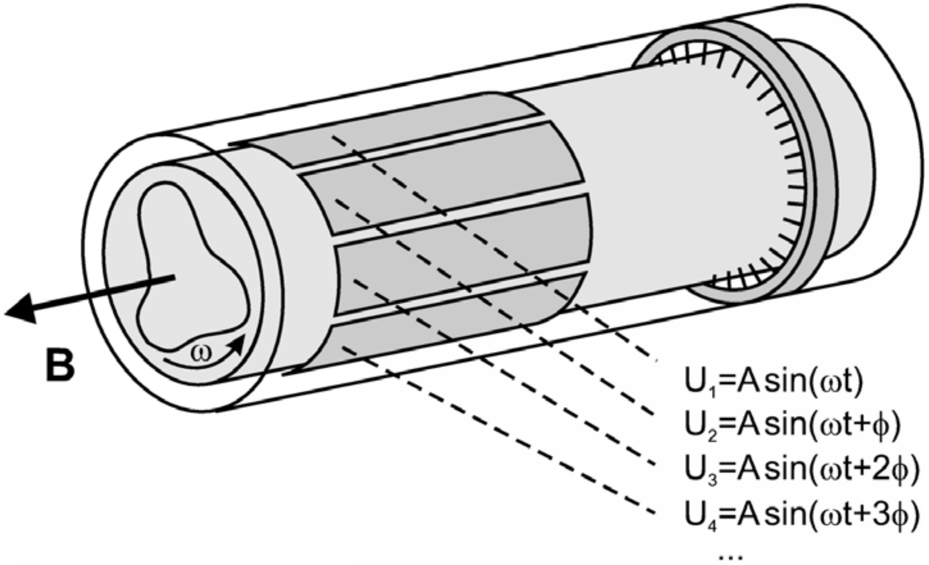
70 Hz

150 Hz

saturation

strong increase

controlling instabilities and turbulence



what is the problem?

- drift waves are generic in the edge of magnetized plasmas
- drift waves and drift wave turbulence cause strong particle transport
- transport properties are determined by the power spectrum (Re and Im!)
- transport is not necessarily undesired but needs to be controlled

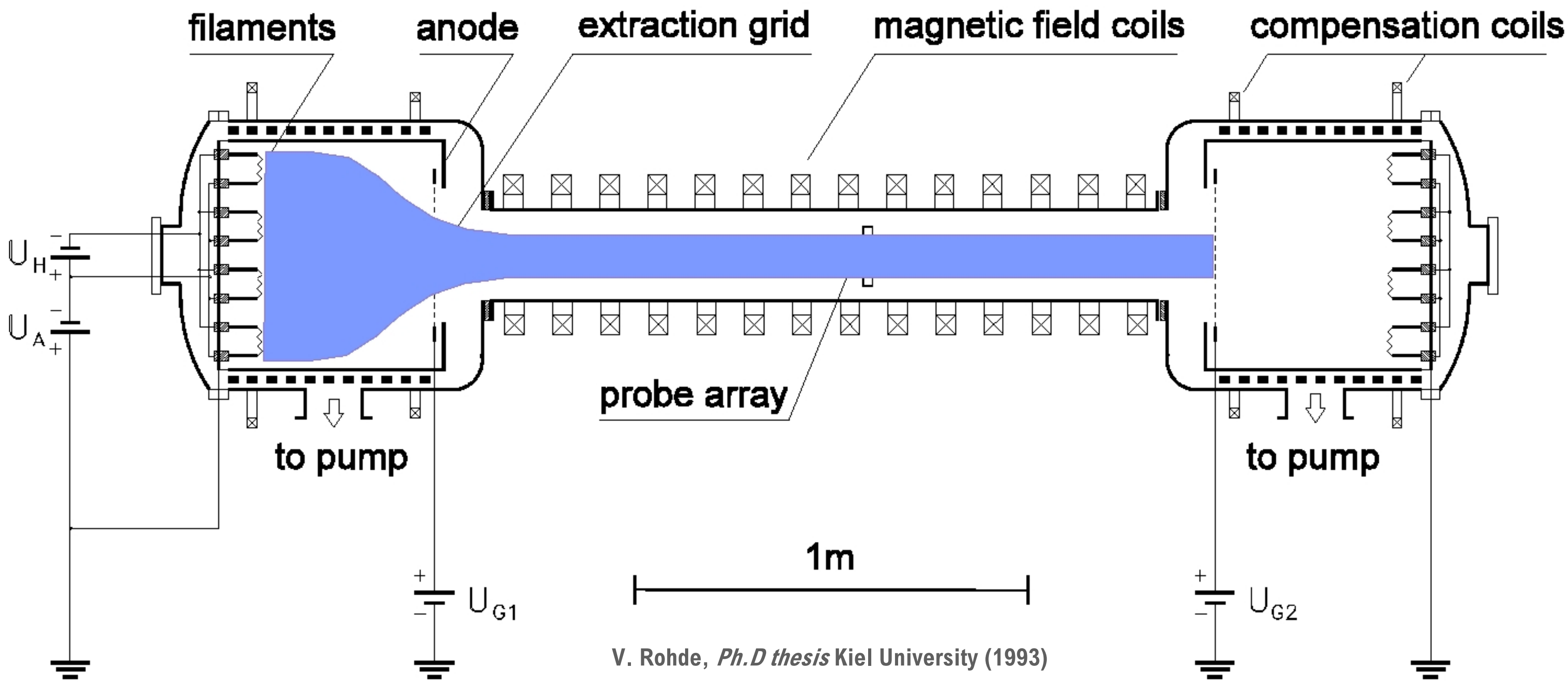
↓

- ► magnetic shear .... fairly static
- ► self-consistent radial electric shear fields .... ITB's – difficult to establish
- ► active open-loop or closed-loop contro .... not yet developed

↓

- simple: open-loop control
- necessary: spatiotemporal control signal

magnetized triple plasma

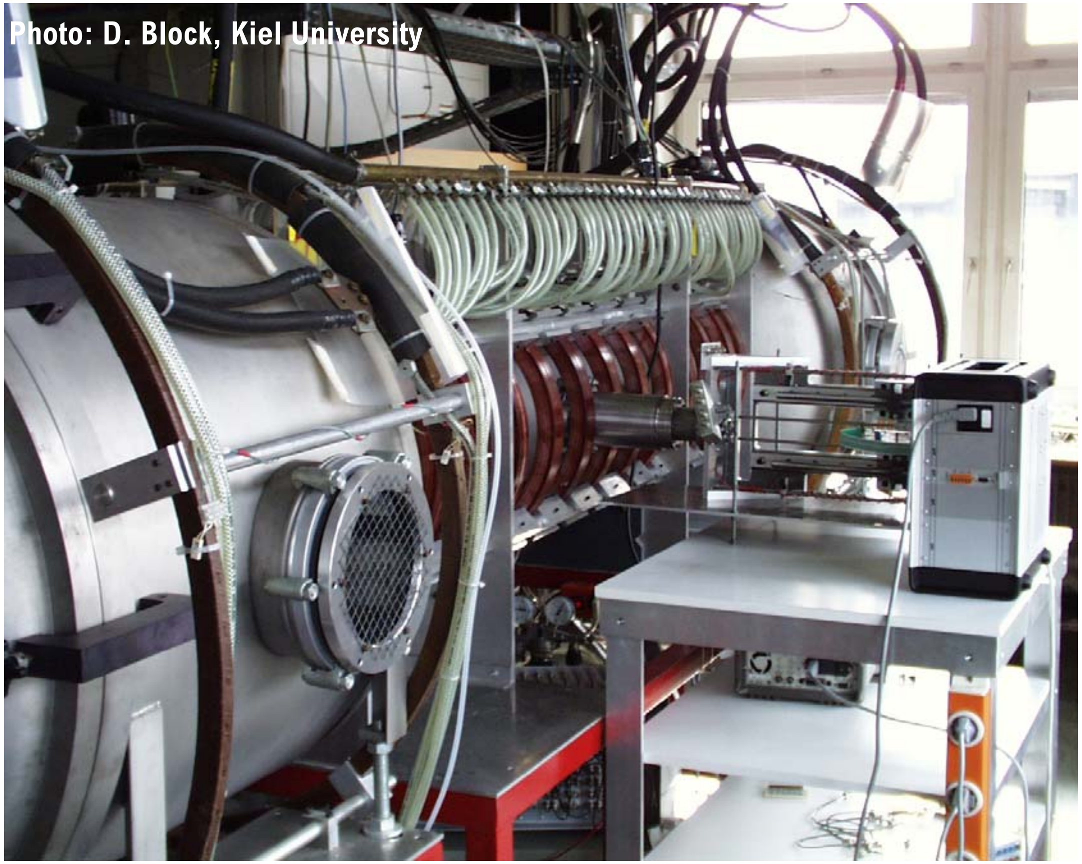


V. Rohde, *Ph.D thesis* Kiel University (1993)

- **thermionic discharges**
- **magnetized mid-section**

~ DLD (Darmouth), MIRABELLE (Nancy), KIWI (Kiel), MISTRAL (Marseille), VINETA (Greifswald)

plasma parameters



magnetized plasma column

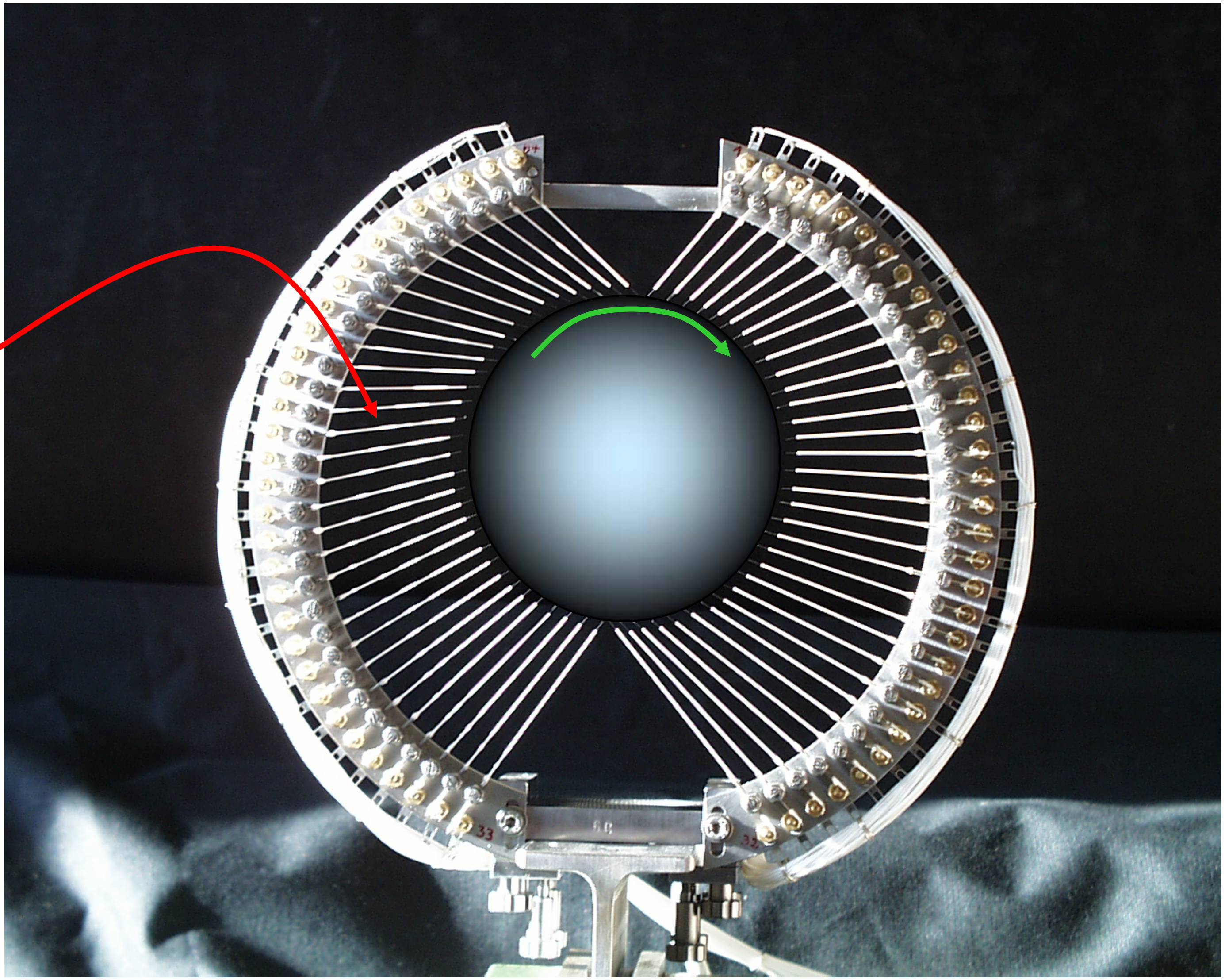
- $L = 1.5$ m and $d = 0.3$ m
- $n_e \leq 5 \cdot 10^{16}\ m^{-3}$
- $T_e \approx 1.5 eV$
- $B \leq 0.1T$ (linear)
- $\beta \leq 2.5 \cdot 10^{-6}$

quiescent plasma

- low-beta plasma
- ρ_s~ other scales
- $\nabla_z n \neq 0 \Rightarrow$ 3d equilibrium
- collisions with neutrals

} features

an array of 64 probes



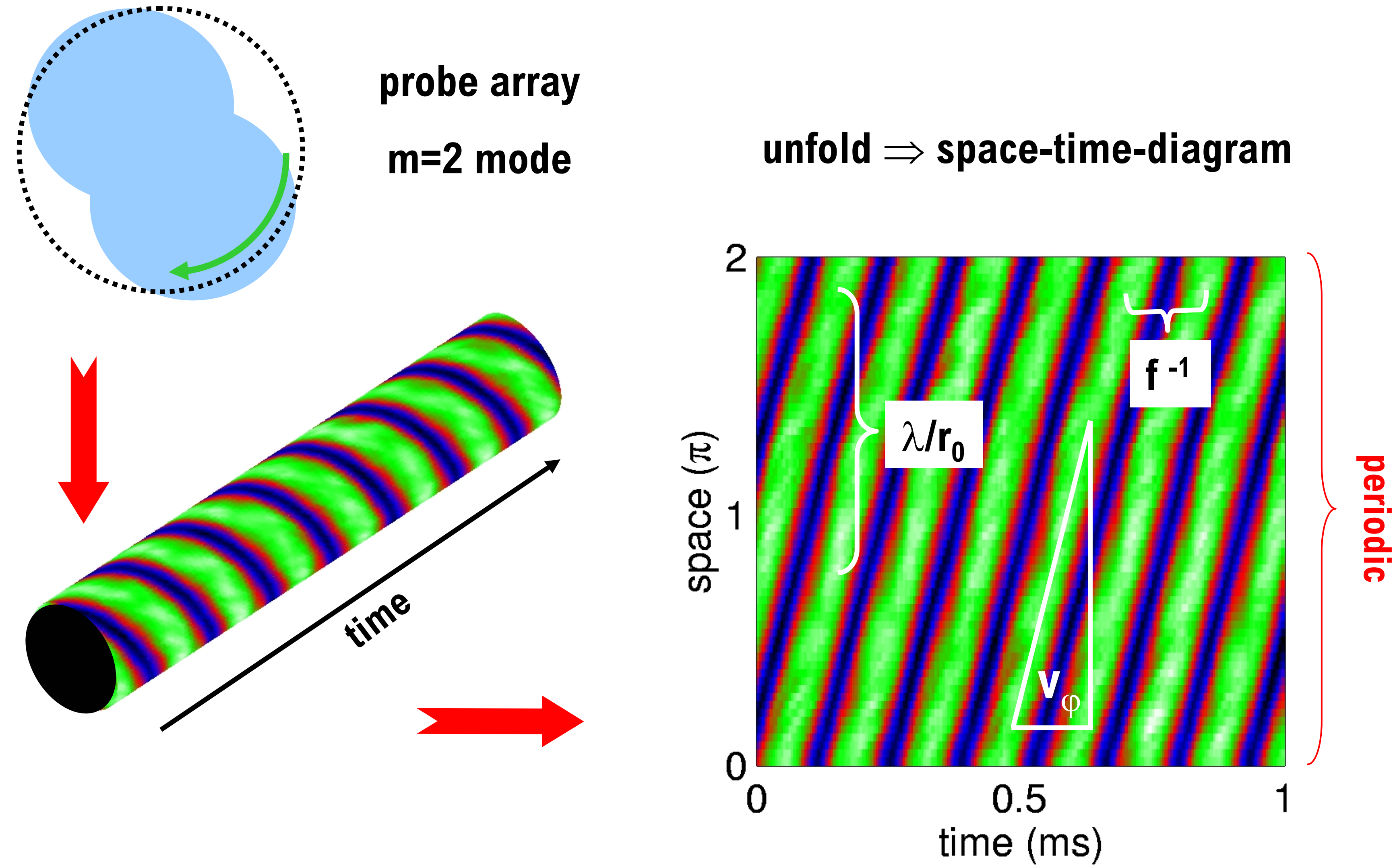
drift wave
v_φ poloidal

probe d=50μ

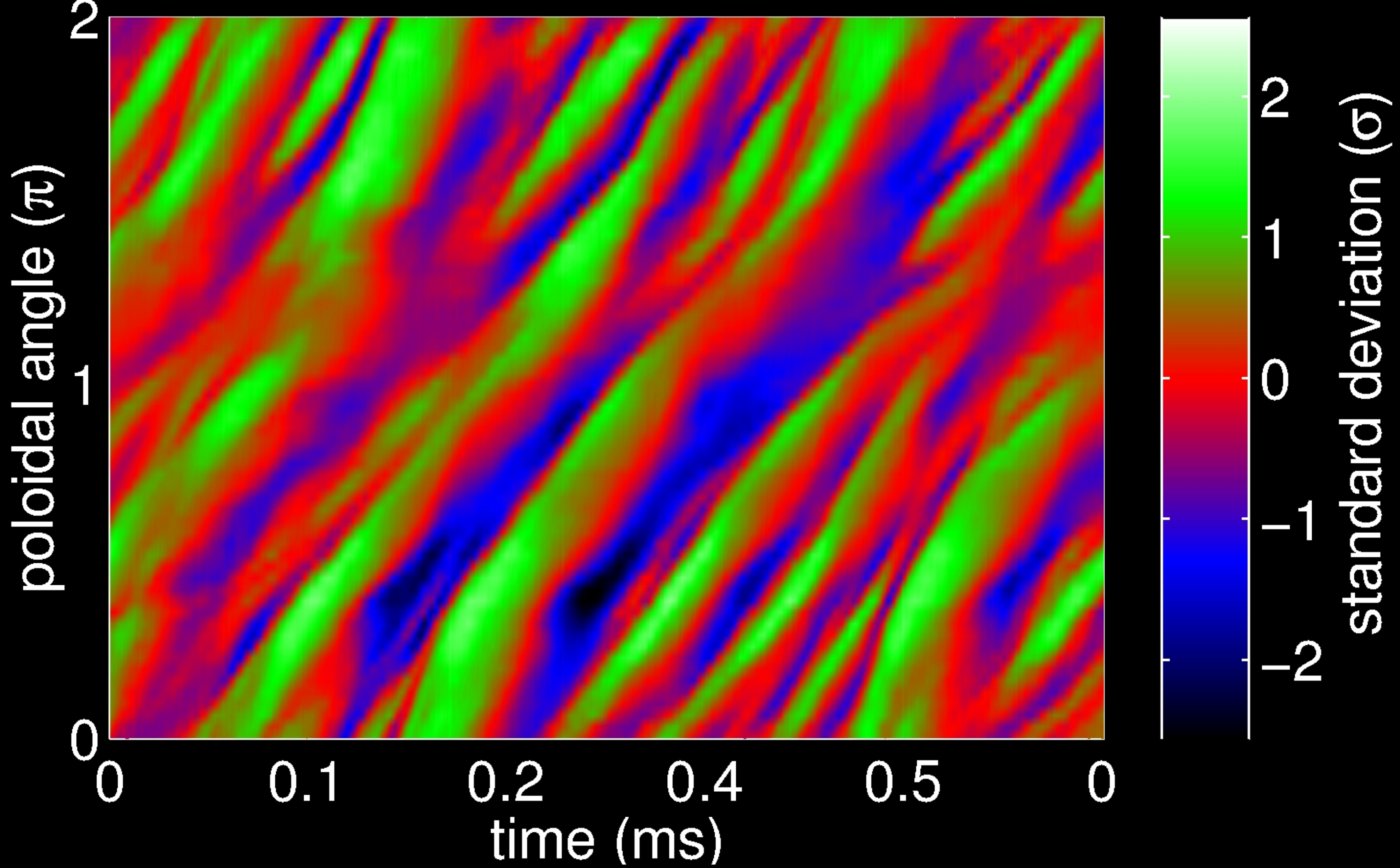
plasma
∇n-region

Photo: D. Block
Dissertation
Kiel University

space-time data



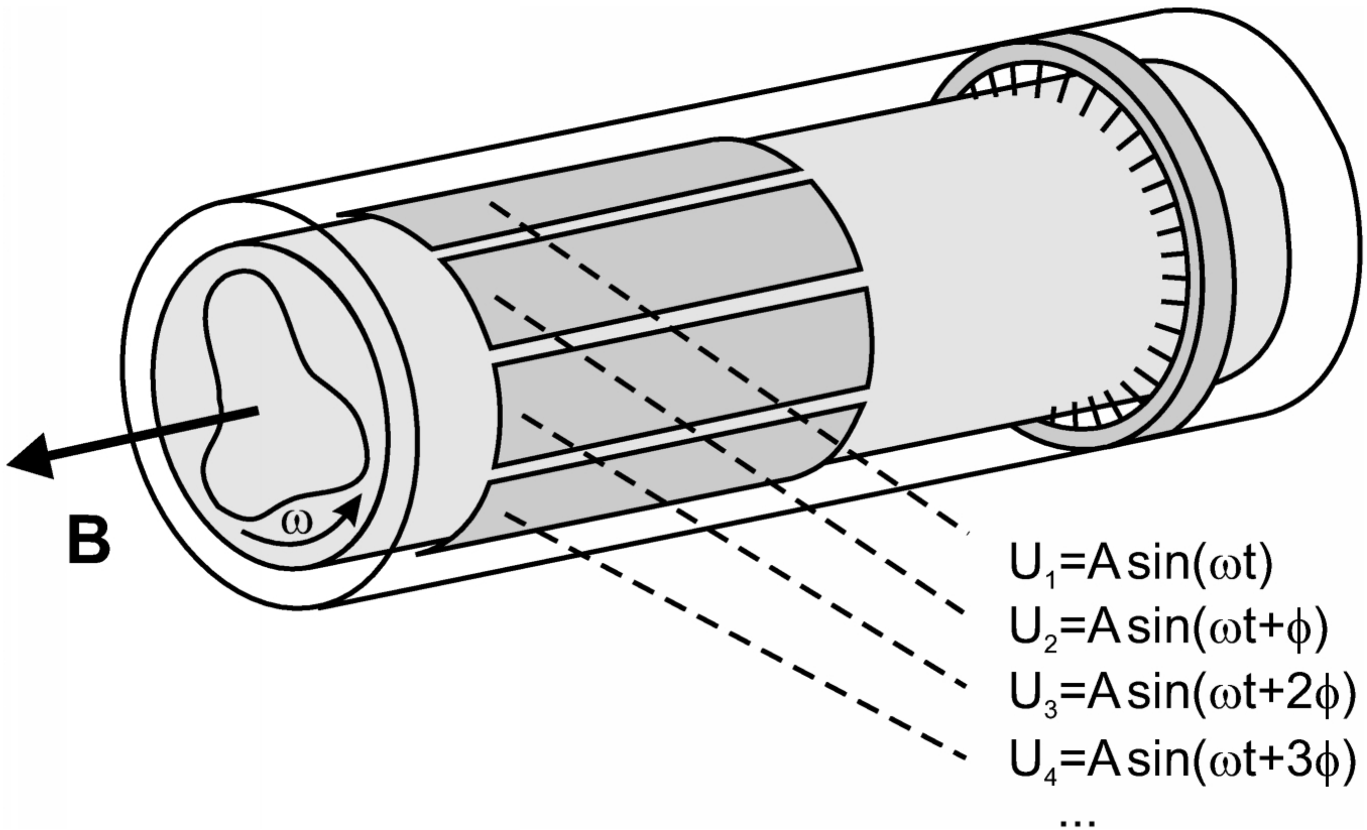
turbulence



2
1
0
poloidal angle (π)
0
0.1
0.2
0.4
0.5
0
time (ms)
2
1
0
−1
−2
standard deviation (σ)

syncronisation of turbulence

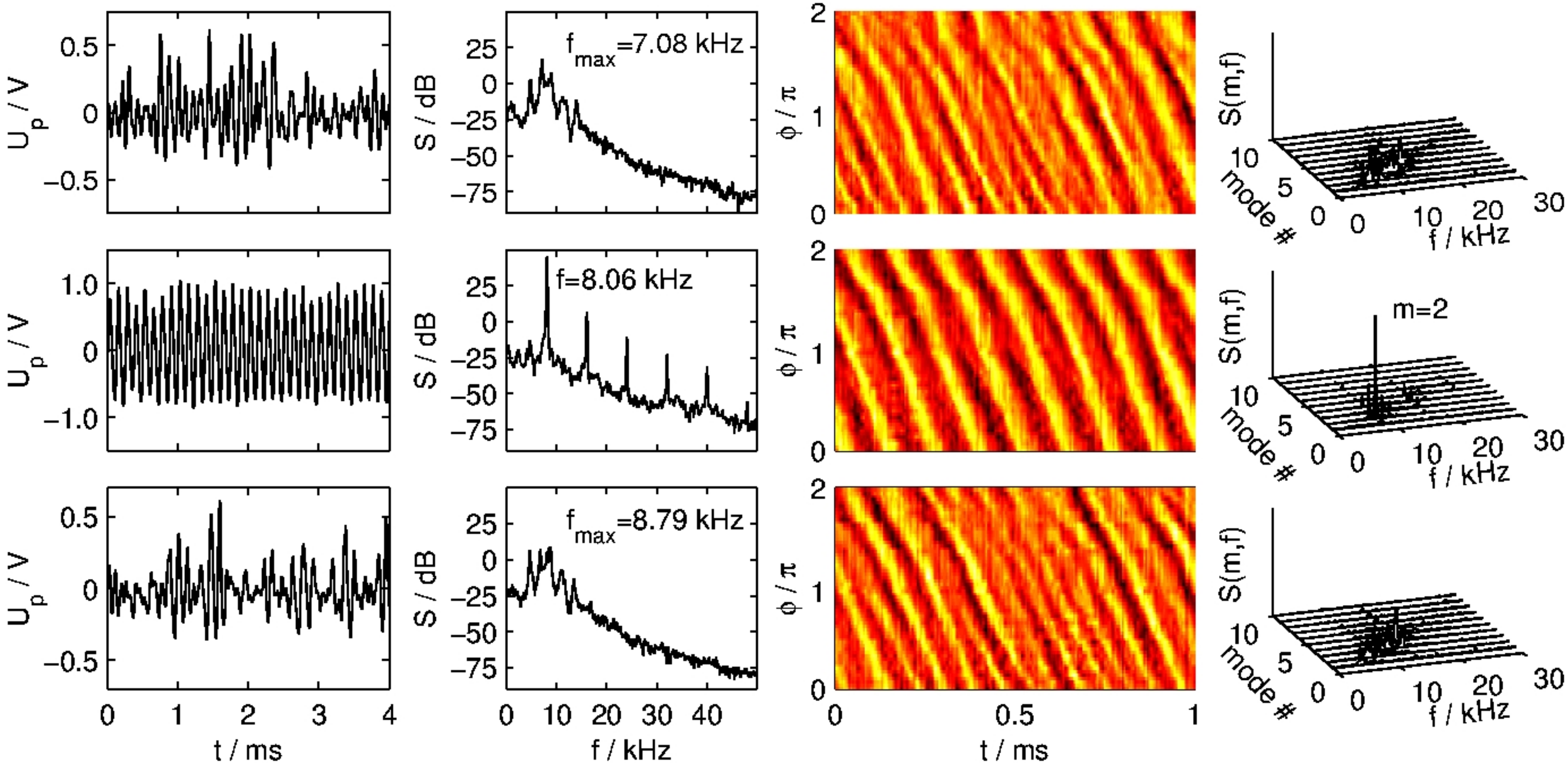
idea: suppression resp. synchronisation of drift wave turbulence by externally applied electric rotation field



Schröder, Klinger, Block, Piel, Bonhomme, Naulin, *Phys. Rev. Lett.* 86, 5711 (2001)

experimental result

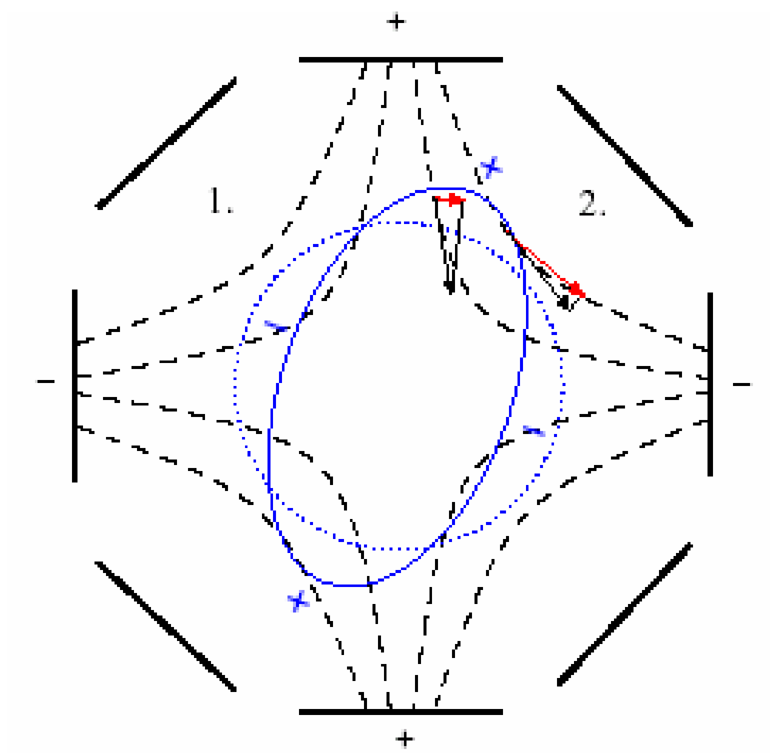
time series | f-spectrum | space-time-diagram | (k,f)-spectrum



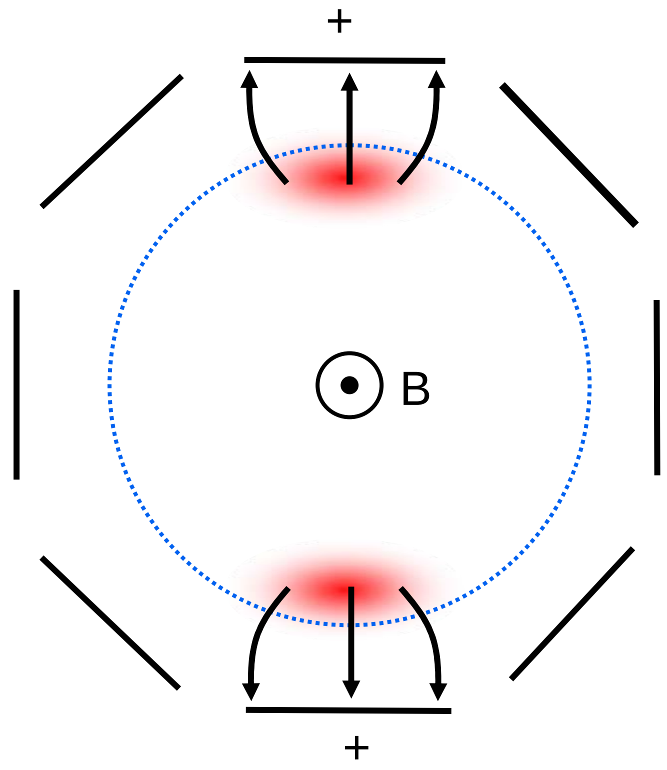
- no external field
- co-rotating field
- counter-rotating field

physical mechanism

direct perturbation of the drift modes's electric field?



indirect perturbation of the drift wave by poloidal current profile?



modelling

extended HW-model (2d)

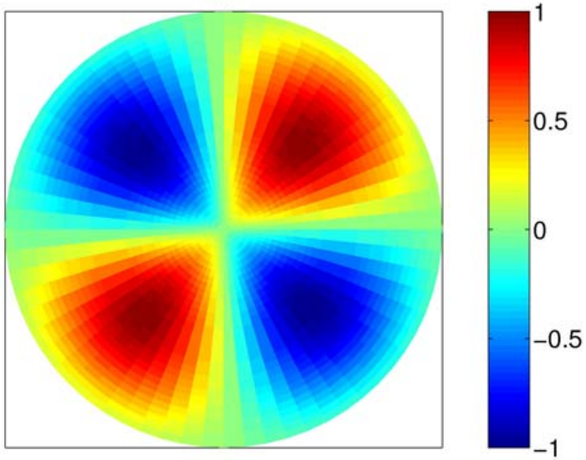
plasma potential

current || B

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

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

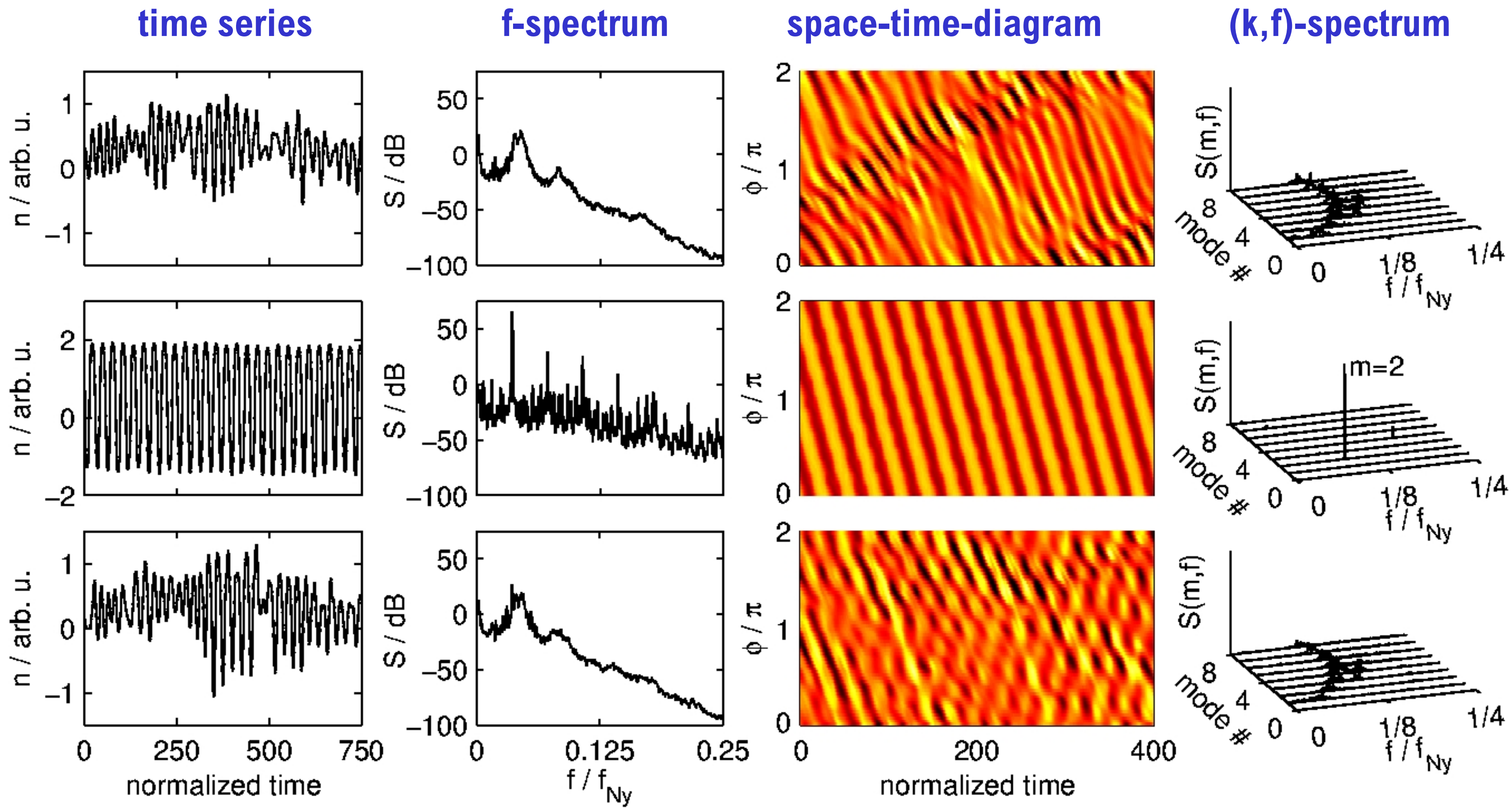
plasma density



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

- **rotating electron current profile || B**
- **poloidal mode structure (m=2)**
- **radially localized**

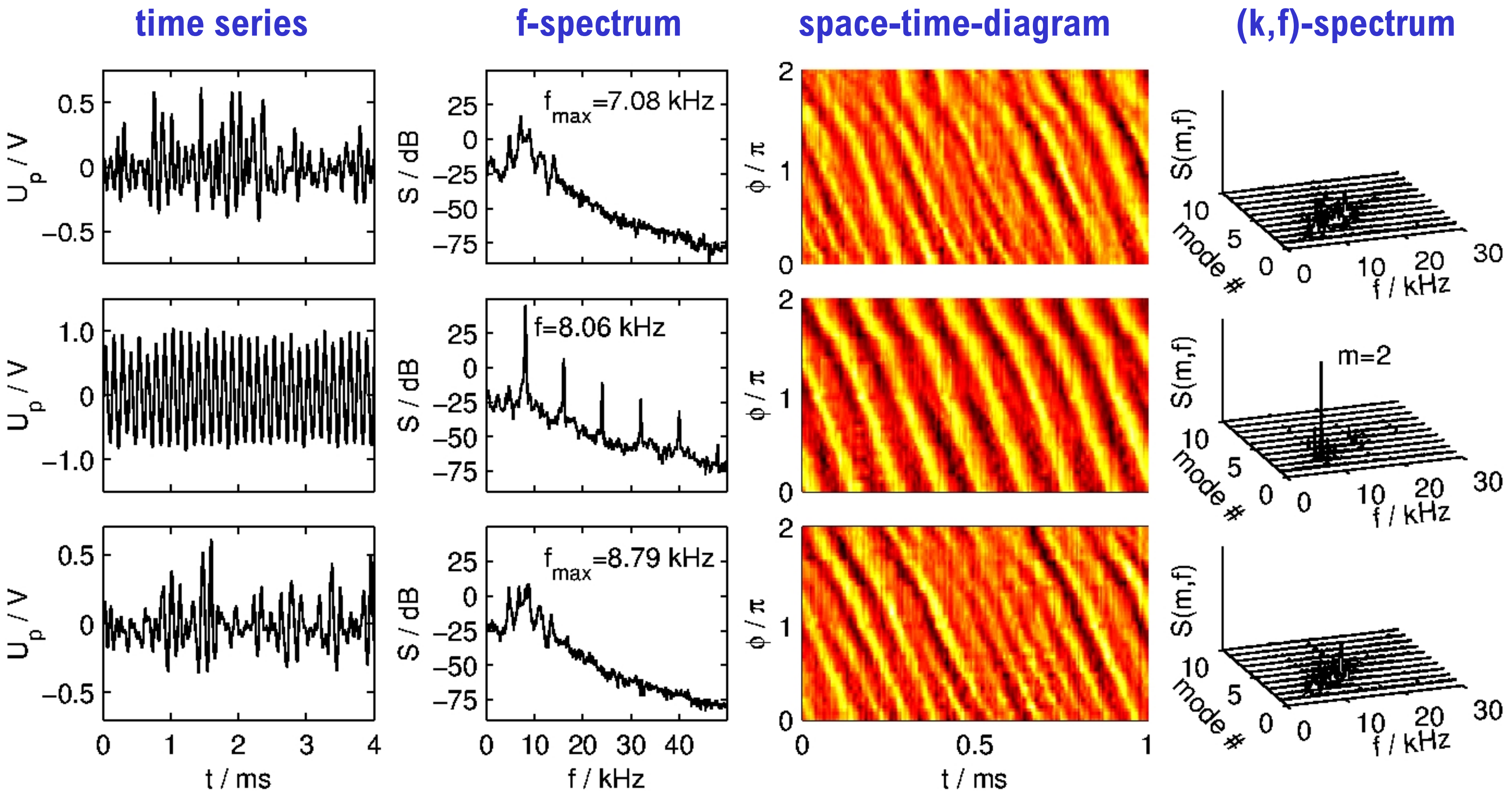
simulation result



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

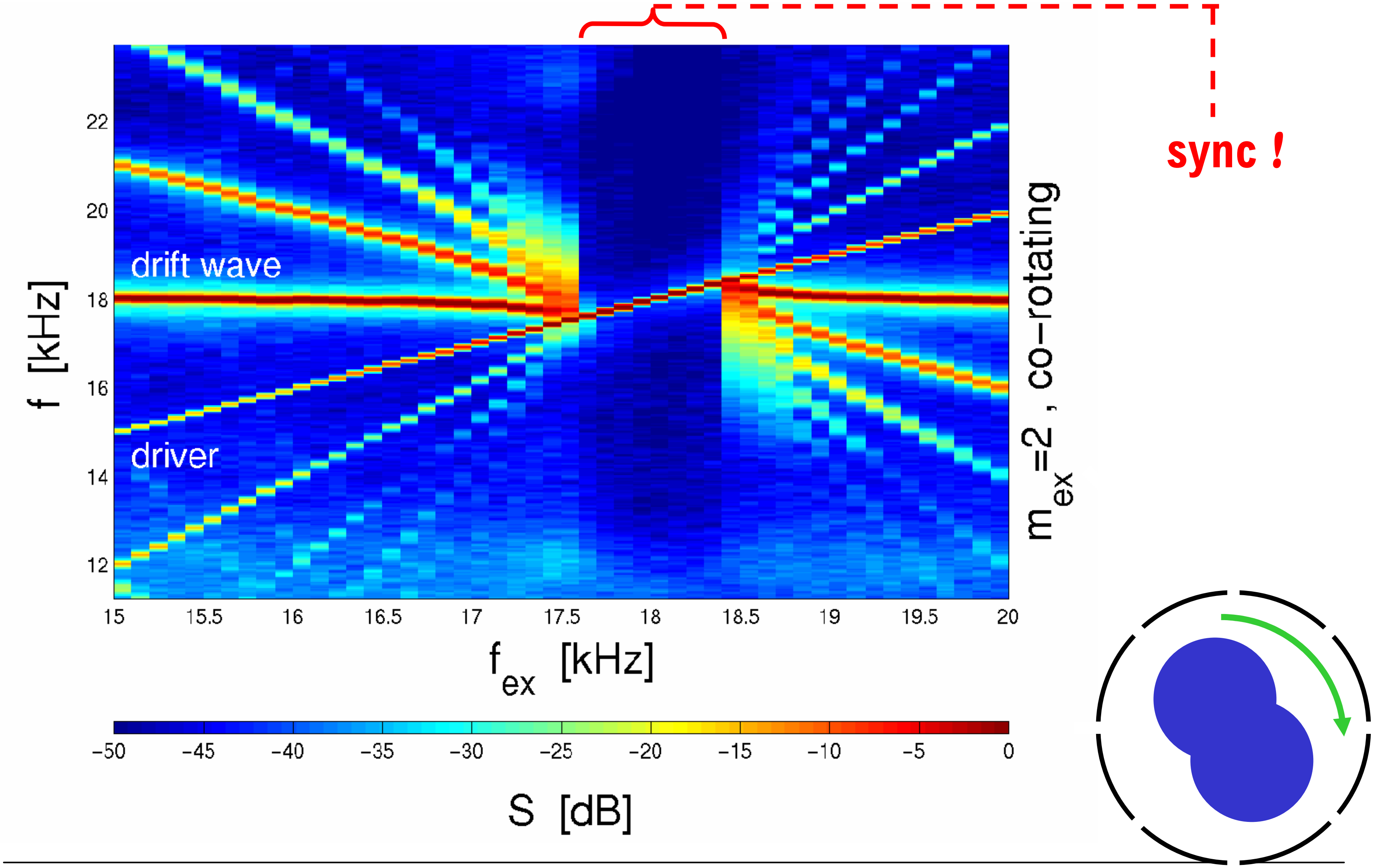
Schröder, T.K., Block, Piel, Bonhomme, Naulin, *PRL* 86, 5711 (2001)

experimental result



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

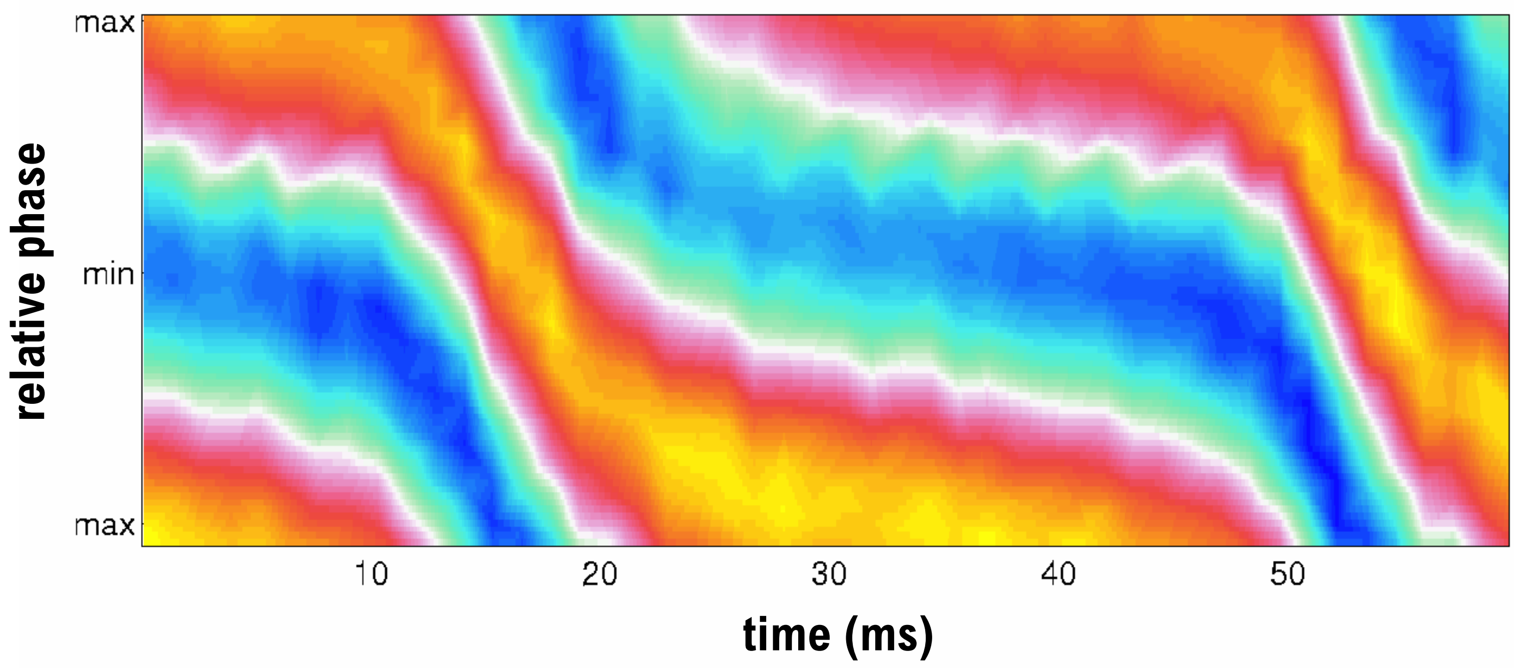
synchronisation of modes



synchronisation dynamics

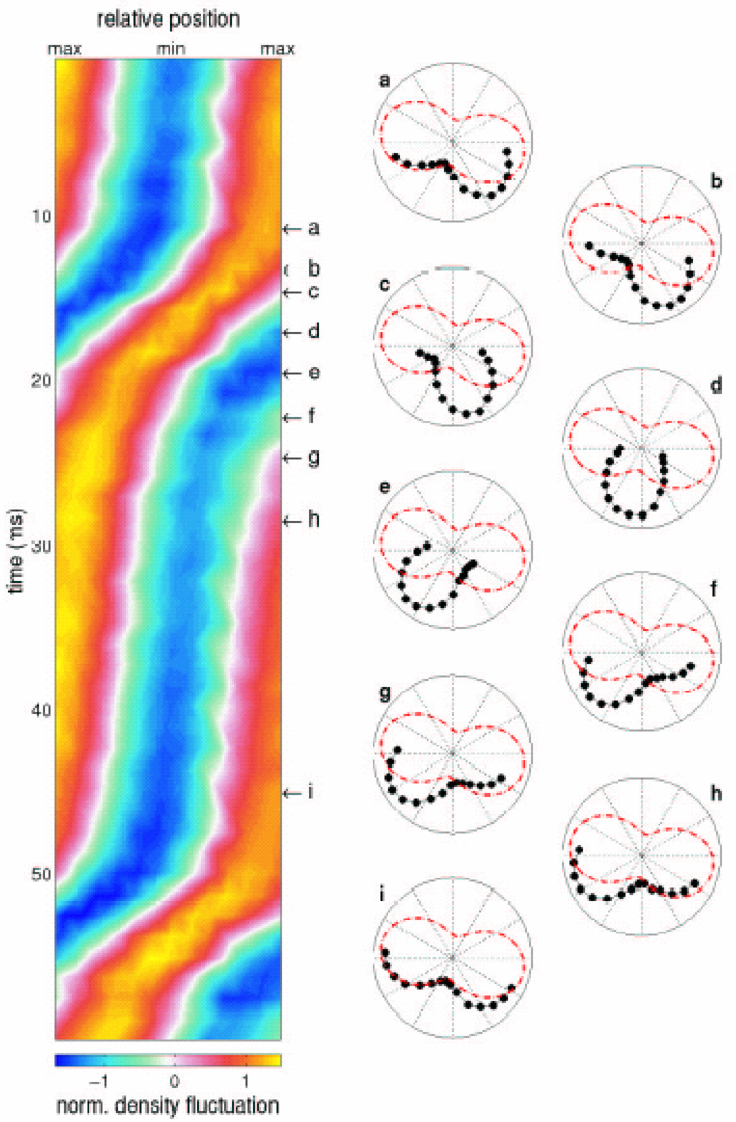
incomplete synchronisation - van-der-Pol behaviour

$$\ddot{x} - \gamma f(x, \dot{x})\,\dot{x} + \omega_0^2\,x = E_0 \cos(\omega_i t)$$

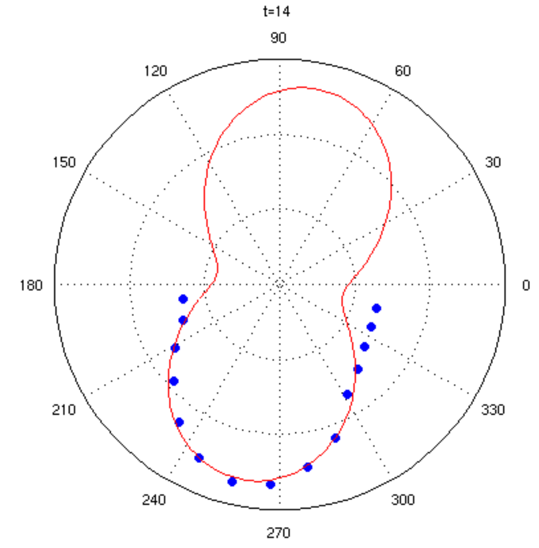


temporal modulation → spatial modulation

phase evolution



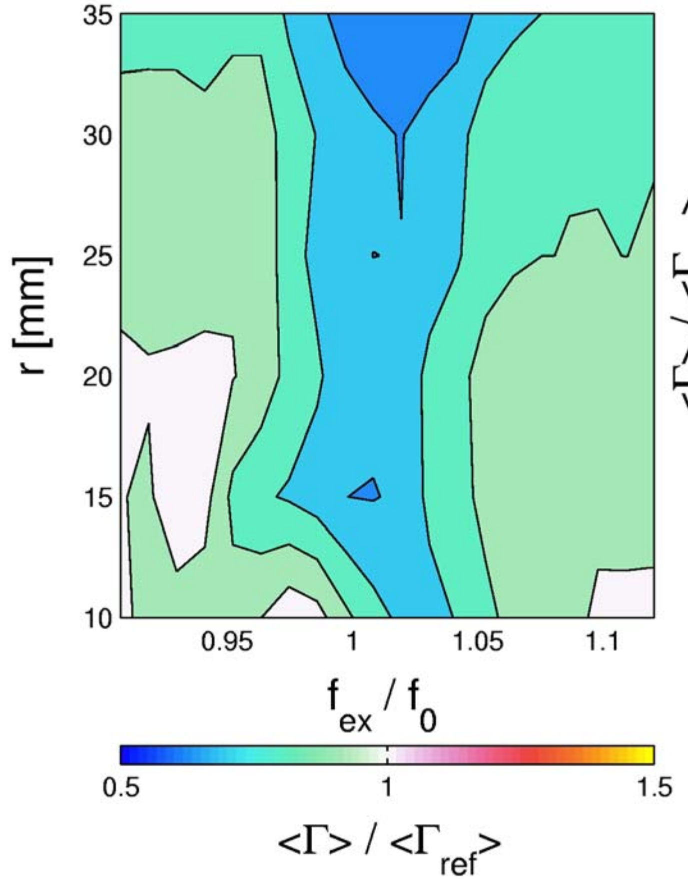
- m=2 exciter field
- moving frame
- drift mode response
- phase slippage
- periodic pulling

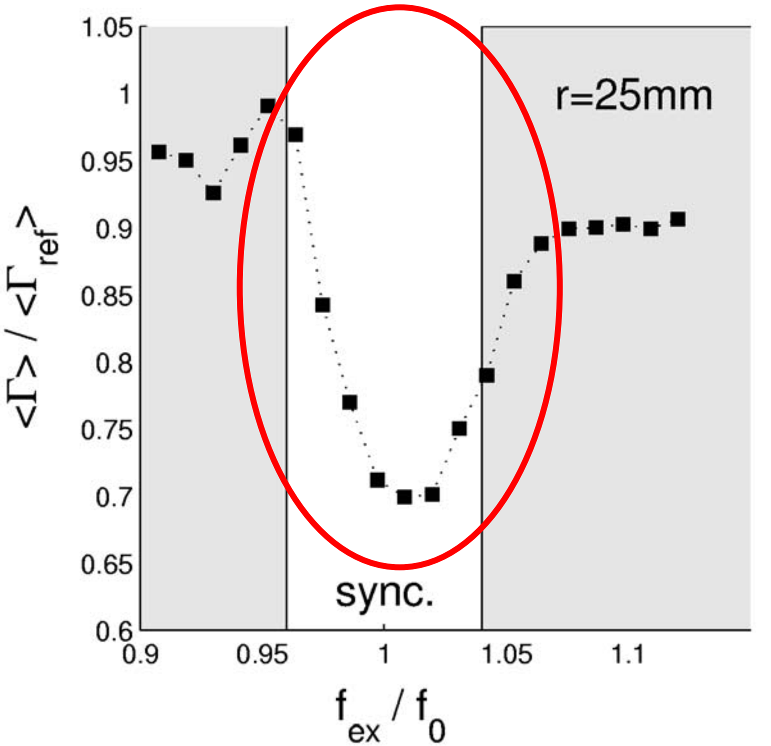


Block, Piel, Schröder, Klinger, *PRE* 63, 056401 (2001)

transport

$$\Gamma(\omega) = \frac{2}{B_0} C_{n,E}(\omega) \quad \text{with} \quad C_{n,E}(\omega) = \Re\, S_{n,E}(\omega) \quad \text{and} \quad \langle\Gamma\rangle = \int_0^\infty \Gamma(\omega)\, d\omega$$





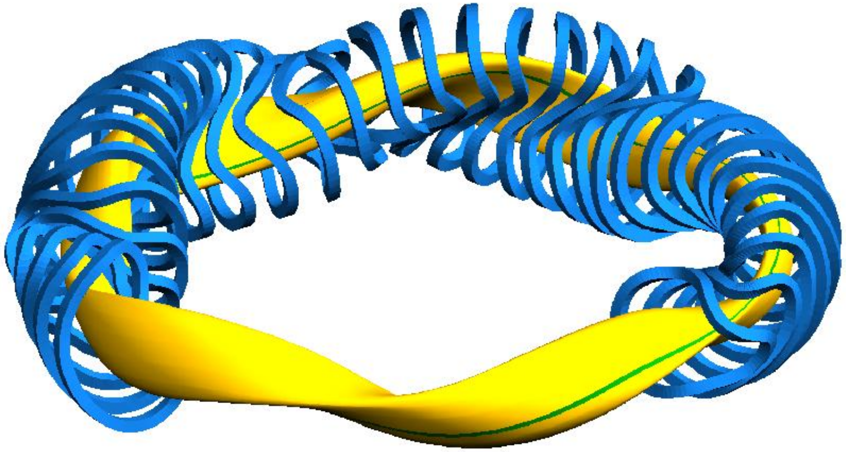
mode transport reduced by synchronisation!

Block, Piel, *PPCF* 45, 413 (2001), *ibd.* 427

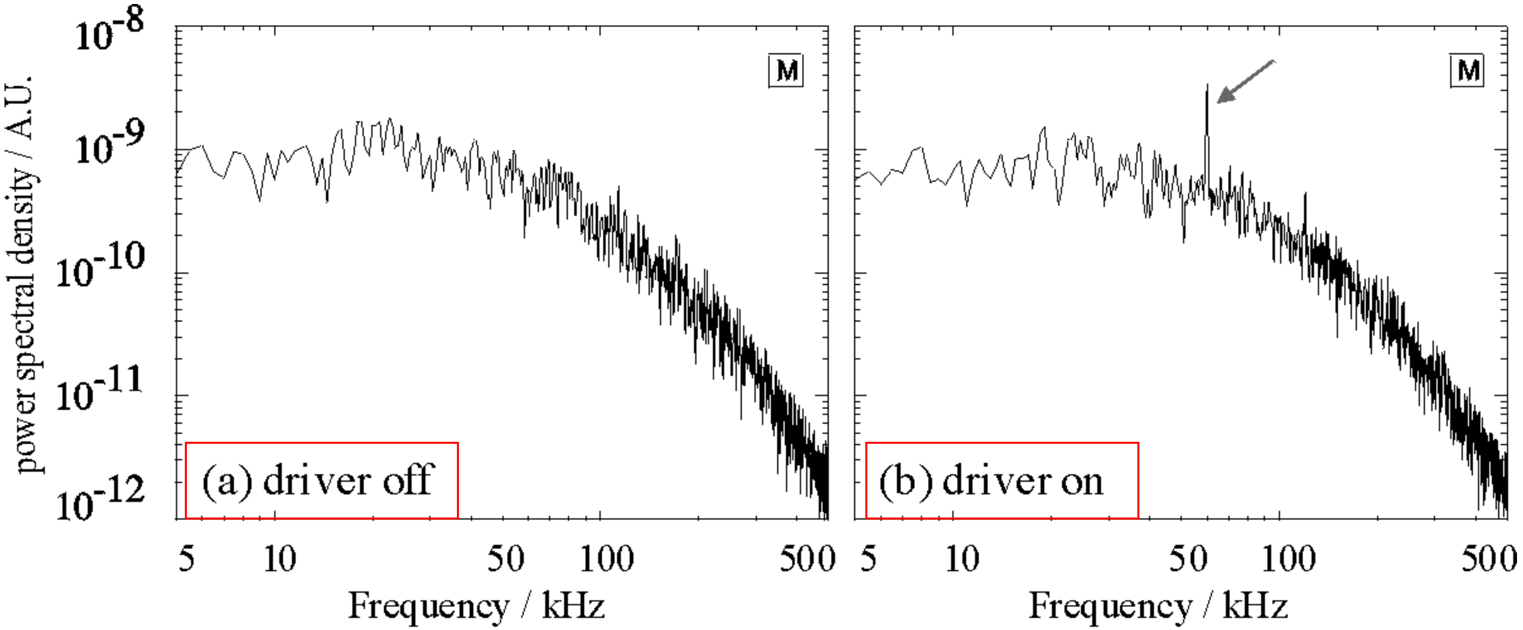
outlook

proof of priciple ✓

how about the big devices?

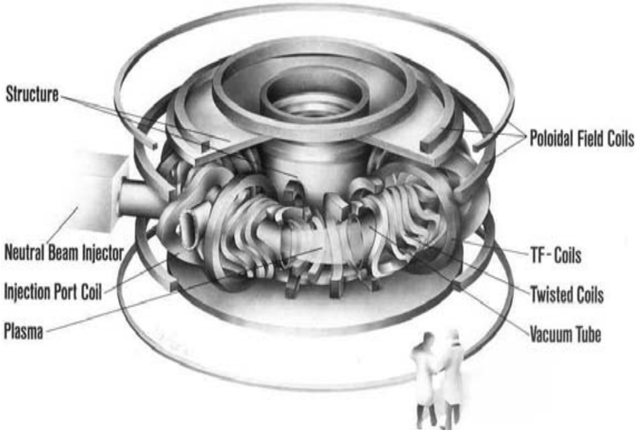


turbulence in W7-AS



driver frequency observed ~ weak impact …

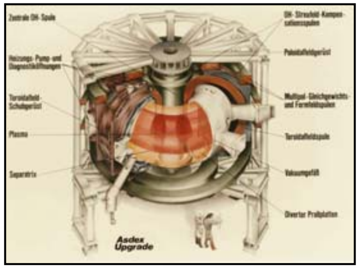
- **E×B co-rotation ⇒ phase coupling**
- **E×B co-rotation ⇒ phase slippage**

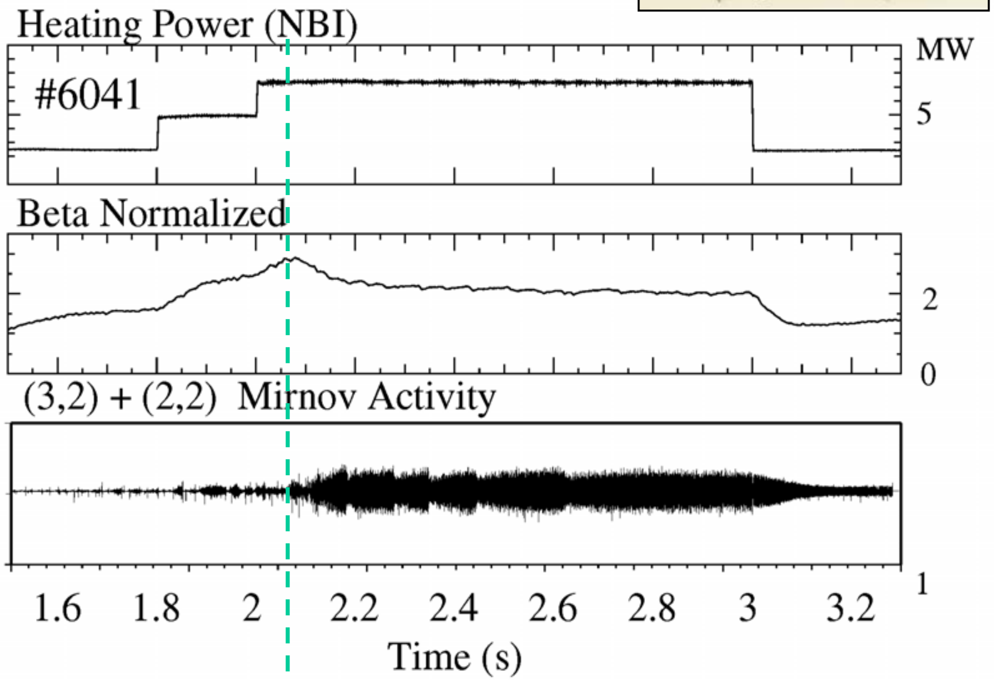


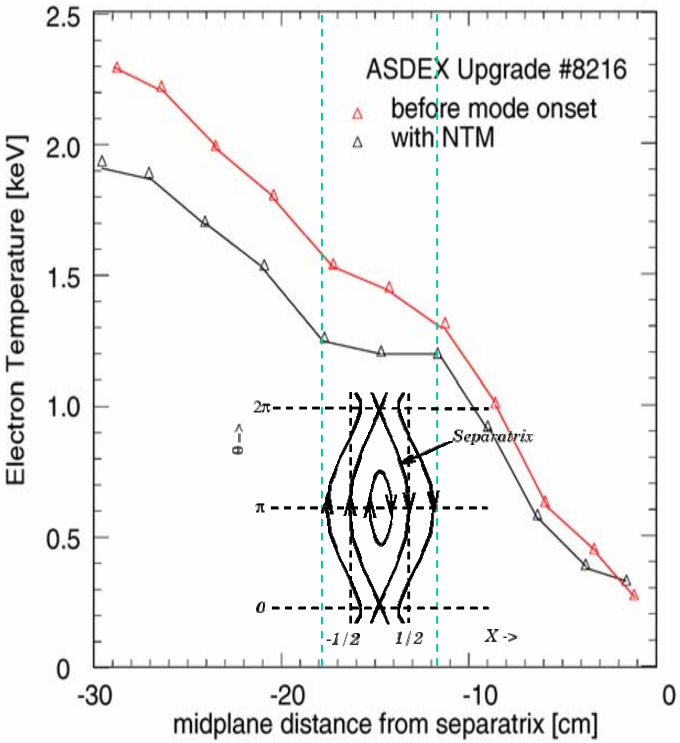
Thomsen et al., *PPCF*, to be published 2004

neoclassical tearing modes

ASDEX Upgrade shot #6041



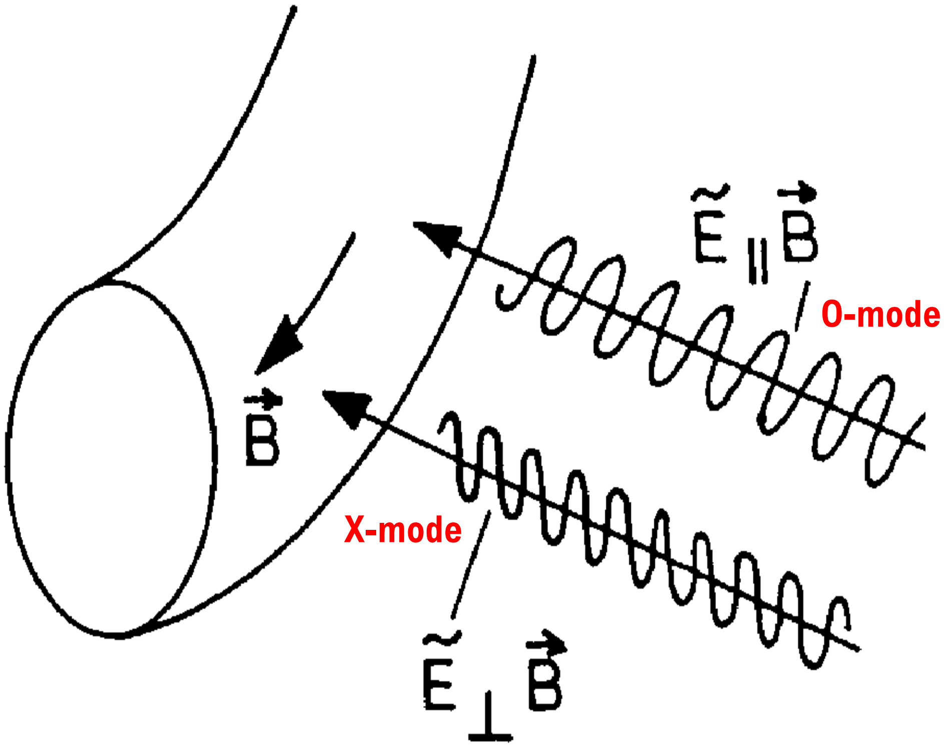


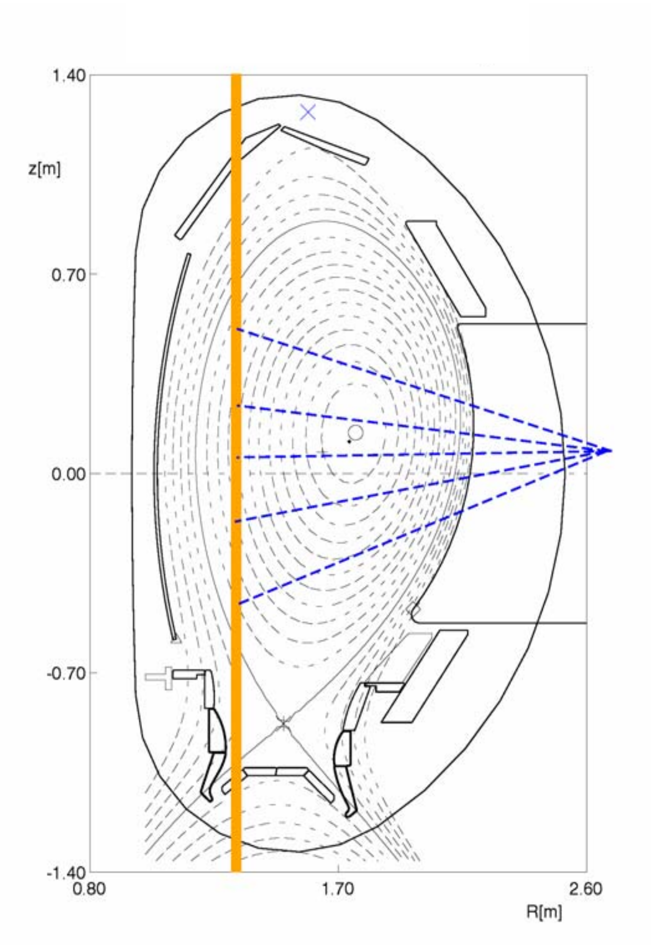


above critical β magnetic islands develop

flattened *p(r)* produces helical 'hole' in bootstrap current

ECCD in magnetic islands

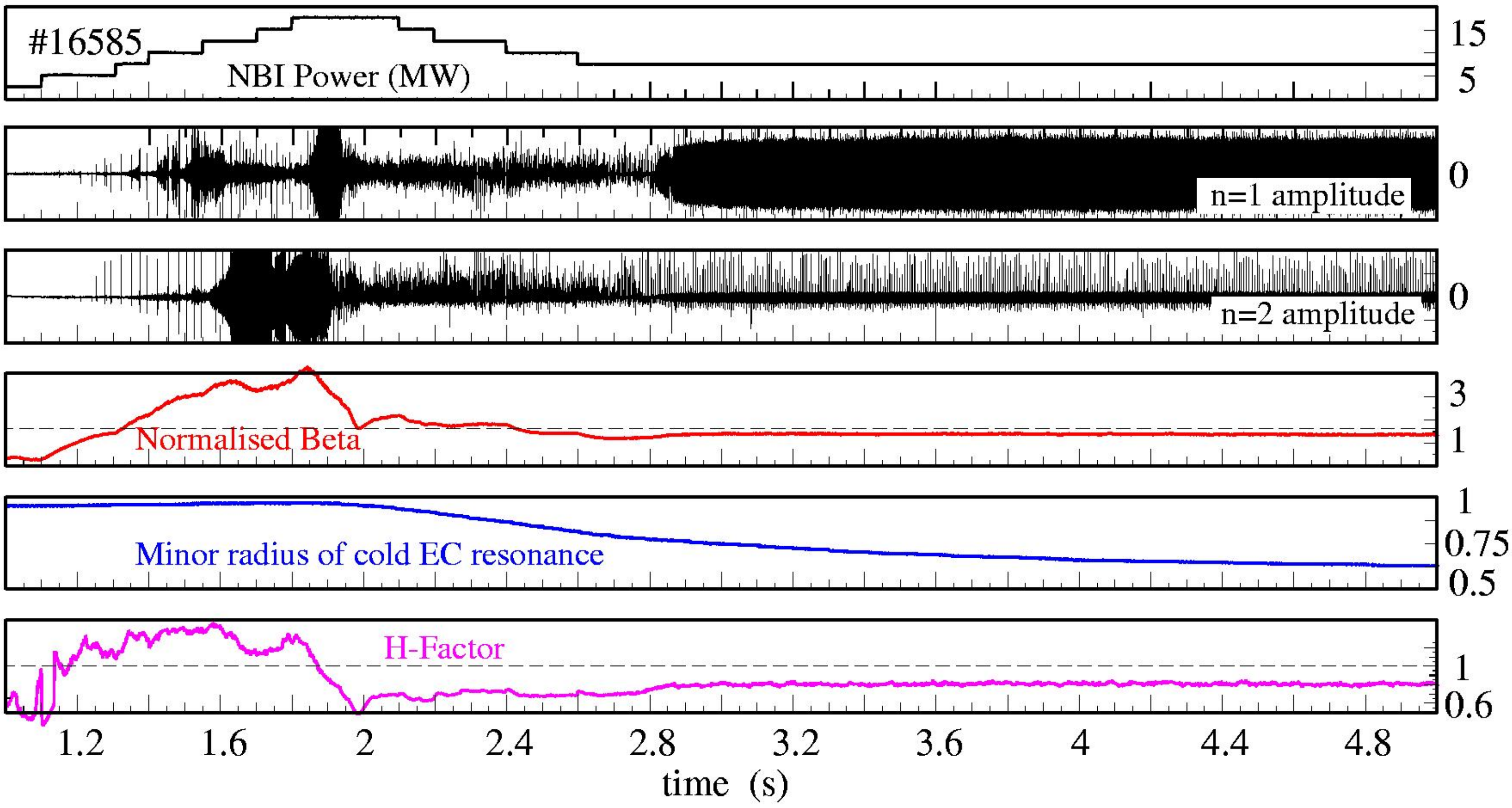




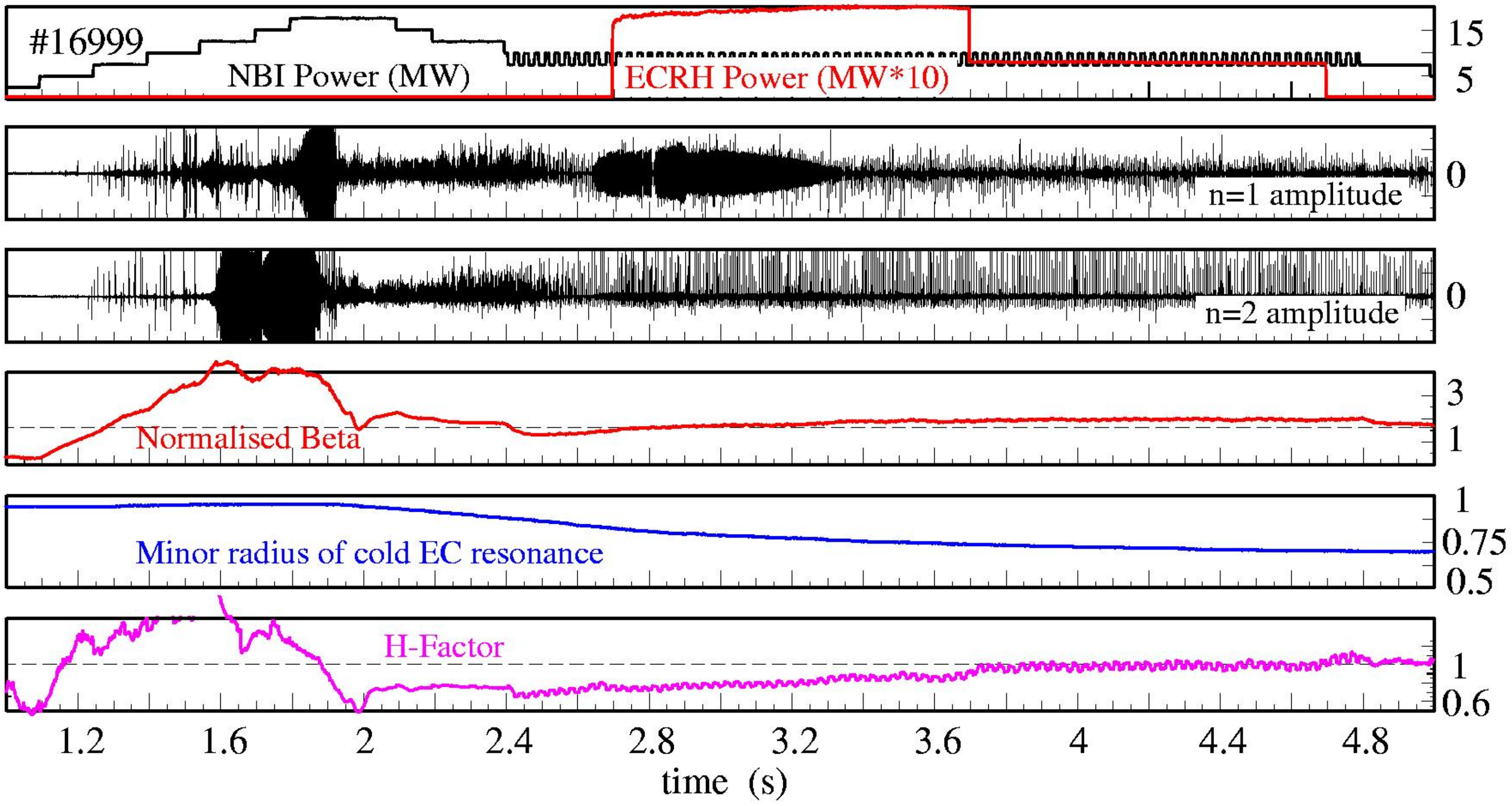
ECR O-mode deposition ~ width down to 2 cm

Can be used to replace the hole in the bootstrap current distribution

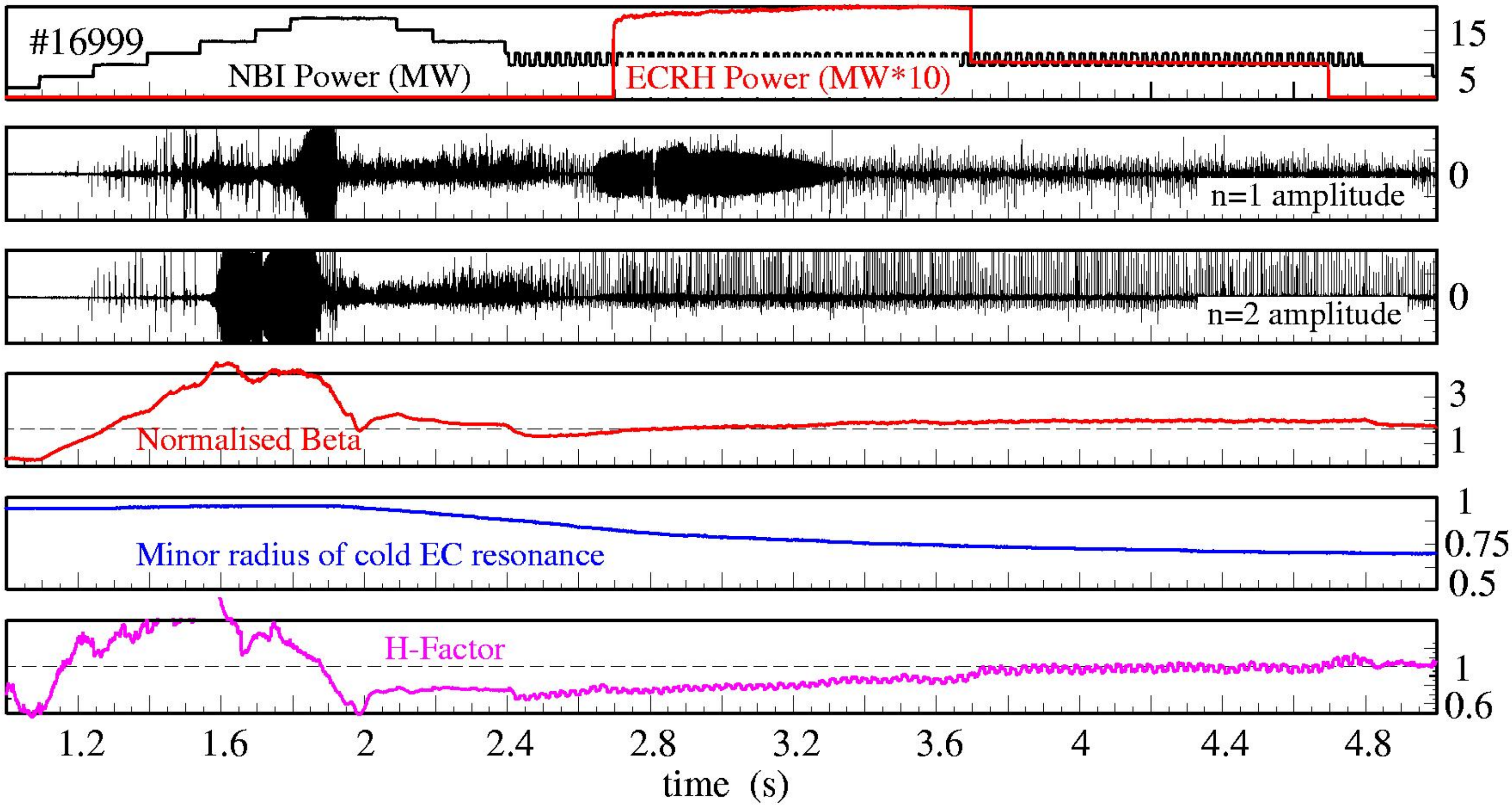
NTMs – no control



NTMs - control



NTMs - control



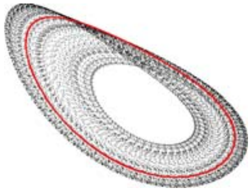
Zohm et al, Nuclear Fusion 39, 557 (1999)

perspective: feedback control

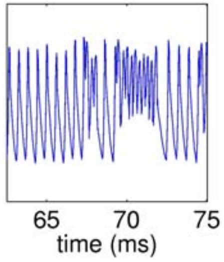
conclusion

Proof-of-principle experiments on control of …

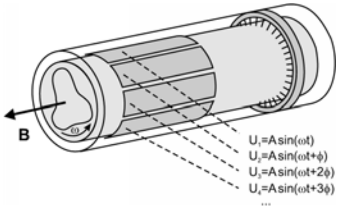
chaos ………… bounded plasmas



noise ………… stochstic resonance



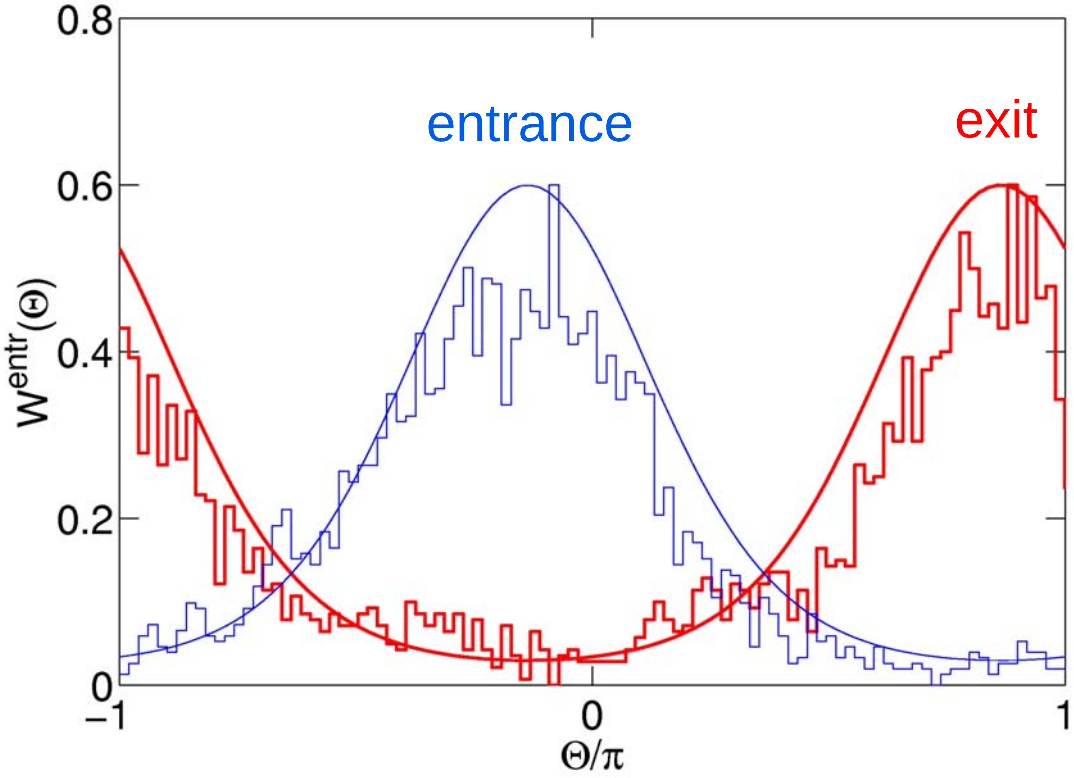
turbulence …… Spatial sychronisation



phase distributions

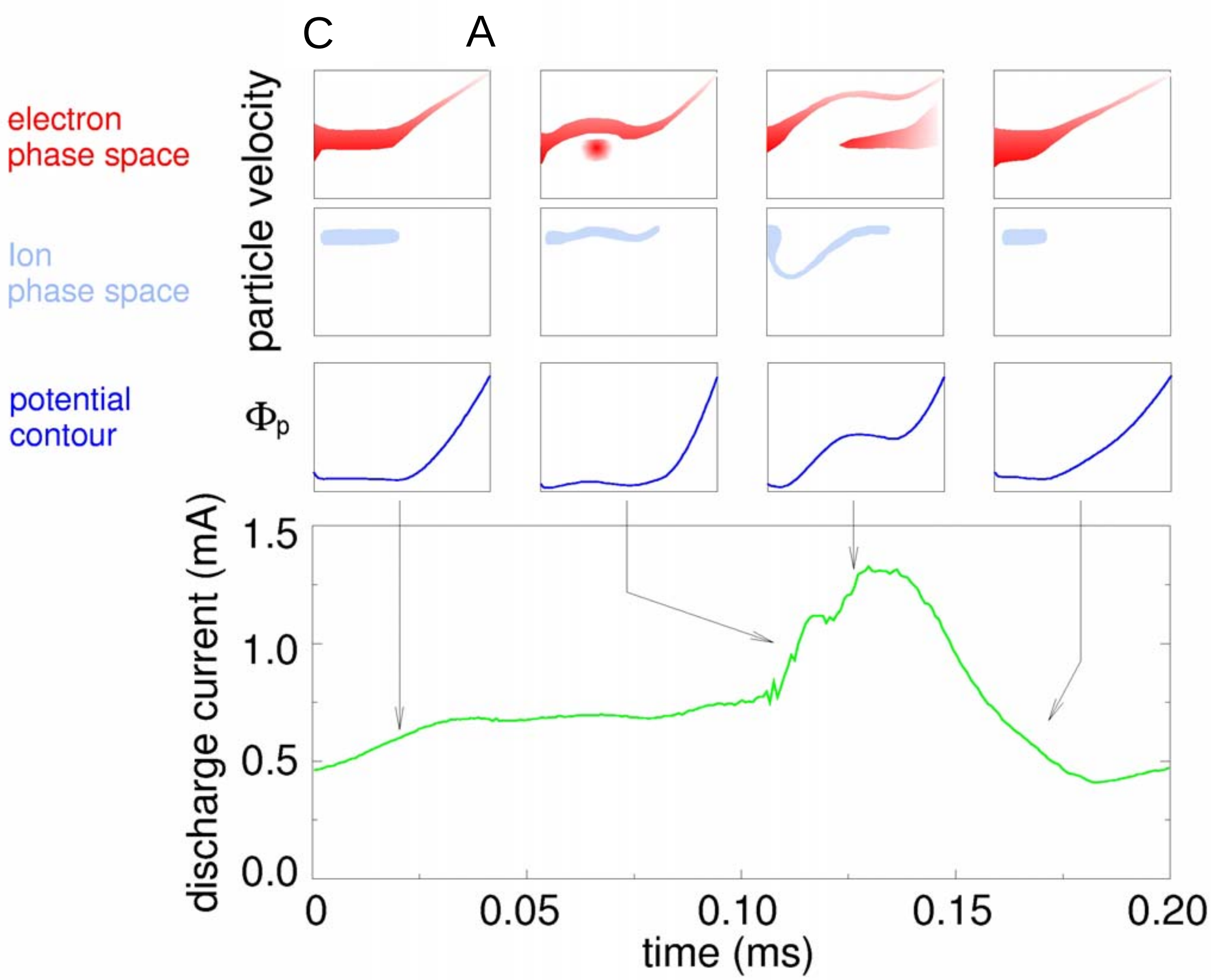
$$W^{entr}(\theta) = \frac{1}{2\pi}\left[1 \pm \frac{\alpha}{\sqrt{1+4\beta^2}}\,\sin(\phi+\delta)\right]$$

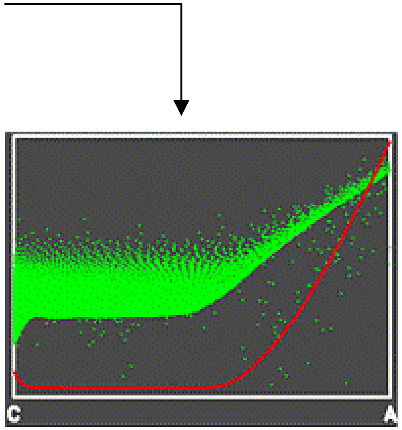
Choi et al., *PRE* **57**, 6335 (1998)



experiment and theory agree well ...

AGM current oscillations

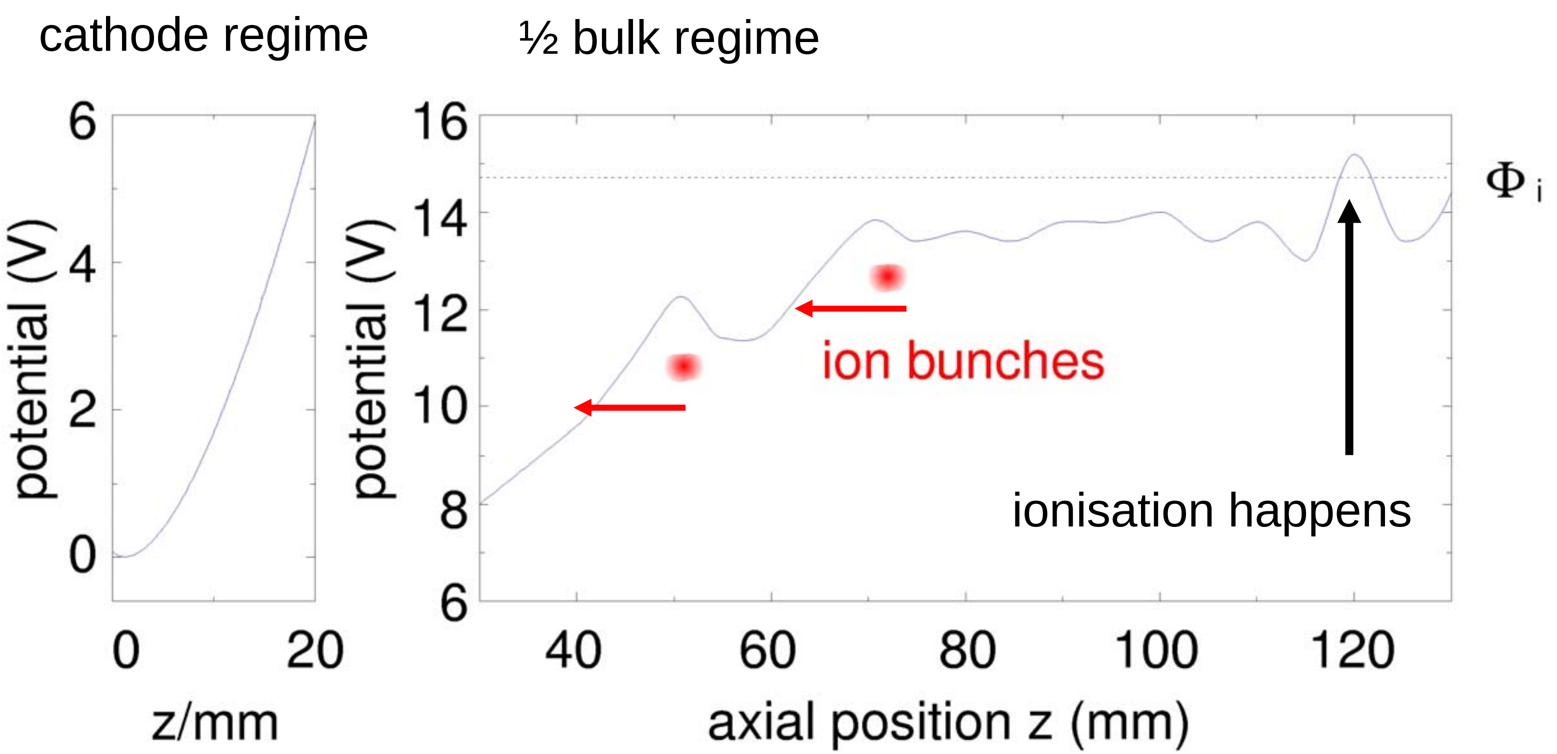




potential
relaxation
oscillation

Greiner et al., *PRL* **70**, 3071 (1993)

LM current oscillations



➢ ion bunches created at ϕ_i – position

➢ travel along axial electric field

➢ eventually neutralize virtual cathode

Ding et al., *PLA* **222**, 409 (1996)

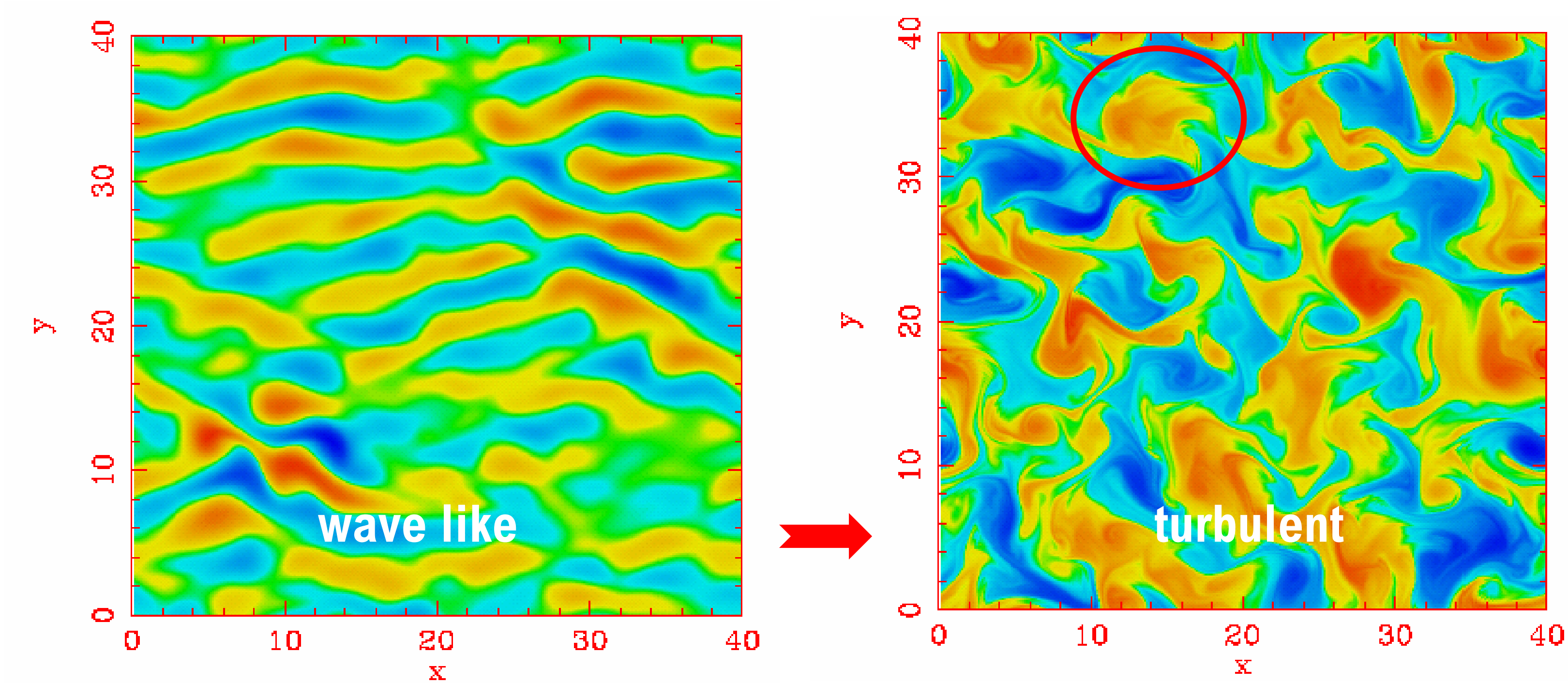
Hasegawa-Wakatani model

plasma potential

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

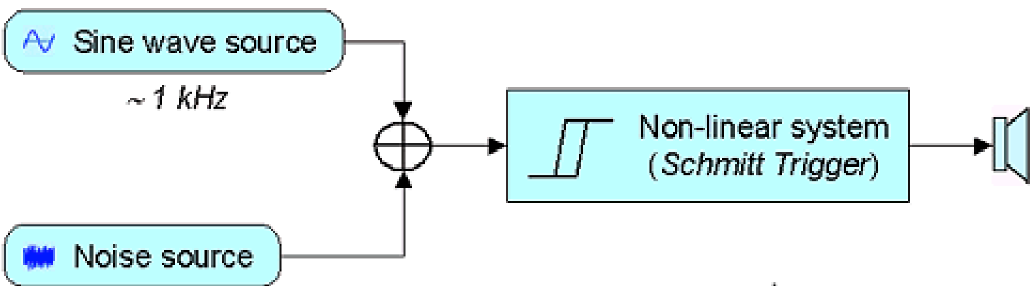
plasma density

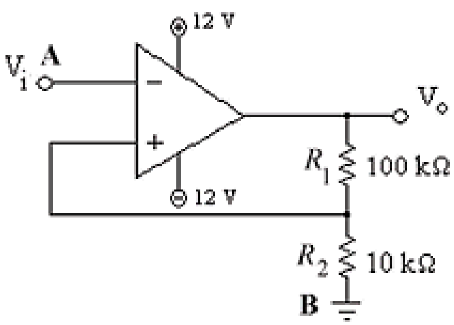
$$\frac{\partial}{\partial t}n + \vec{V}_{E\times B}\cdot\nabla\left(N_0 + n\right) = \tilde{\sigma}\left(\phi - n\right) + \mu_n\nabla_\perp^2 n$$

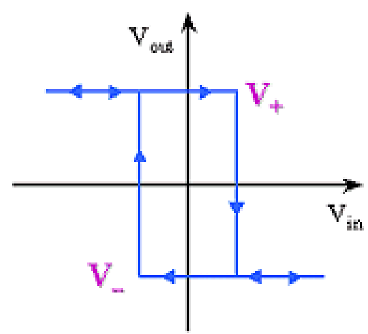


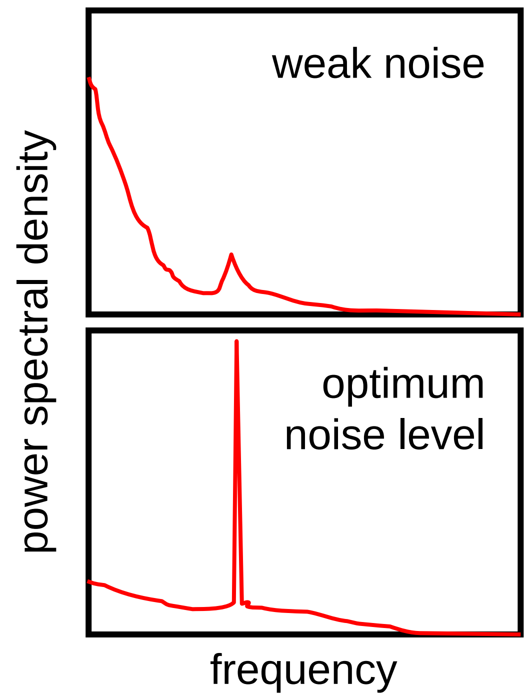
simple example

bistable → Schmitt trigger
- periodic drive
- superimposed white noise



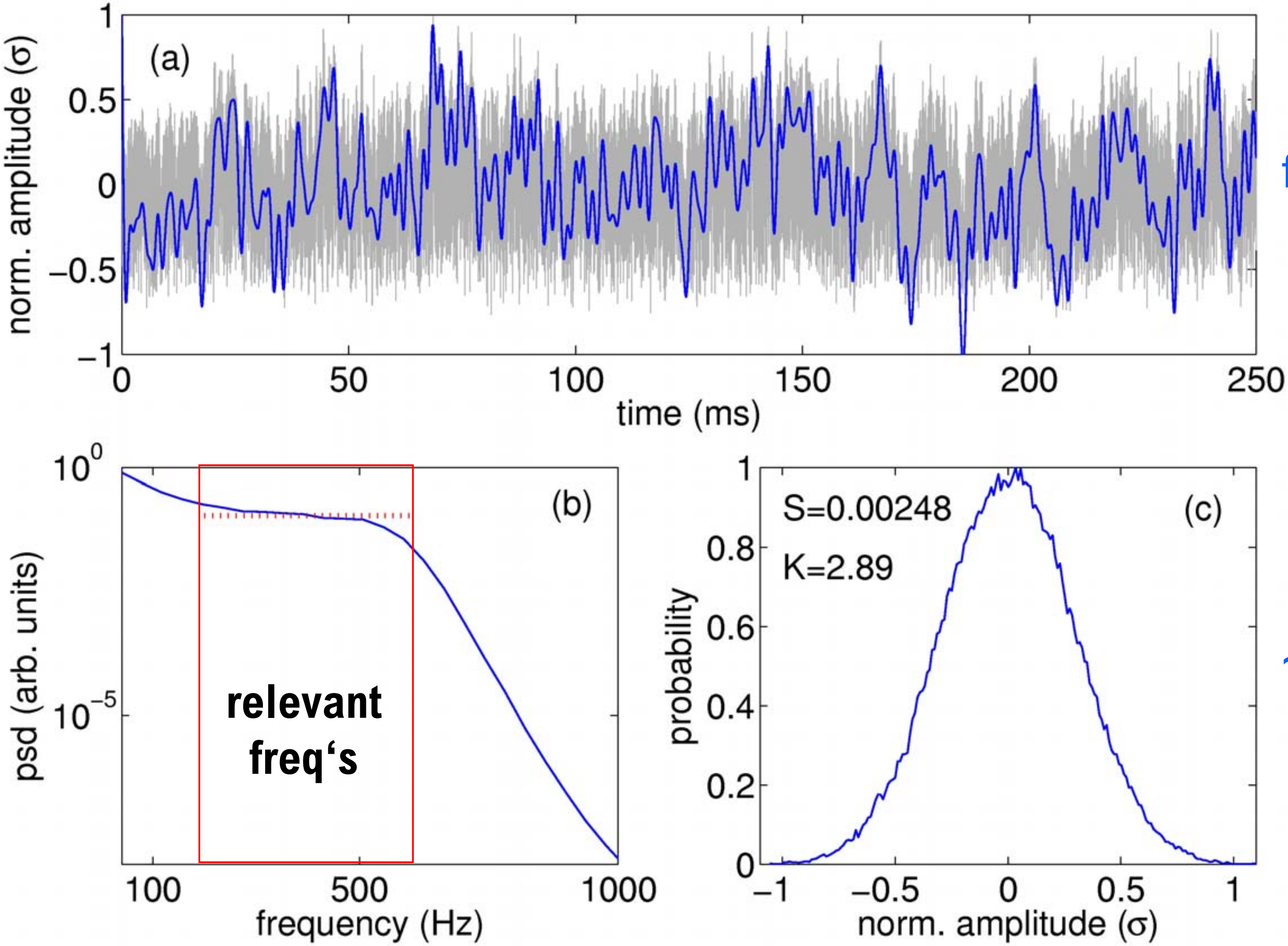






Fauve and Heslot, *PLA* **97**, 5 (1983)

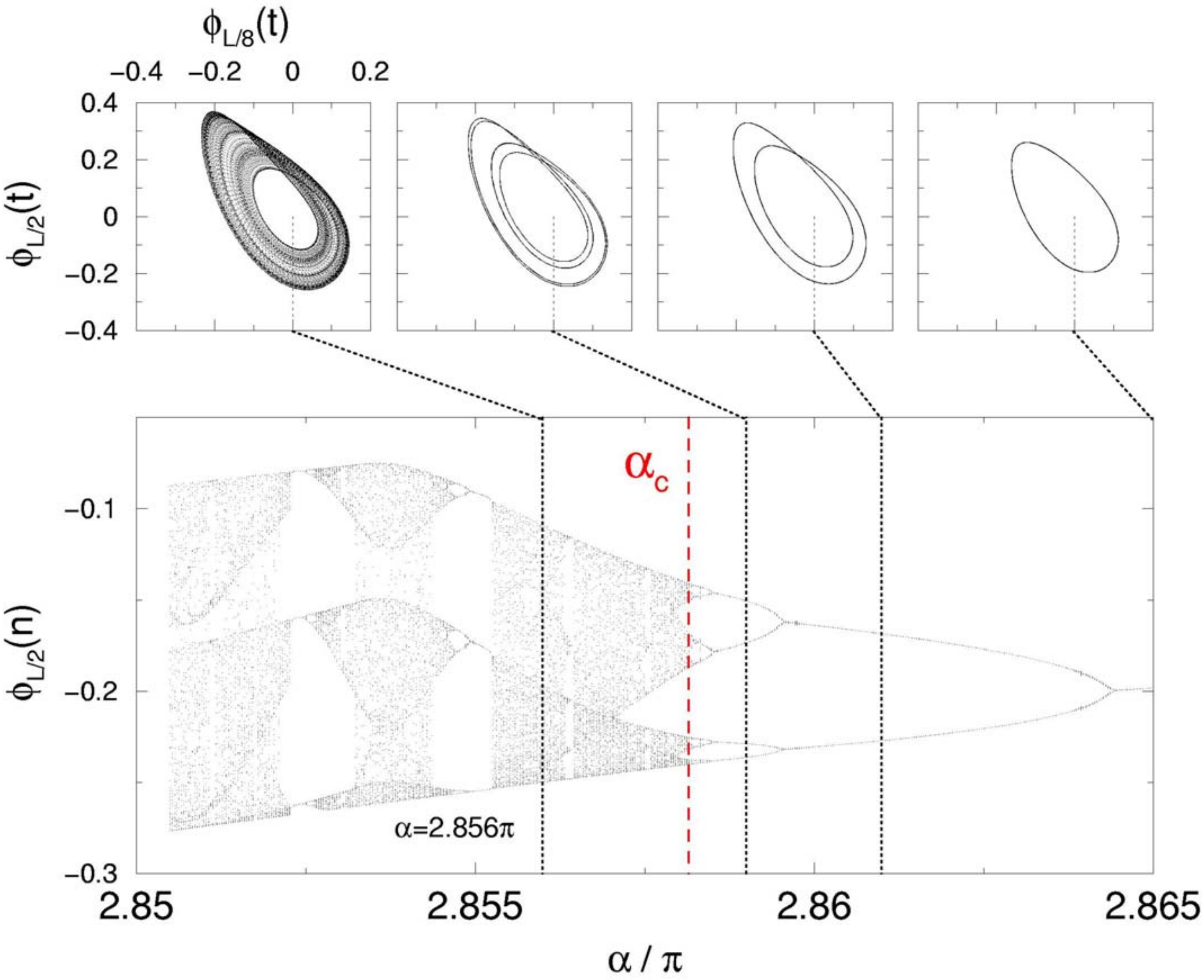
intrinsic noise



filtered data

~ Gaussian

period doubling cascade



control schemes