Transport Control in Tokamaks

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2010

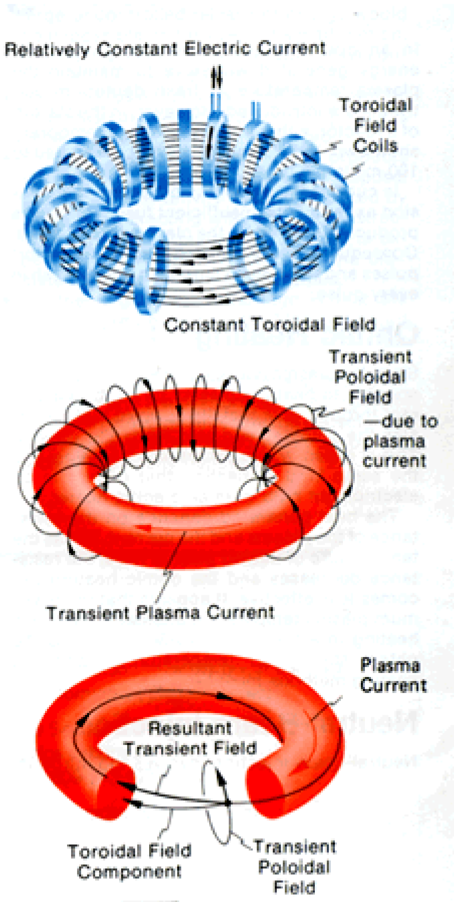
I - Introduction

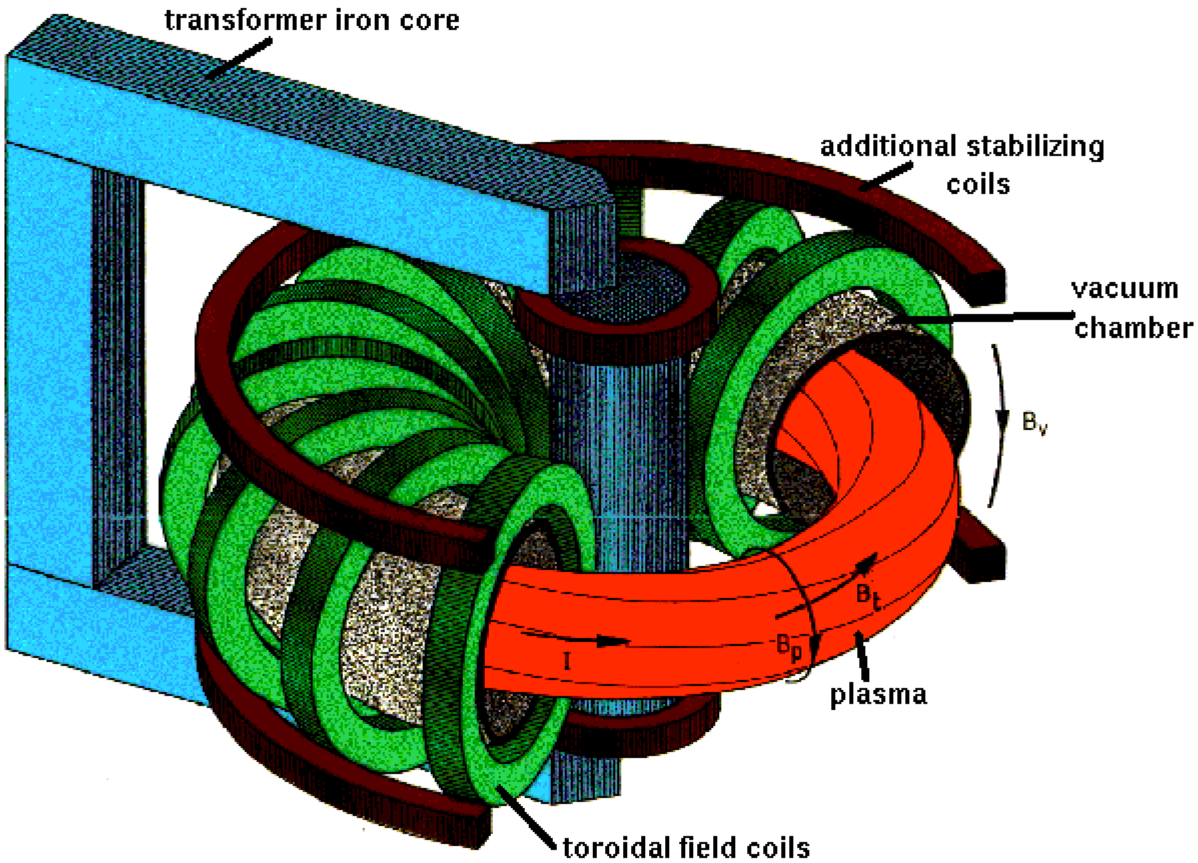
Controlled Nuclear Fusion

Particle transport at the plasma edge

Plasma wall interaction

Plasma Confined in Tokamaks





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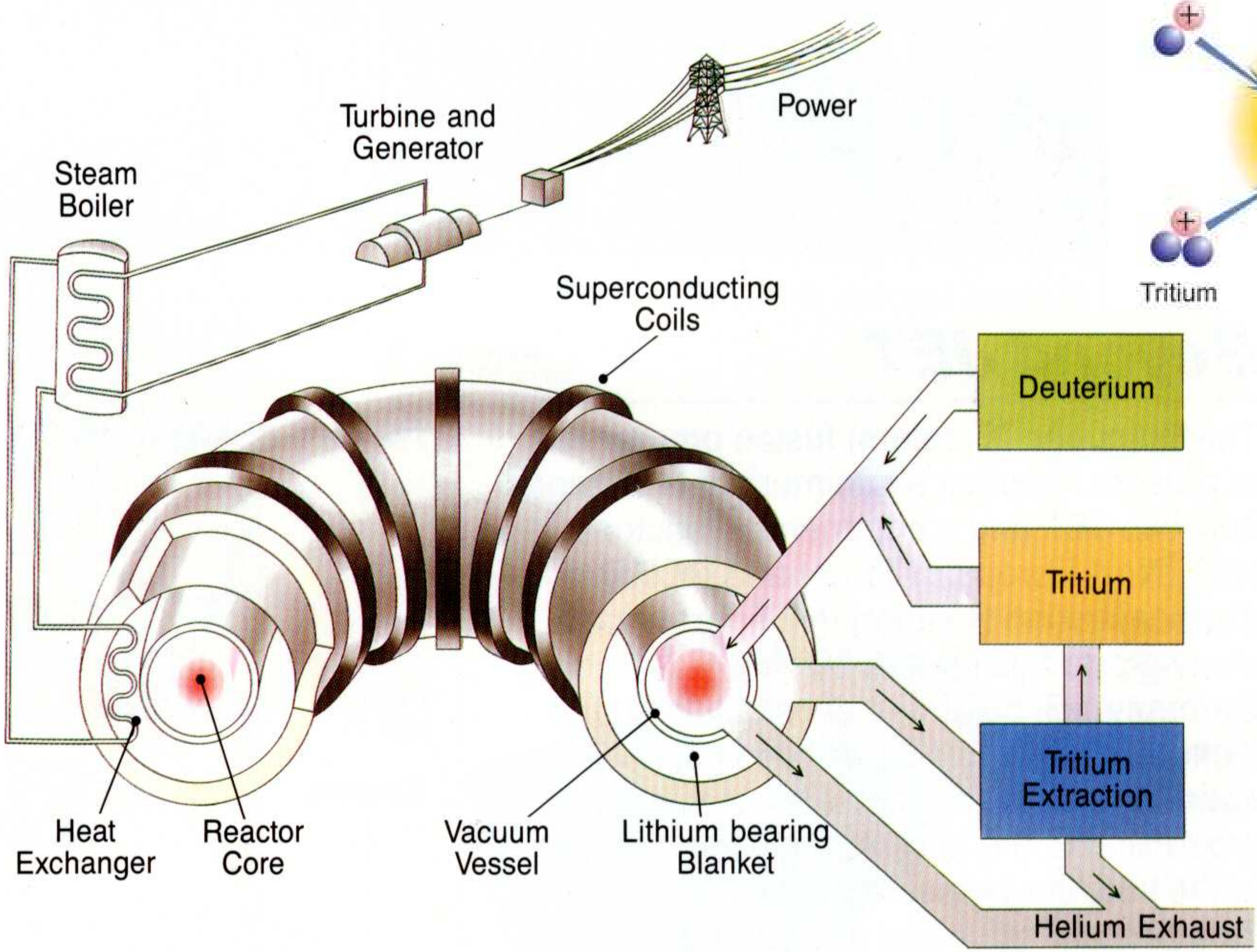
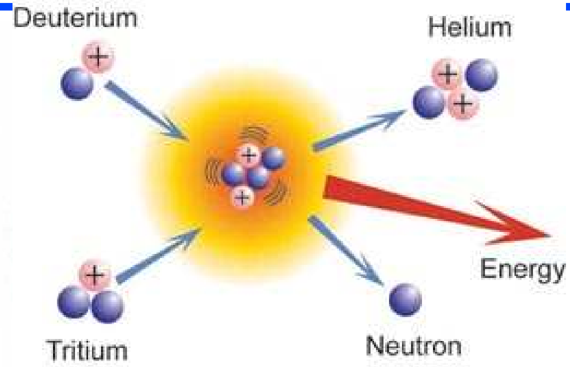
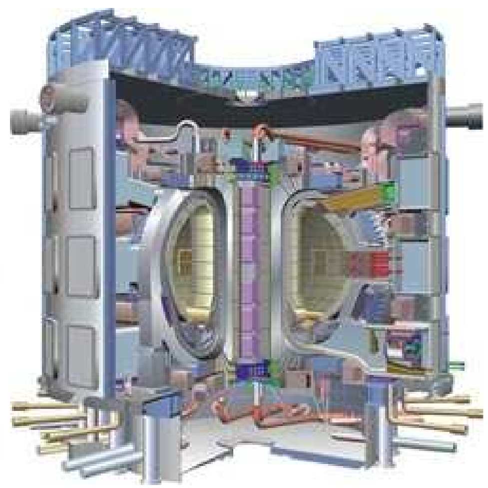






Controled Nuclear Fusion

- Tokamaks present the best performance for magnetic plasma confinement.

- Nowadays, investigations in several tokamaks.

- ITER test of nuclear fusion viability.

Nonlinear Dynamics

- In tokamaks, plasma edge particle transport and plasma wall interaction limits the confinement.

- Physics and dynamics of these processes are not well understood.
- Non linear dynamics is necessary to explain present experimental knowledge.

- Mapping is introduced to investigate chaos at the plasma edge.

Two of the main problems for fusion are adressed in this work

- Anomalous plasma edge particle transport

- Palsma-wall interaction

II- Chaotic Particle Transport

F. A. Marcus, I. L. Caldas (University of São Paulo, Brazil)

P. J. Morrison, W. Horton (University of Texas at Austin, USA)

Marcus, Ph. D. thesis, IFUSP, 2007.
Marcus et al., Nuclear Fusion (2008)
Marcus et al., Physics of Plasmas (2008)

Particle Transport in Tokamaks

- Anomalous particle transport limits plasma confinement in tokamaks.

- Recently, several procedures are tried to reduce this trasnport.

Experimental observation: at plasma edge, a non uniform electric field leads to formation of particle transport barriers and to improved confinement.

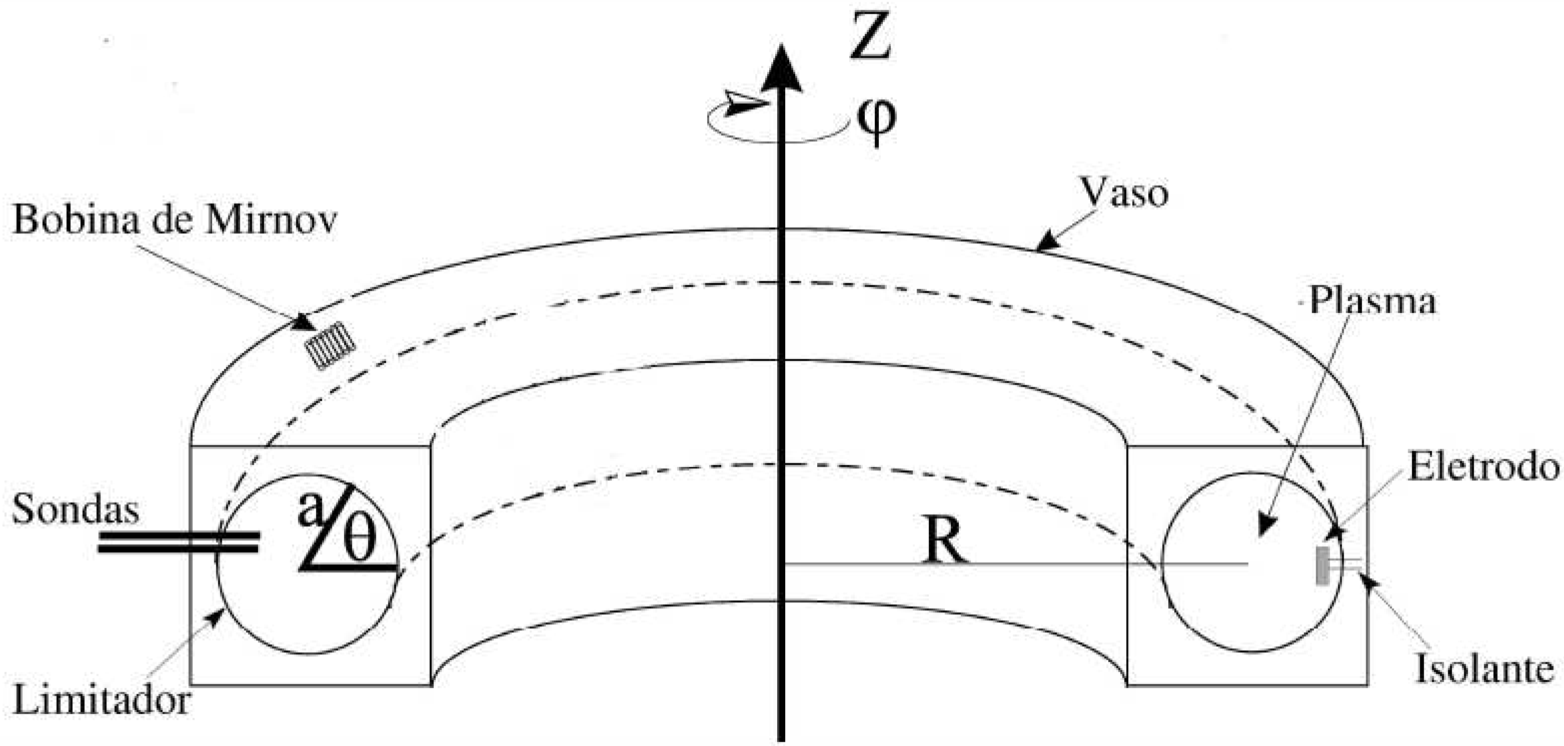
Text Upgrad tokamak – Ritz et al., Phys. Rev. Let., 1989.

Castor tokamak – Devinck et al., Phys. Plasmas, 2005.

TCA BR tokamak – Nascimento et al., Nuclear Fusion 2005, 2007

Our theoretical result: dynamical effects explain this experimental observation

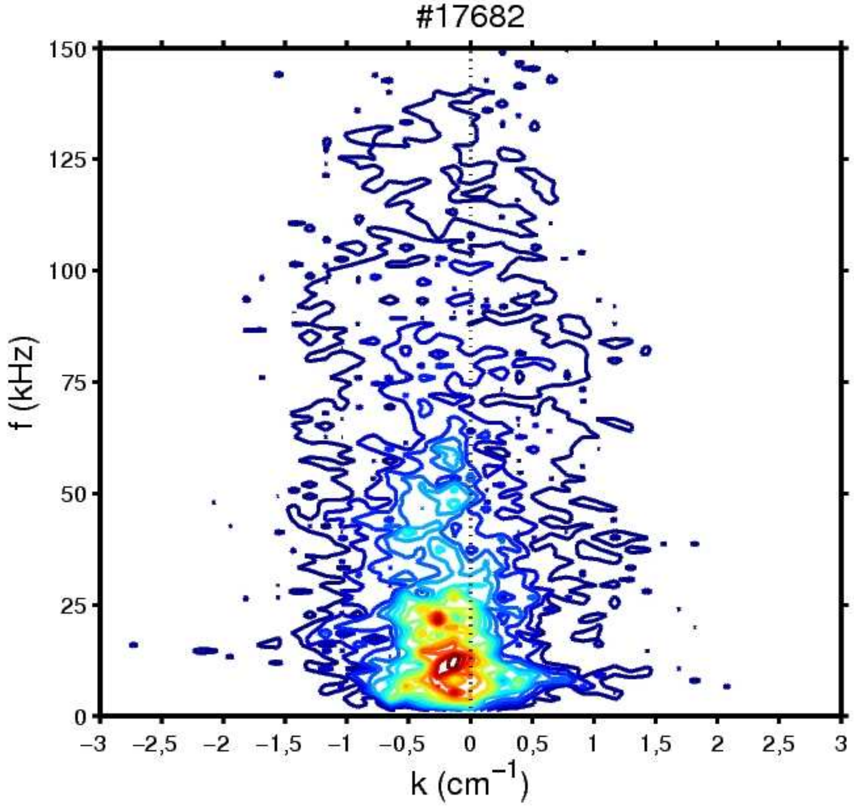
Tokamak TCABR



Languimir probes and electrode

Dispersion Relation Measured in TCABR

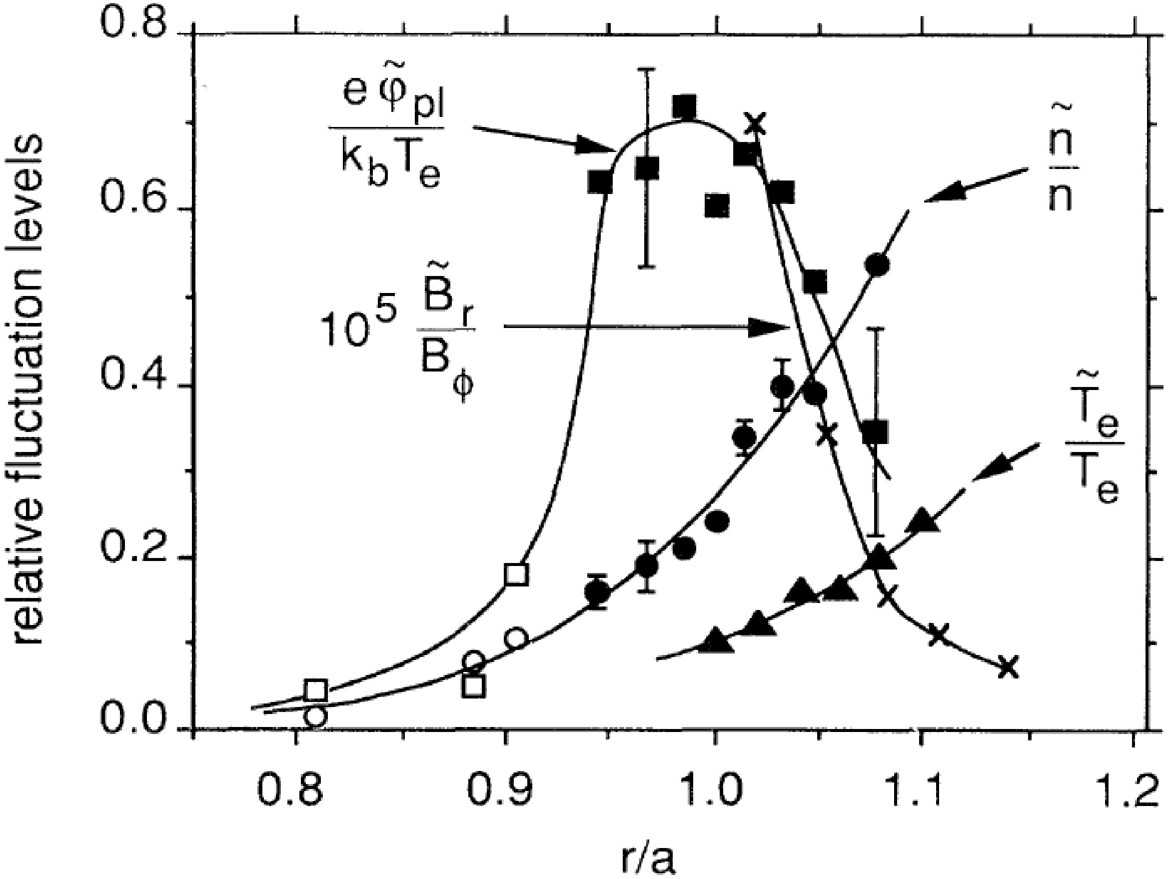
Choose dominant wave



Frequency and poloidal wave nember

Plasma Edge Turbulence

Text Upgrade
Ritz, PRL 1989



Normalized radial coordinate

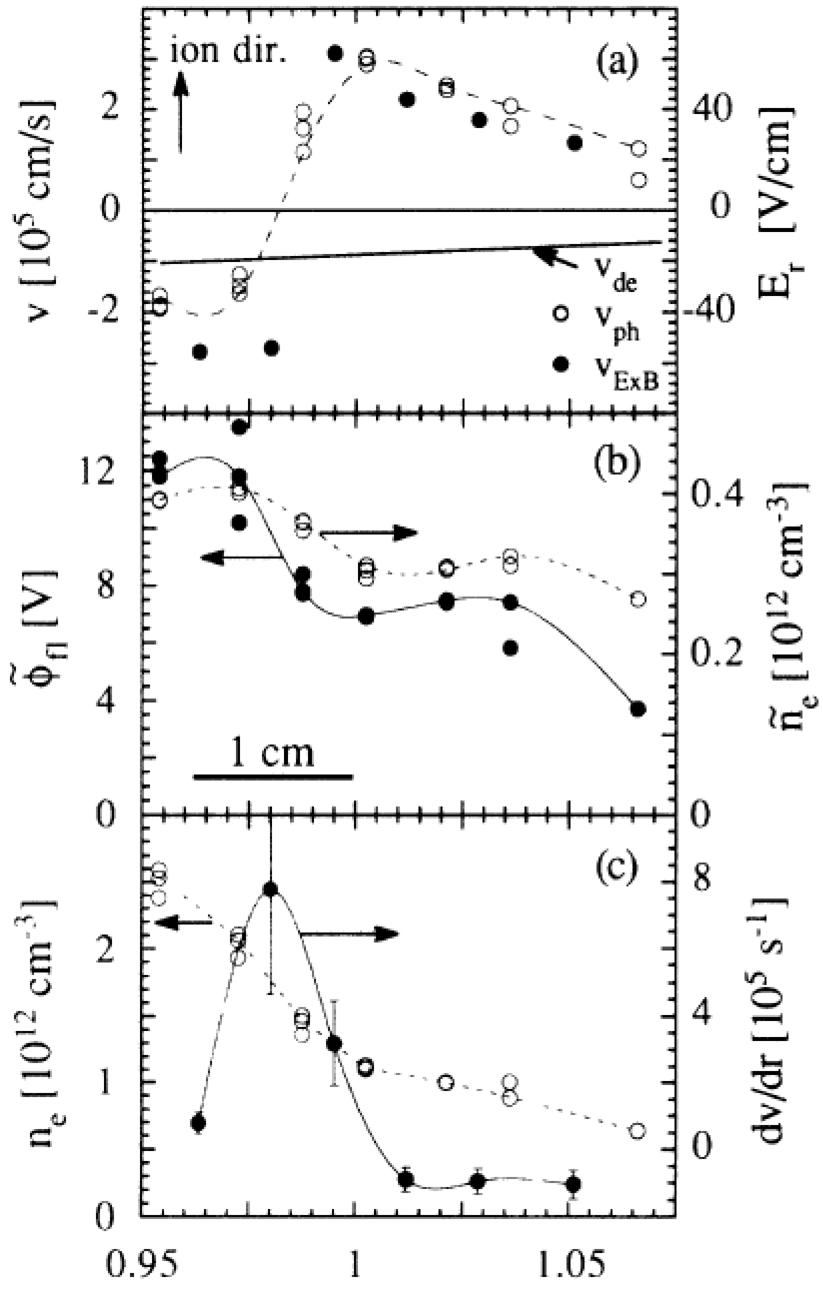
Plasma edge:
r/a ~ 1

Text Upgrade
tokamak
Ritz, PRL, 1989

$V_E \approx V_{ph} \rightarrow$ relevant contribution

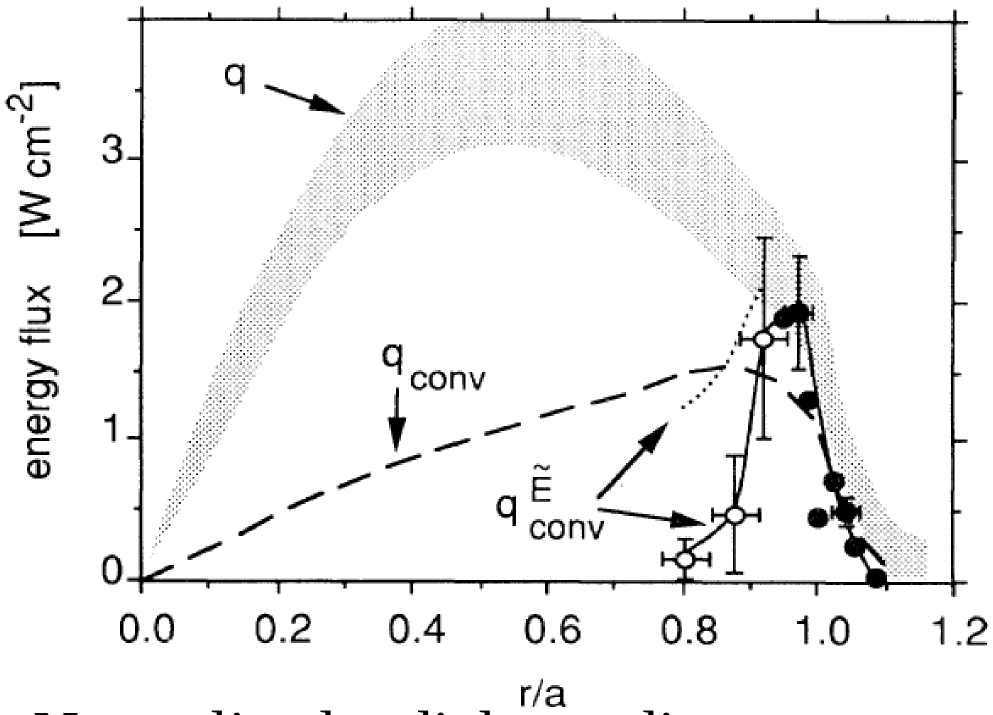
$U \approx 0$ (high transport)

$U \approx 1$(barrier)



Energy Flux at Plasma Edge is Caused by Drift Waves

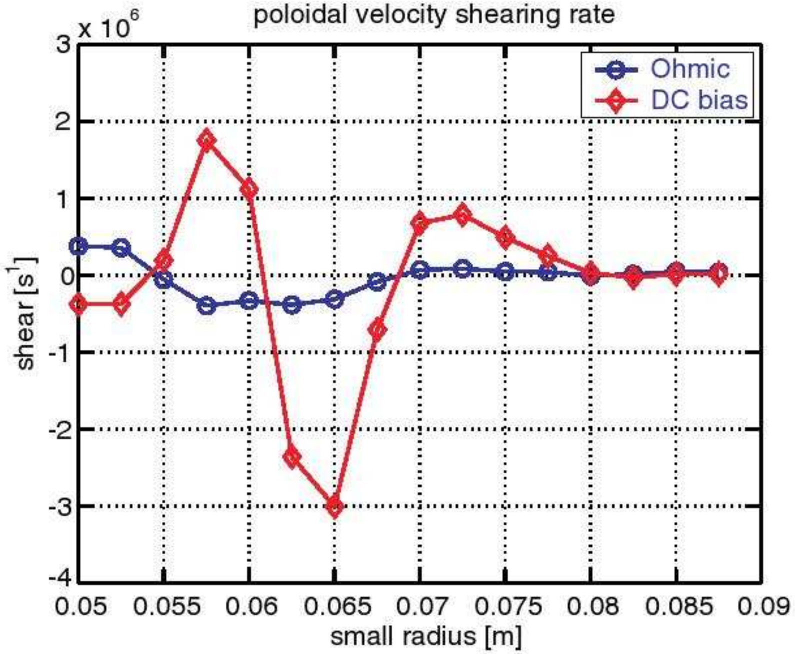
Text Upgrade
Ritz, PRL 1989



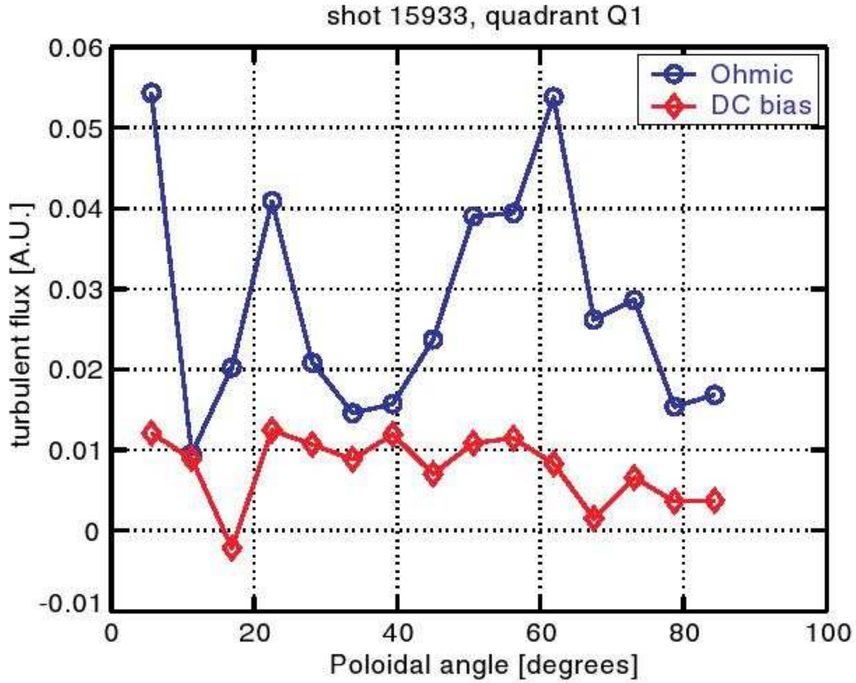
Normalized radial coordinate

At the plasma edge, r/a ~ 1, the flux is due to drift wave turbulence

Evidence of Influence of Electric Field Radial Profile (Tokamak Castor, Devinky, Phys. Plasmas 2005)



Gradient of radial electric field
X
Radial coordinate



Particle flux
X
Poloidal coordinate

II - Drift Wave Driven Transport

Chaotic trajectories caused by the particle drift, due to given poloidal electrostatic waves and the toroidal magnetic field.

Guiding center drift velocity

$$\frac{\mathrm{d}\vec{\mathrm{r}}}{\mathrm{dt}} = \vec{v} = \frac{\vec{E} \times \vec{B}}{B^2}$$

Fluctuating potential

$$\vec{E} = -\nabla \phi$$

Hamiltonian

$$H(x, y, t) = \frac{\phi(x, y, t)}{B_0}$$

Marcus, Ph. D. thesis, IFUSP (2008). Submitted to Phys. Plasmas.
Horton, PPCF (1985)

Drift waves in y (poloidal) direction due to gradient density in x (radial) direction. Uniform magnetic field, B, in z (toroidal) direction.

$$\nabla n = \frac{dn}{dx}\,\vec{e}_x \qquad \vec{E} = E\,\vec{e}_x \qquad \vec{v}_E = \frac{\vec{E} \times \vec{B}}{B^2} = \frac{E}{B}\,\vec{e}_y$$

Uniform Flow

Two wave Hamiltonian in dimensionless variables

$$H(x,y,t) = \left(E - u_1\right)x + A_1 \operatorname{sen}(k_{x1}\,x)\cos(k_{y1}\,y)$$
$$+A_2 \operatorname{sen}(k_{x2}\,x)\,\cos\left(k_{y2}\left(y - u\,t\right)\right)$$

$$u_1 = \frac{\omega_1}{k_{y1}} \qquad u = \frac{\omega_2}{k_{y2}} - \frac{\omega_1}{k_{y1}}$$

Resonance

Two wave Hamiltonian in dimensionless variables.

$$H(x,y,t) = \left(E - u_1\right)x + A_1 \,\mathrm{sen}(k_{x1}\, x)\cos(k_{y1}\, y)$$
$$+A_2 \,\mathrm{sen}(k_{x2}\, x)\, \cos\left(k_{y2}\left(y - u\,t\right)\right)$$

Confinement parameter

$$\mathrm{U(x)} \propto \mathrm{E} - \mathrm{u}_1 = \mathrm{v}_{\mathrm{E}} - \mathrm{v}_{\mathrm{ph}} \qquad (\mathrm{B} = 1)$$

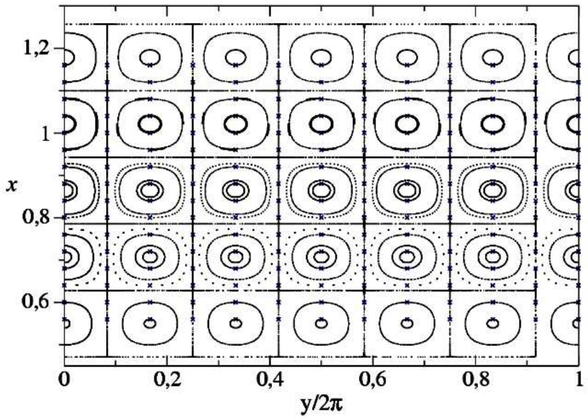
$$\mathrm{U} = 0 \rightarrow \mathrm{resonance}$$

Phase Space (One wave)

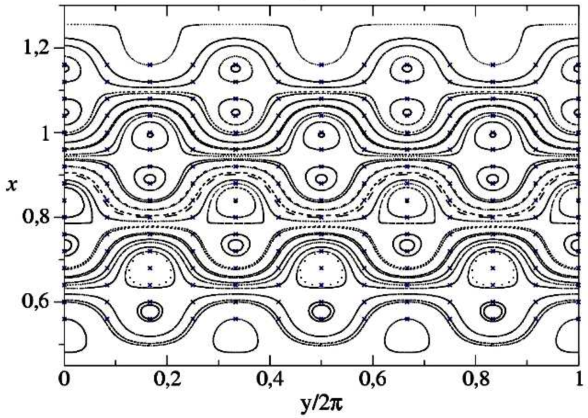
$$A_2/A_1 = 0$$

Electric field with a uniform radial profile

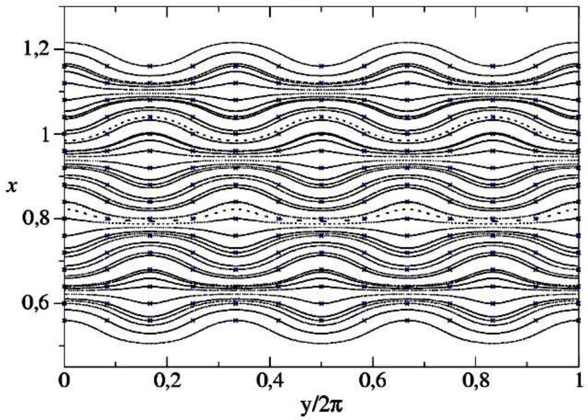
U = 0 $\rightarrow$ cells separatrix



U=0.5 Cells barriers



U=1.5 barriers



U > 1 $\rightarrow$ barriers

Phase Space (Two Waves)

Electric Field with a uniform radial profile

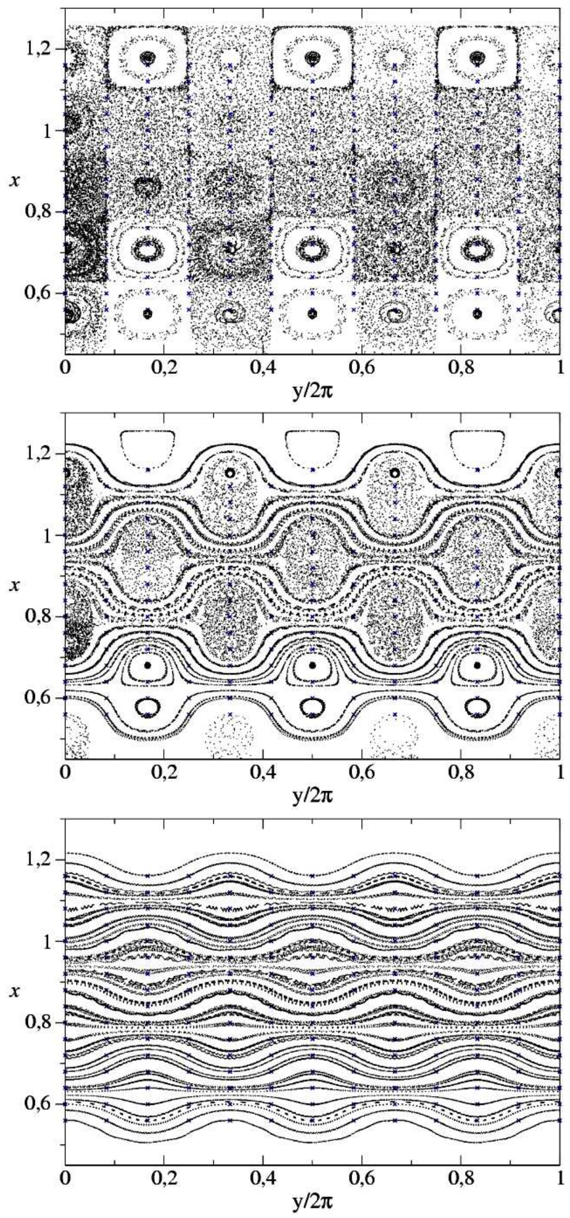
Chaotic Orbits

$$A_2 / A_1 = 0.1$$

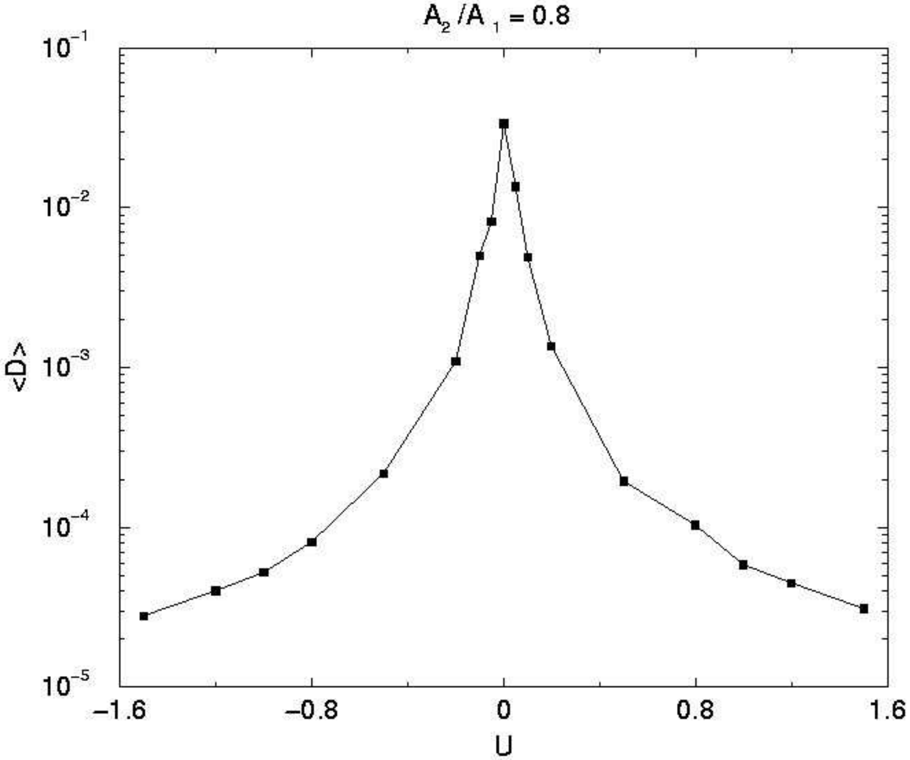
U=0

U=0.5

U=1.5



Radial Diffusion Coefficient



Values comparable to the measured diffusion coefficient

High transport for U ~ 0

Diffusion coefficient as a function of the confinement parameter *U*.

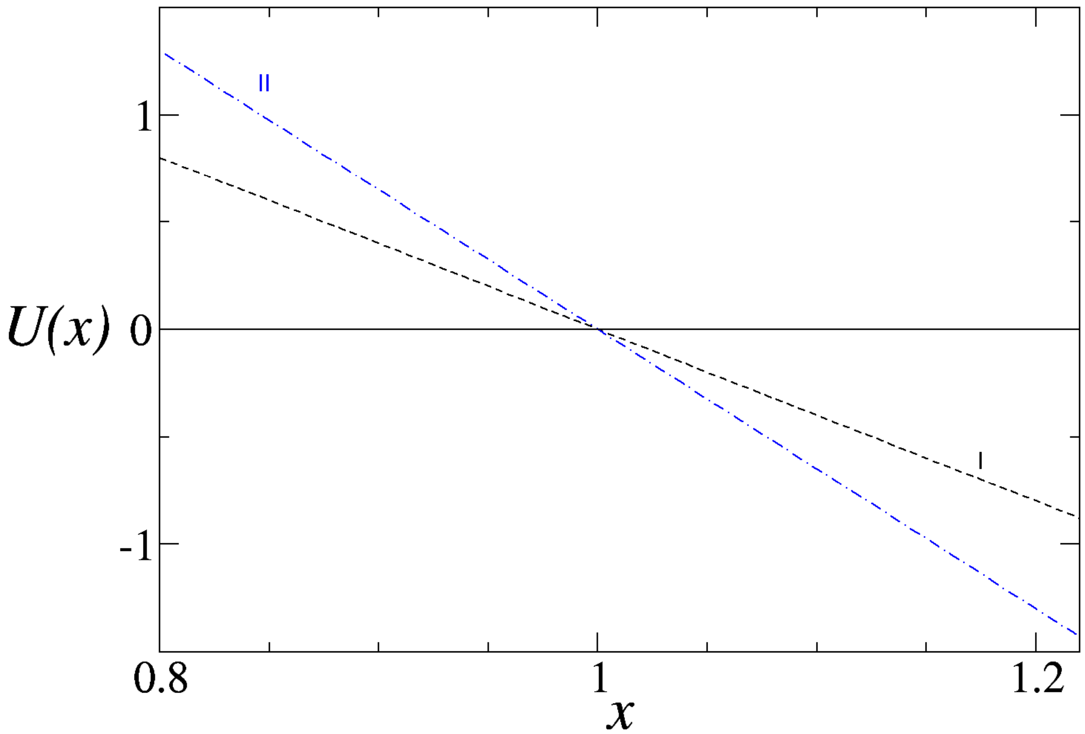
Reduction of Particle Transport at Plasma Edge

Modify the electric field radial profile $\Rightarrow$

move the transport barrier (region with U~ 1) on the plasma edge

Two Radial Profiles for the Confinement Parameter U

(used to show displacement of transport barriers)



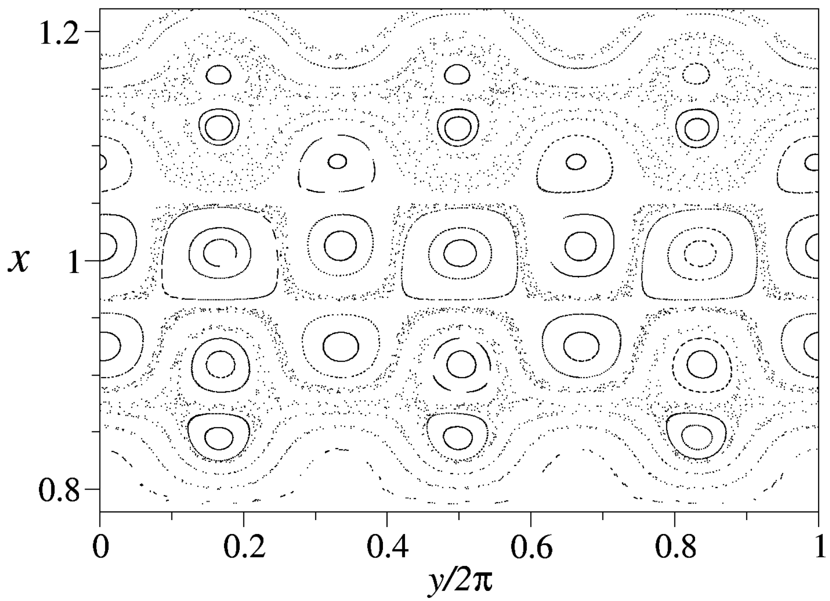
Confinement parameter

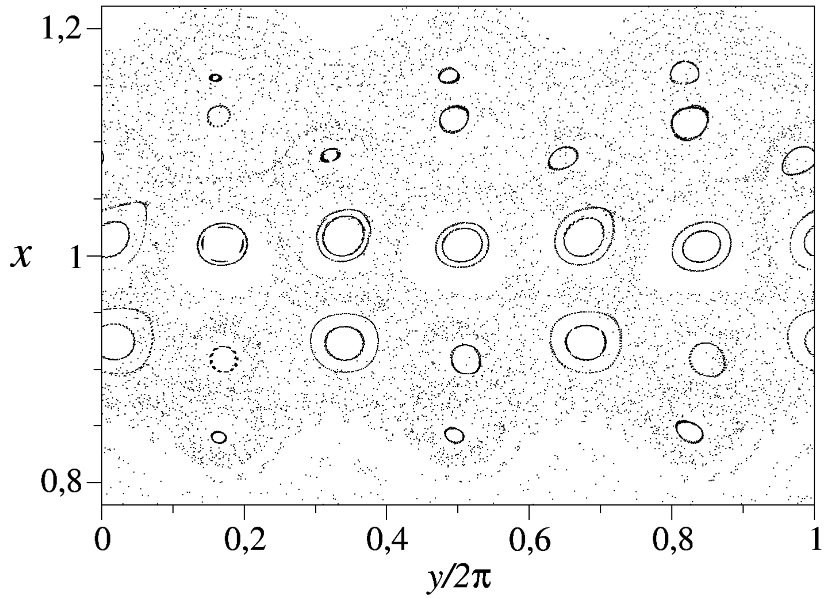
X

Radial coordinate

Phase Space (Two waves)
Eletric field radial profile I
Barriers outside the plasma

Plasma radius
x = 1



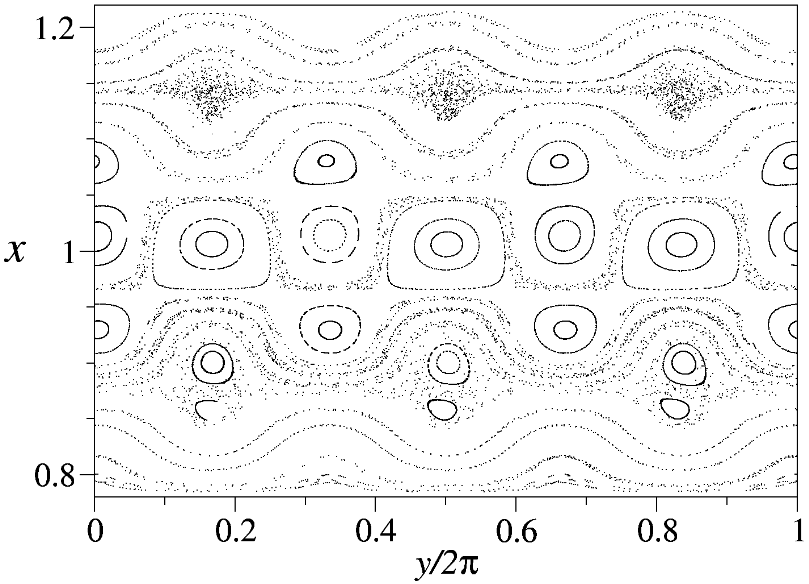


$A_1/A_2 = 0.1$

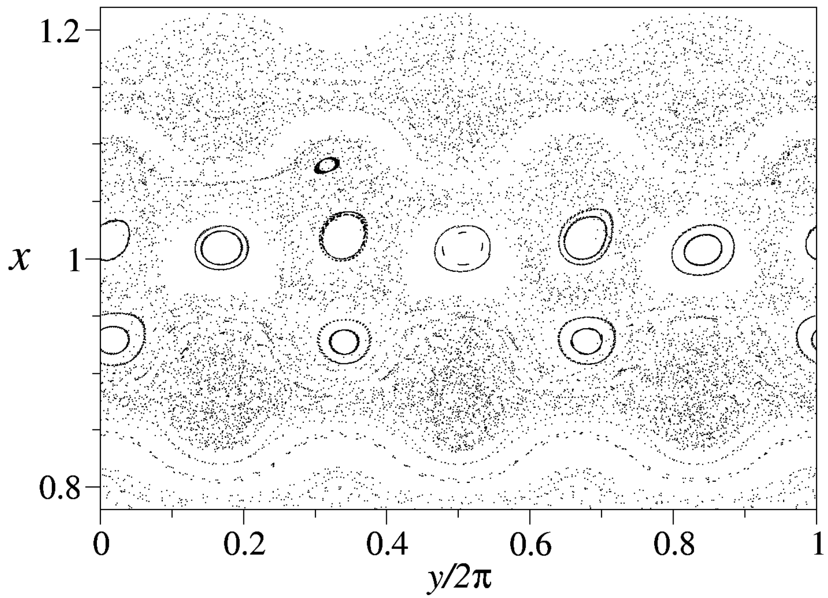
$A_1/A_2 = 0.4$

Phase Space (Two waves)
Eletric field radial profile II
Barriers moves to the
plasma edge

Plasma radius
x = 1



$A_1/A_2 = 0.1$



$A_1/A_2 = 0.4$

Conclusions

- In tokamaks, the chaotic flow due to drift waves explains experimental observation of transport dependence on confinement parameter U

$U \sim 0 \;\rightarrow\;$ high transport

$U \sim 1 \;\rightarrow\;$ transport barrier

III - Escape Pattern of Magnetic Field Lines in Tokamaks

T. Kroetz, M. Roberto (Aeronautic Technological Institute-CTA)

I. L. Caldas, E. C. Silva (University of São Paulo)

R. L. Viana (Federal University of Paraná)

Kroetz et al., Submitted to Phy. Plasmas

Roberto et al., Phys. Plasmas (2006)

Introduction

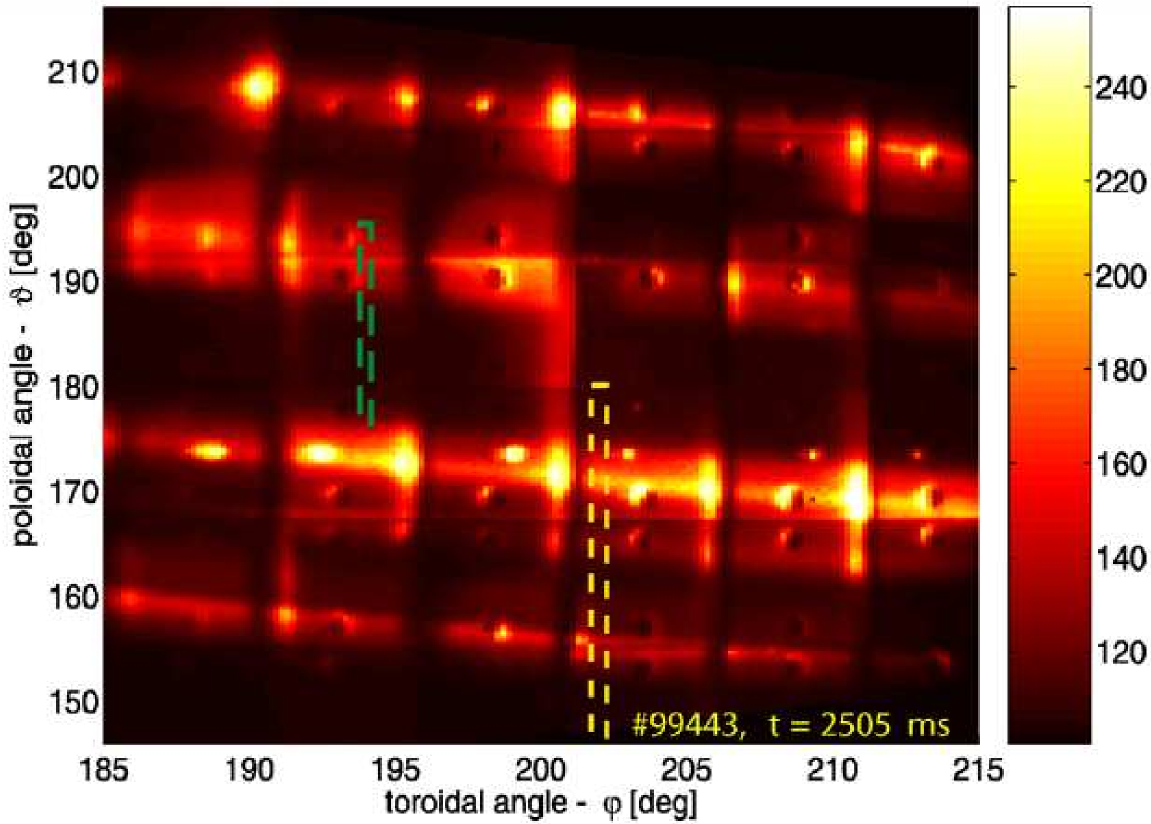
- In tokamaks, plasma wall interation can be characterized by the heat flux to the wall.

- Our work: this flux depends on the escape of the chaotic magnetic field lines to the wall (magnetic footprint).

Temperature Distribution at Target Plates
Experimental Evidences

Textor

Jakubowski
J. Nuclear
Materials
(2007)



Celsius
centigrade

Fig. 1. The temperature distribution over the DED target plates in Celsius centigrade. The image of the curved and oblique surface is corrected with LEOPOLD [12], such that the tiles form a regular pattern. The yellow ($m/n = 6/2$) and green ($m/n = 12/4$) rectangles indicate the areas, where the heat flux density is evaluated with the THEODOR code.

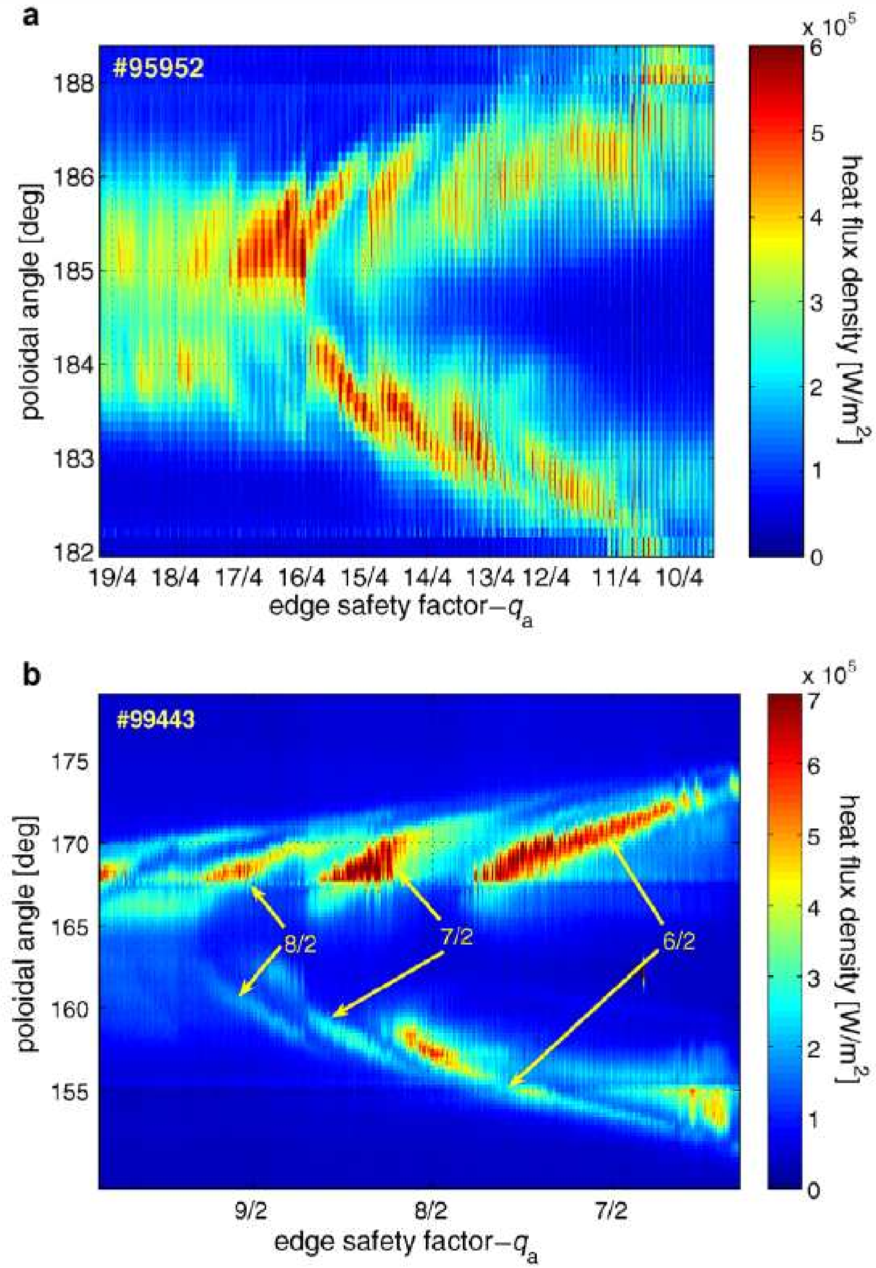
These measurements give evaluation of heat flux

Resonant Character of Heat Flux

Textor
Jakubowski
J. Nuclear Materials
(2007)

Evaluated Heat Flux to target plates

as a function of edge safety factor
and poloidal angle at the wall



Zoom of previous figure

ig. 2. Heat flux to the divertor target plates as a function of the edge safety factor and the poloidal angle: (a) in the 12/4 mode; (b) in the

Hamiltonian Systems

- Magnetic field lines described by almost integrable hamiltonian systems:

Integrable MHD equilibrium

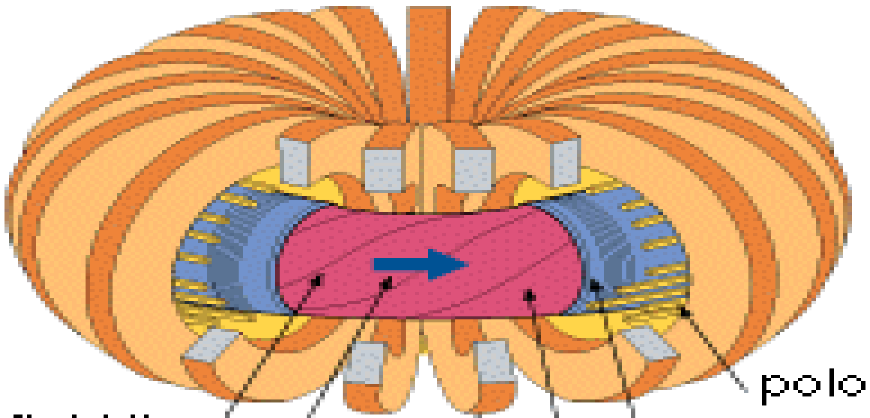
+

Resonant magnetic perturbations (external electric currents in an ***ergodic magnetic limiter)***.

Equilibrium Magnetic Field in Tokamaks

Lines are on toroidal magnetic surfaces.

toroidal (ϕ) and poloidal (θ) angles



Equation of line

Integrable Field

$$\vec{B}_0 \times d\vec{l} = 0 \quad \rightarrow \quad \dot{\vartheta} = \frac{\partial H_0(J)}{\partial J}, \quad \dot{J} = -\frac{\partial H_0(J)}{\partial \vartheta}$$

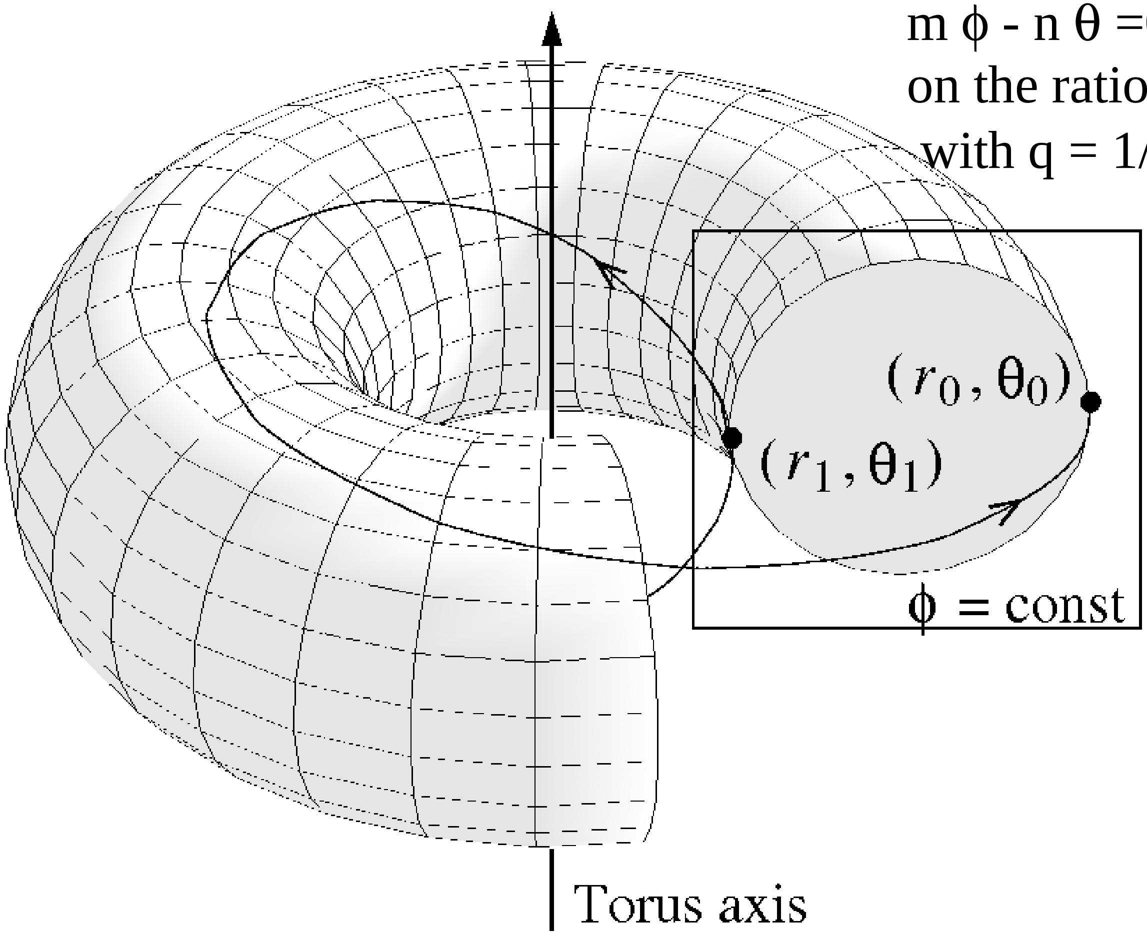
t (canonical time) $\equiv \phi$ (toroidal angle)

Frequency $\omega(J) = \dfrac{\partial H_0}{\partial J}$

Poincaré Section

φ (toroidal) and θ (poloidal) angles

$m\,\phi - n\,\theta = 0$ equation of lines on the rational surface with $q = 1/\iota = d\theta/d\phi = m/n$

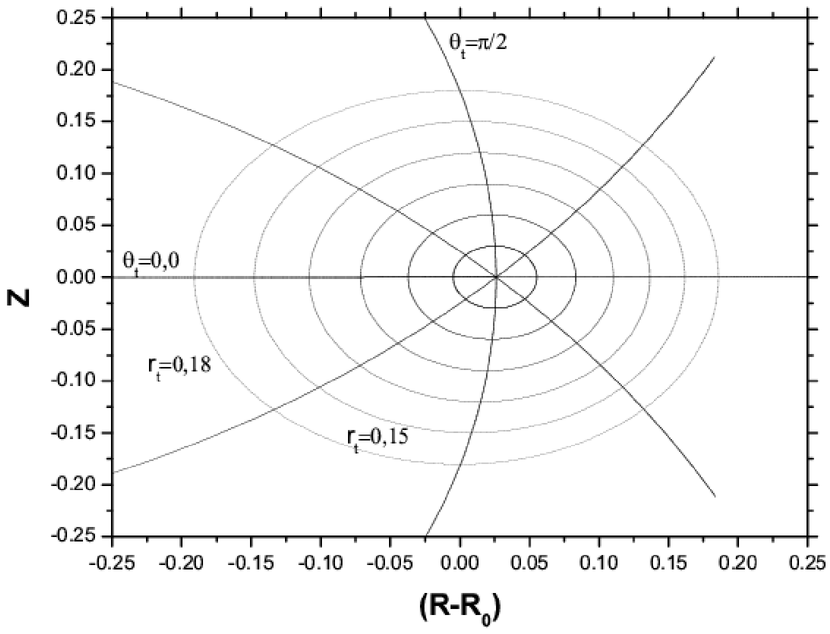


Rational magnetic surface with rotational transform ½.

Period – 2 magnetic field lines

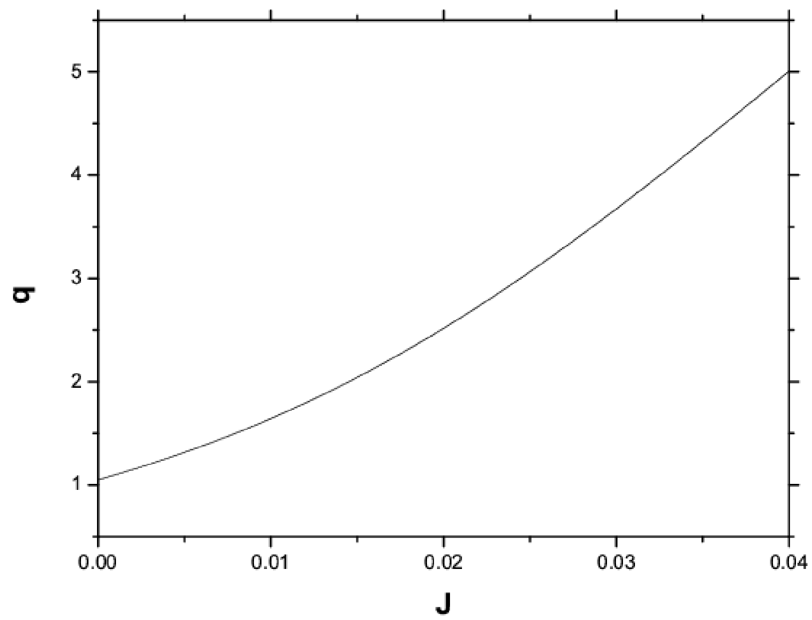
MHD Equilibrium

Magnetic Surfaces



Normalized distances
in polar coordinates

Monotonic Radial Profile



Safety factor x normalized
radial coordinate

Magnetic Surfaces

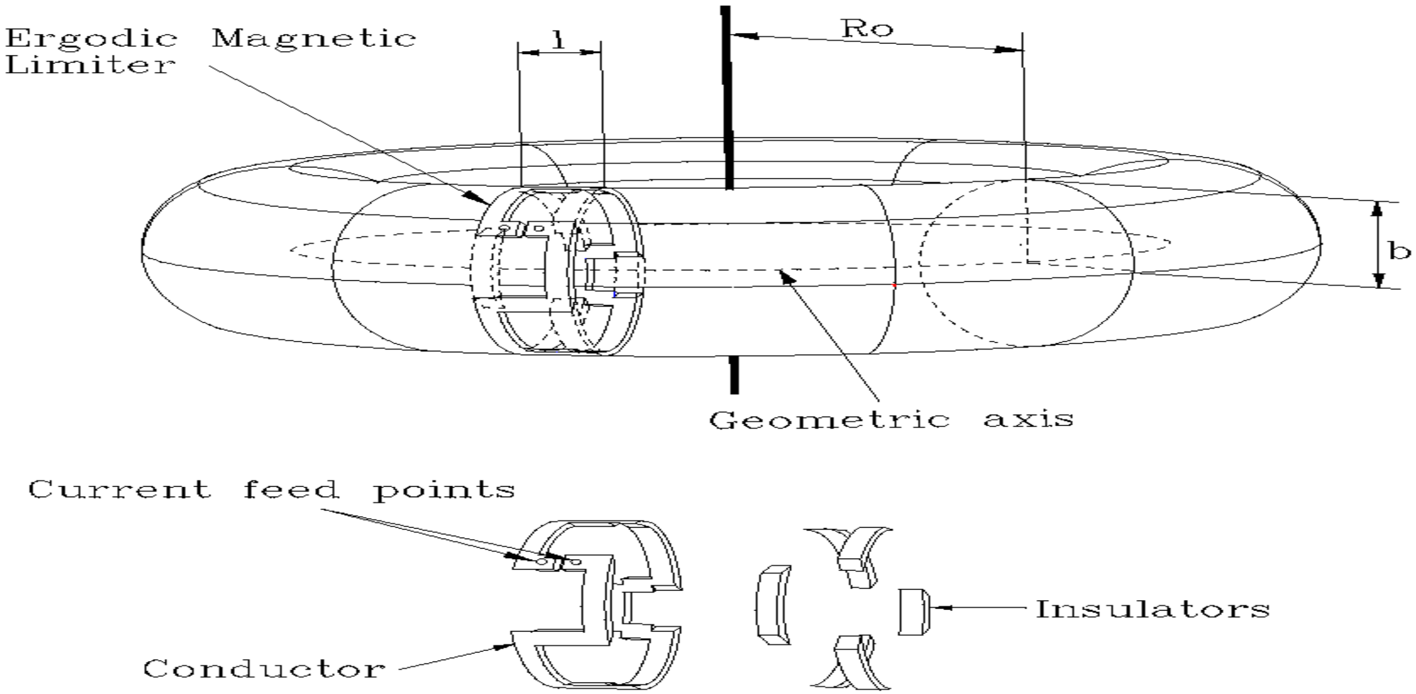
I= constant

Symmetry $\Rightarrow$ integrable system

$H=H_0(I) \Rightarrow I=I_0, \ \vartheta=\omega t+\vartheta_0$

(I, ϑ) action/ angle of H_0

Chaotic Limiter to Improve Confinement
Resonant perturbations on magnetic surfaces



Dominant m/n resonant perturbation in toroidal geometry.
Control parameter: coil current I_h .

Silva et al., IEEE Trans. Plasma Science (2001)

Lagrangian Chaos

(regular and chaotic field lines)

Symmetry $\Rightarrow$ integrable system

$H = H_0(I) \Rightarrow I = I_0, \ \vartheta = \omega t + \vartheta_0$

(I, ϑ) action/angle of H_0

Helical perturbations $(\varepsilon \neq 0) \Rightarrow$ symmetry loss

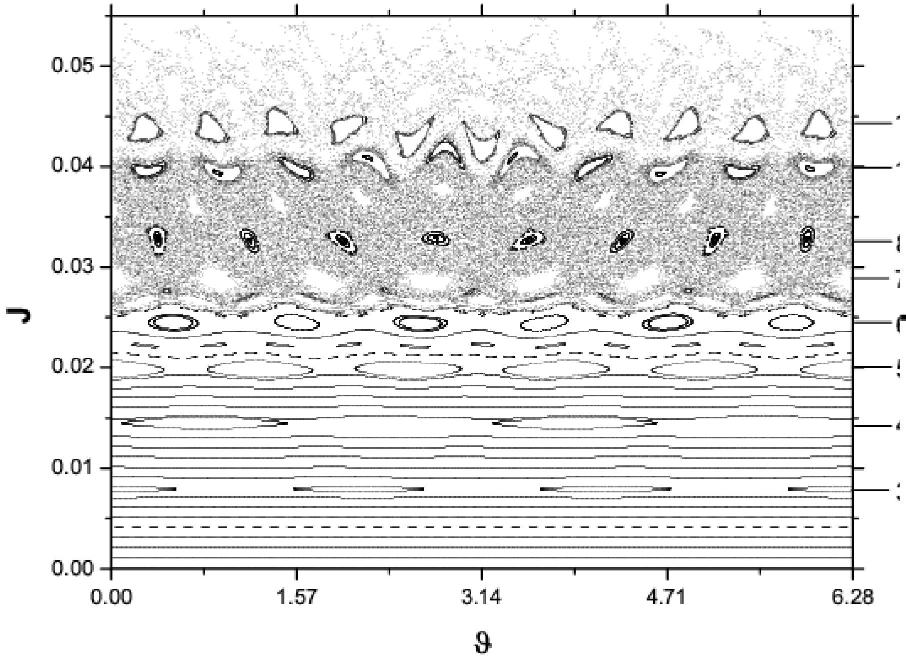
$H = H_0(I) + \varepsilon H_1(I, \vartheta)$

$\varepsilon \ll 1 \Leftrightarrow$ almost integrable system

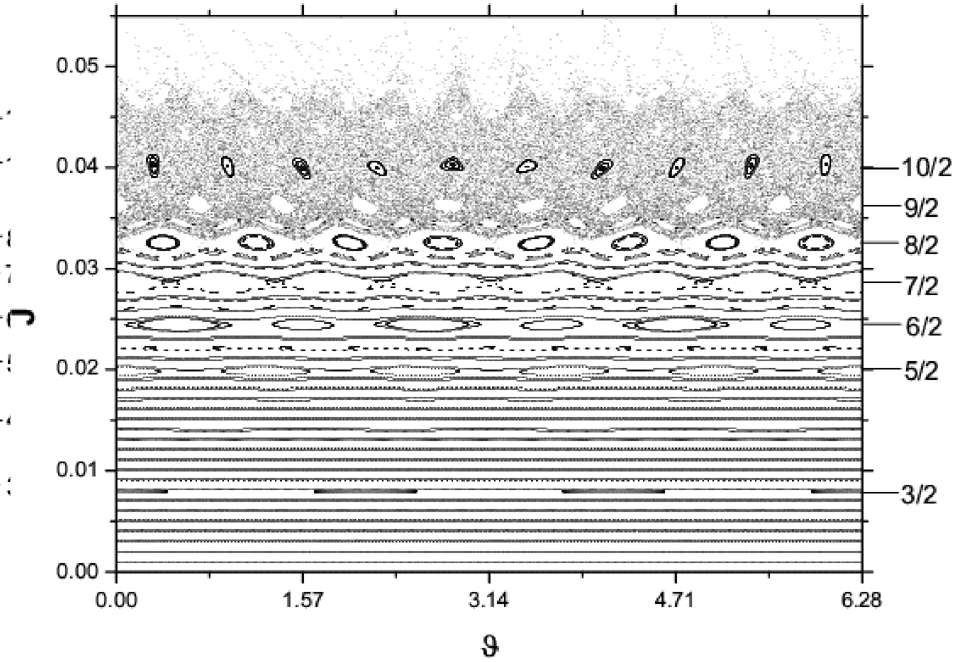
Poincaré Surfaces

(action-angle variables)

m/n = 8/2 dominant mode



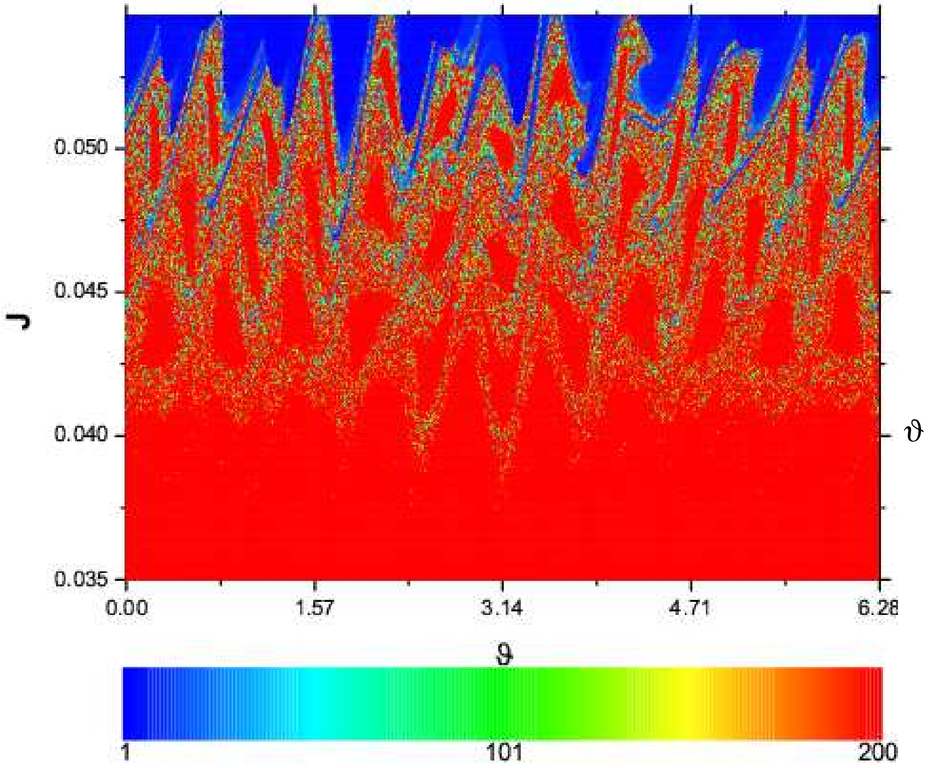
10/2 dominant mode



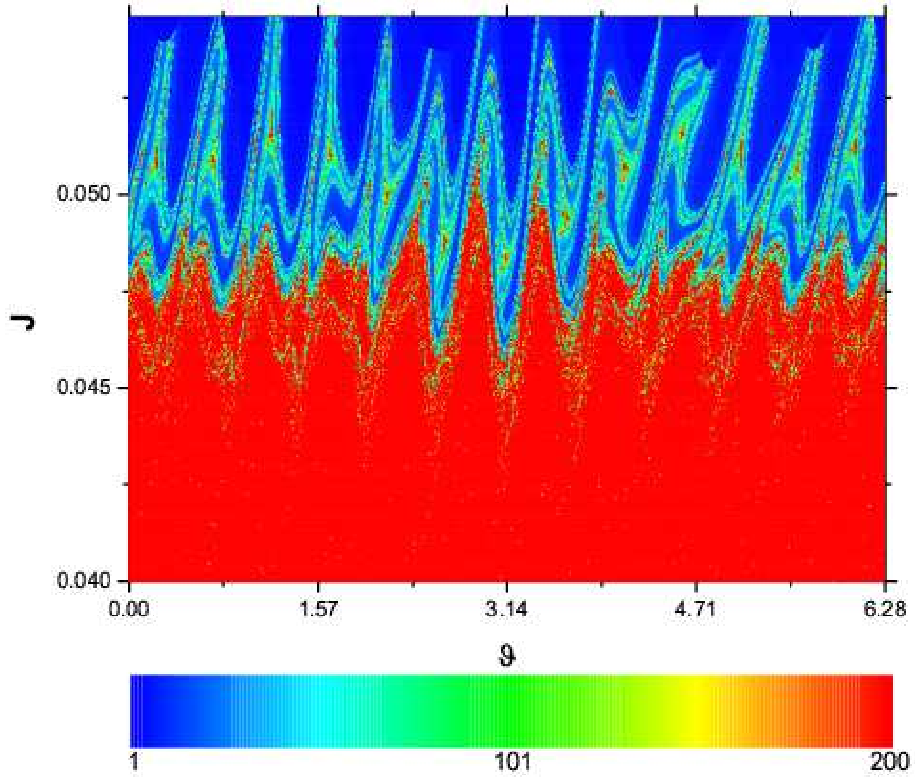
Action x angle

Conection Lengths for Field Lines

8/2 mode



10/2 mode



Action x angle

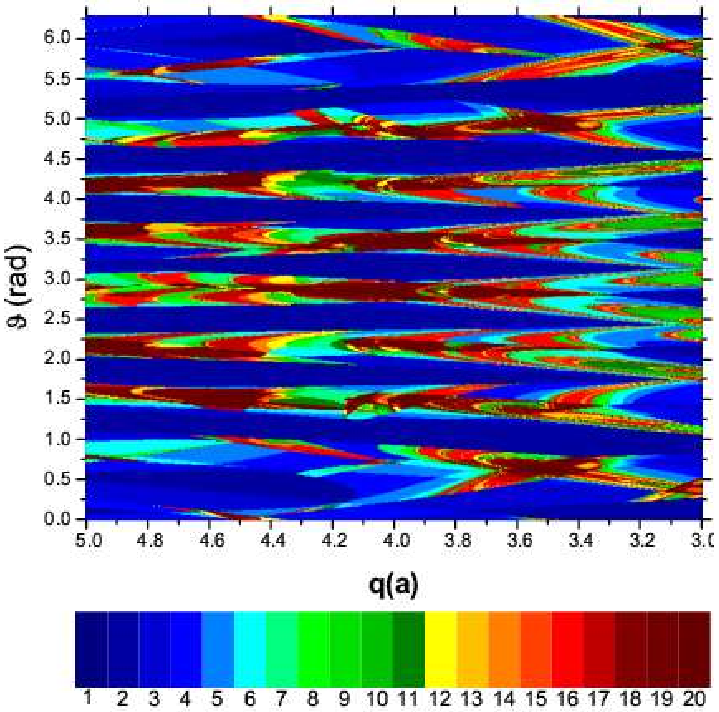
Scales in the range [1, 200]

(number of toroidal turns, for a line, from (J, ϑ) to the wall)

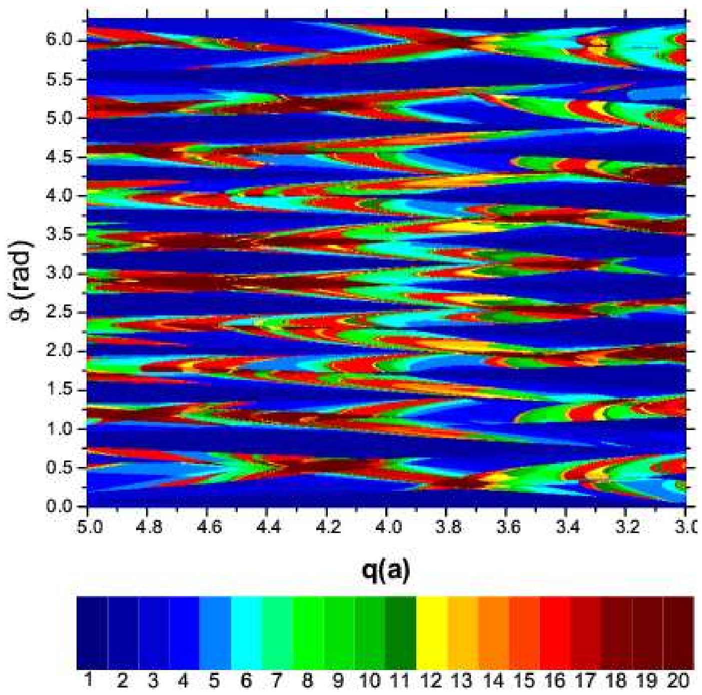
Wings

Resonant character of field lines escape to the wall

8/2 mode

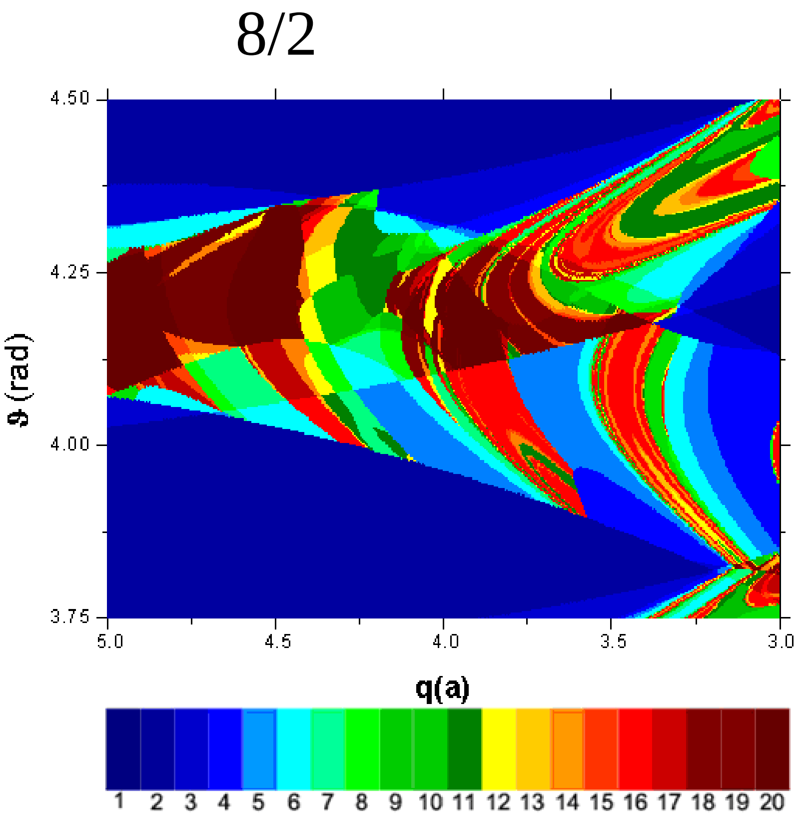


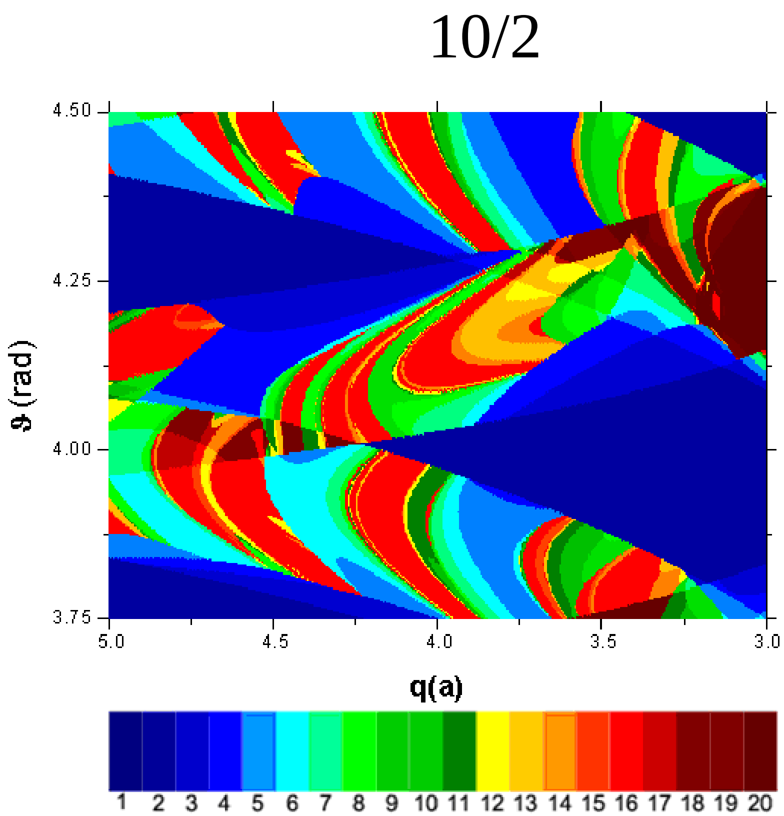
10/2 mode



Escape lengths in the range [1, 20] at the wall
Poloidal angle at the wall x safety factor at the edge

Blow Up of the Wings





Escape lengths in the range [1, 20] at the wall
Poloidal angle at the wall x safety factor at the edge

Conclusions

- Perturbed magnetic configuration described by ***maps***.
- Escape of field lines determined by homoclinic tangle.
- For some high amplitude resonances, magnetic lines with long correlation lengths reach the wall in concentrated footprints.
- Ergodic limiter requires a convenient coil configuration for a uniform heat deposition on the wall.

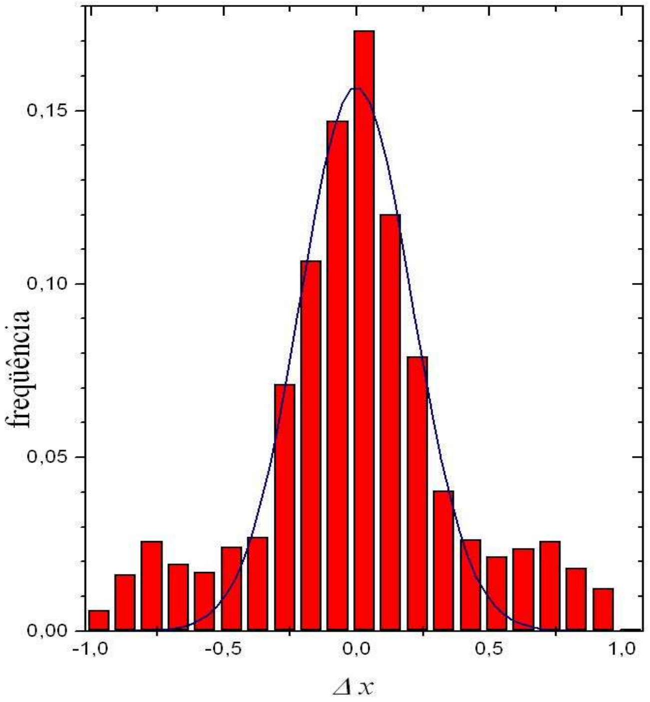
Distribution of Radial Displacements

$U = 0 \quad {}^{A_2}\!/_{A_1} = 0.6$

$u_2 \cong u_1$

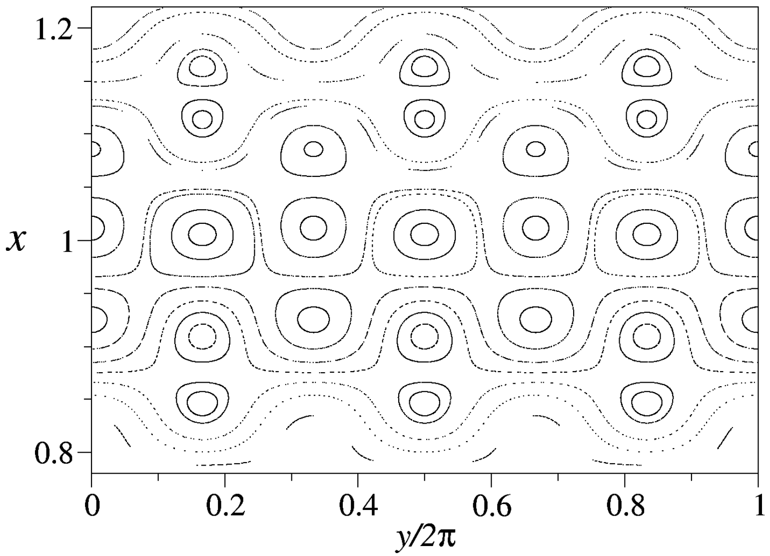
$\kappa = 3.6$

$\beta = 0.005$



define a local diffusion coefficient <D>

Phase Space for a Non Uniform Electric Field

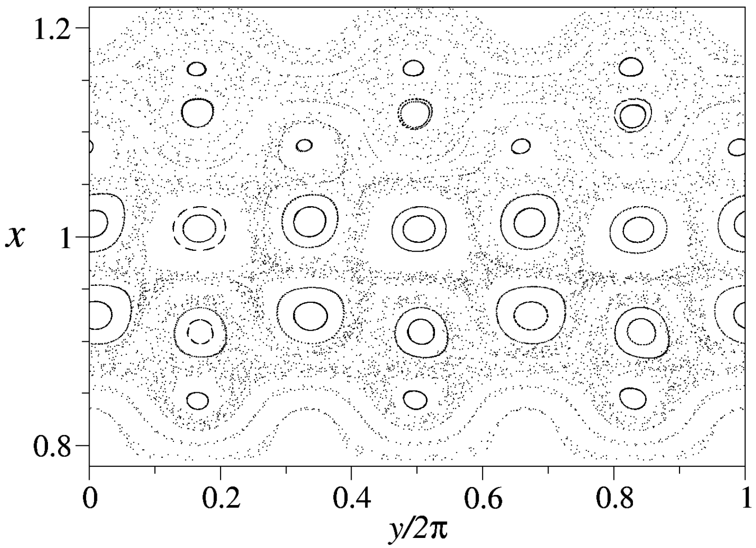


$$A_2 / A_1 = 0$$

Structures:
Convective Cells
and Barriers

$$|U_{max}| = 0.8 \quad \text{Profile I}$$

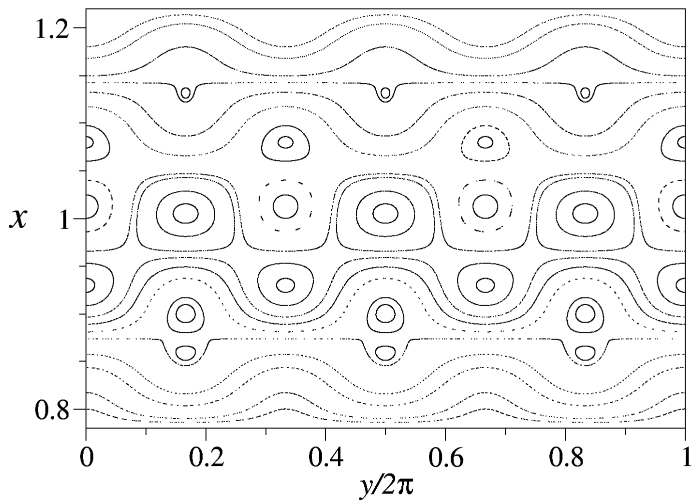
for $x = 0.85$ and 1.25



$$A_2 / A_1 = 0.2$$

Chaotic trajectories

Phase Space for a Non Uniform Electric Field
Transport barrier where U > 1

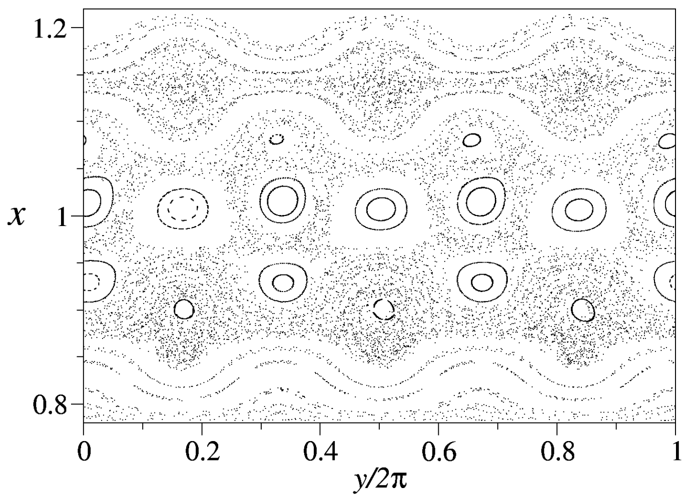


$$A_2 / A_1 = 0$$

Structures:
Convective Cells
and Barriers

$\left|U_{max}\right| = 1.3$ Profile II

for x = 0.85 and 1.25



$$A_2 / A_1 = 0.2$$

Chaotic trajectories

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Journal of Nuclear Materials 363–365 (2007) 371–376
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www.elsevier.com/locate/jnucmat

Observation of the heteroclinic tangles in the heat flux pattern of the ergodic divertor at TEXTOR

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PHYSICS OF PLASMAS **14**, 042502 (2007)

Traces of stable and unstable manifolds in heat flux patterns

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TEXTOR team

Wingen
Physics Plasmas (2007)

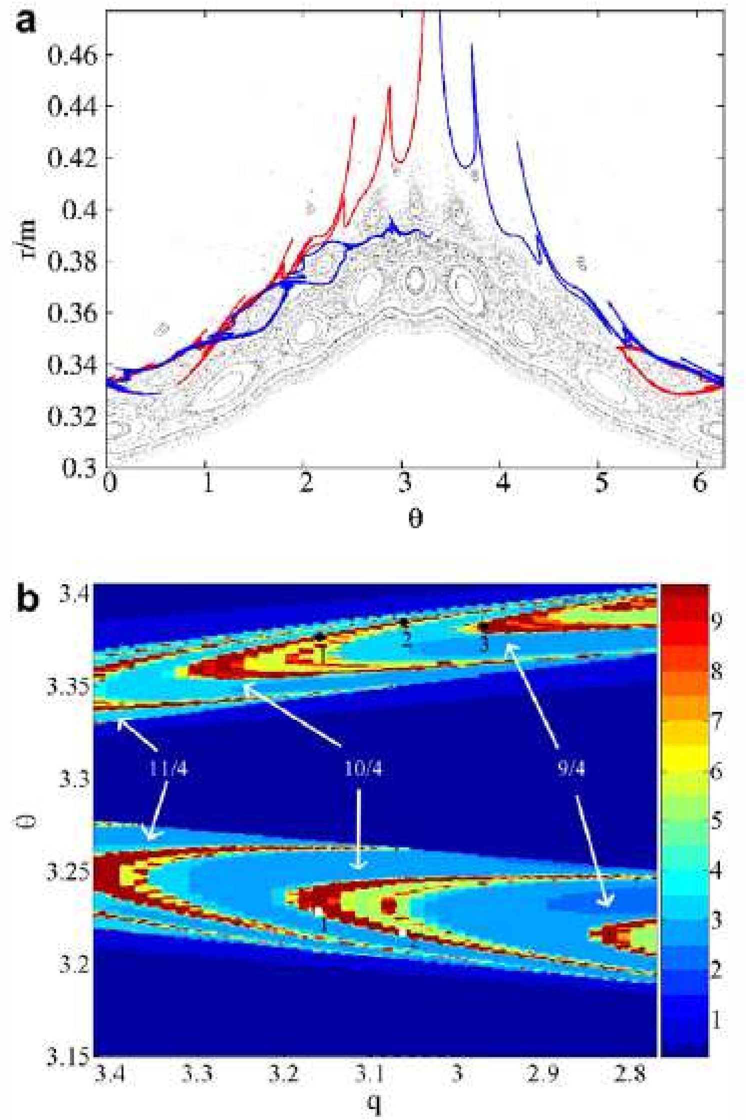

Fig. 4. Calculated topology of the (un)stable manifolds for the case of the DED (#95952): (a) the stable (red) and unstable (blue) manifolds of the outermost existing island chain ($m/n = 9/4$); (b) the structure of the magnetic footprints as a function of the edge safety factor q and poloidal angle θ. The color scale refers to the connection length of the magnetic field lines expressed in toroidal turns.

8/2 Mode

Stable and unstable manifolds

Heteroclinic tangle

Action x angle

10/2 Mode

Stable and unstable manifolds

Heteroclinic tangle

Action x angle