CONSORZIO RFX
Ricerca Formazione Innovazione

Consiglio Nazionale delle Ricerche

Bifurcation in the MHD behaviour of a self-organizing system: the Reversed Field Pinch (RFP)

Susanna Cappello

with contributions from RFX team …

CNR - CONSORZIO RFX - PADOVA - ITALY

31st EPS London 2004

Overview

In the last few years:

Experimental evidence of quasi helical configurations for RFPs

- With different transport mechanisms,
- and milder plasma-wall interaction,

Motivated

renewed interest in

theoretical-numerical work on transitions to "helical RFP"

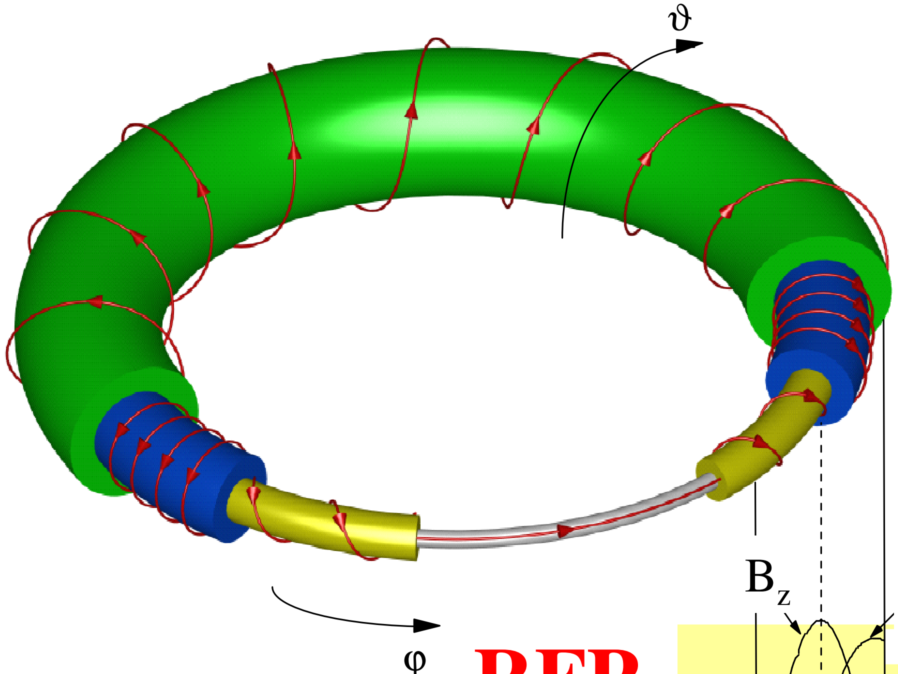
"precursors":

Turner,Prager 87
Finn,Nebel,Bathke 92
(helical ohmic equilibria)

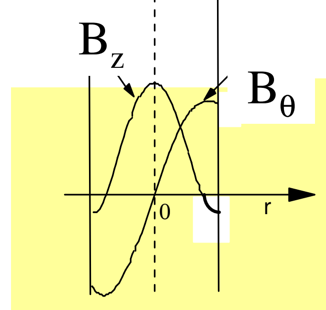
Cappello,Paccagnella 90-92
Finn,Nebel,Bathke 92
(dynamical simulations)

- introduction,
- progress on this subject.

RFP magnetic configuration ('70-'90)



RFP



Pinch Parameter
$1.2 \leq \Theta \leq 2.2$

(Θ ==> $I_{plasma} / \Phi_{toroidal\ flux}$)

Turbulent dynamo,

Cowling's theorem

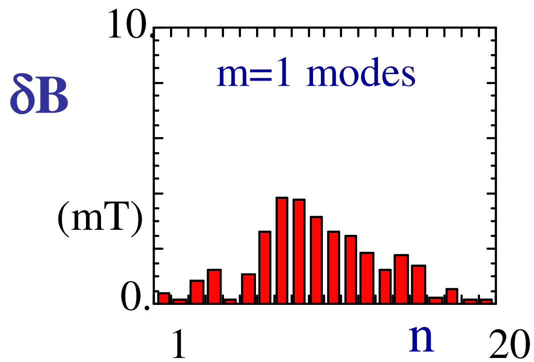
Turbulent relaxation,

Taylor's theory ('74)

minimum energy states,
constraint on:
- toroidal magnetic flux,
- total magnetic helicity:

Axis-symmetric solutions …

example of the “deformation” which affects the “axis-symmetric” turbulent (conventional) RFP :

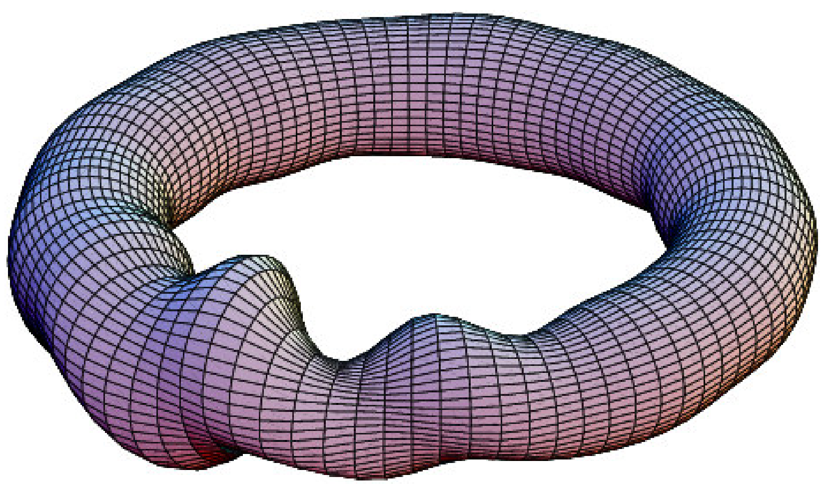


Turbulence characterized by

a **<u>wide spectrum of</u>** (mainly) **<u>m=1 modes</u>**

Resistive kink - tearing modes

as a result:



(From RFX data)

(ξ x 10)

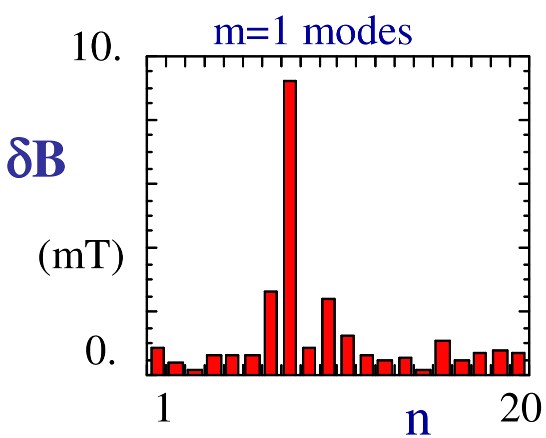
Zanca & Terranova PPCF 2004

More recent experimental observations '90 -'00:

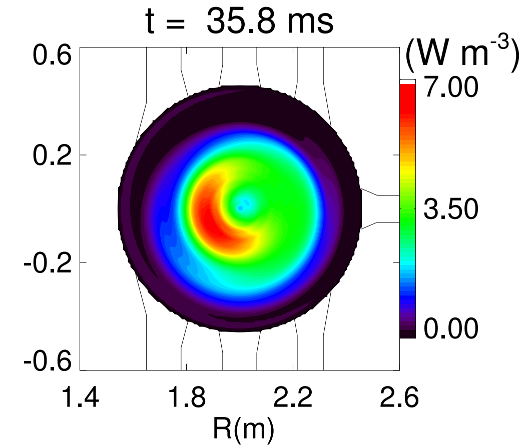
Quasi Helical Symmetric RFP :

(QSH regimes)

TPE '93,'97
T1 '94
MST '97
RFX '98-'99
T2,TPE-RX,MST 2003



SXR imaging reveals a helical structure in the plasma core during QSH states (measure available in RFX)



Escande, Martin, Ortolani, et al. PRL 2000

Helical-Symmetric RFP

- MHD simulations
- ohmic equilibria

laminar dynamo

Two approaches to RFP description:

AXIS-SYMMETRIC CONFIGURATION
whose symmetry **is** broken
by INTENSE MHD TURBULENCE

MH

HELICAL EQUILIBRIUM
whose symmetry **may be** broken
by SMALL MHD PERTURBATIONS

SH

QSH

OUTLINE:

Turbulent

RFP

Numerical simulations

(cylindrical approx.)

$$H \sim (\nu\eta)^{-1/2}$$

(dissipative forces)

Laminar

OUTLINE:

RFP

Numerical simulations (cylindrical approx.)

Turbulent ↔ **MH** : 3D non linear coupling resistive-kink tearing modes:

δB scaling law (Sweet - Parker regime) --> viscosity effect

- Quasi periodic relaxation events, with formation of current sheet structures,
- *mode-mode phase locking (slinky mode)*...

H~ $(\nu\eta)^{-1/2}$

Laminar ↔ **SH** : 2D Stationary <u>helical symmetric</u> configurations

Chaos healing by separatrix expulsion: helical structures in RFX SXR tomography

Grad-Shafranov helical equilibrium + Ohm's law

Model equations

3D MHD nonlinear code SpeCyl

Cappello & Biskamp Nucl. Fus. 1996

$$\frac{\partial B}{\partial t} = \nabla \wedge (\mathrm{v} \wedge B) - \nabla \wedge (\eta J)$$

$$\frac{d\mathrm{v}}{dt} = J \wedge B + \nu \nabla^2 \mathrm{v}$$

$$\rho \equiv 1, p \equiv 0$$

$\eta = \tau_A / \tau_R$

(Lundquist: $S = 1 / \eta$)

$\nu = \tau_A / \tau_\nu$

Cappello & Escande PRL 2000

re-scaling : $t \rightarrow \bar{t} = \sqrt{\frac{\eta}{\nu}}\, t \qquad \mathrm{v} \rightarrow \bar{\mathrm{v}} = \sqrt{\frac{\nu}{\eta}}\, \mathrm{v}$

Hartmann: **$H = (\nu\eta)^{-1/2}$**

(highlighted before in linear stability studies

by D. Montgomery and Tebaldi,Ottaviani)

magnetic Prandtl: **$P = \nu / \eta$**

$$\frac{\partial \bar{B}}{\partial \bar{t}} = \nabla \wedge (\bar{\mathrm{v}} \wedge \bar{B}) - \nabla \wedge (H^{-1} \bar{J})$$

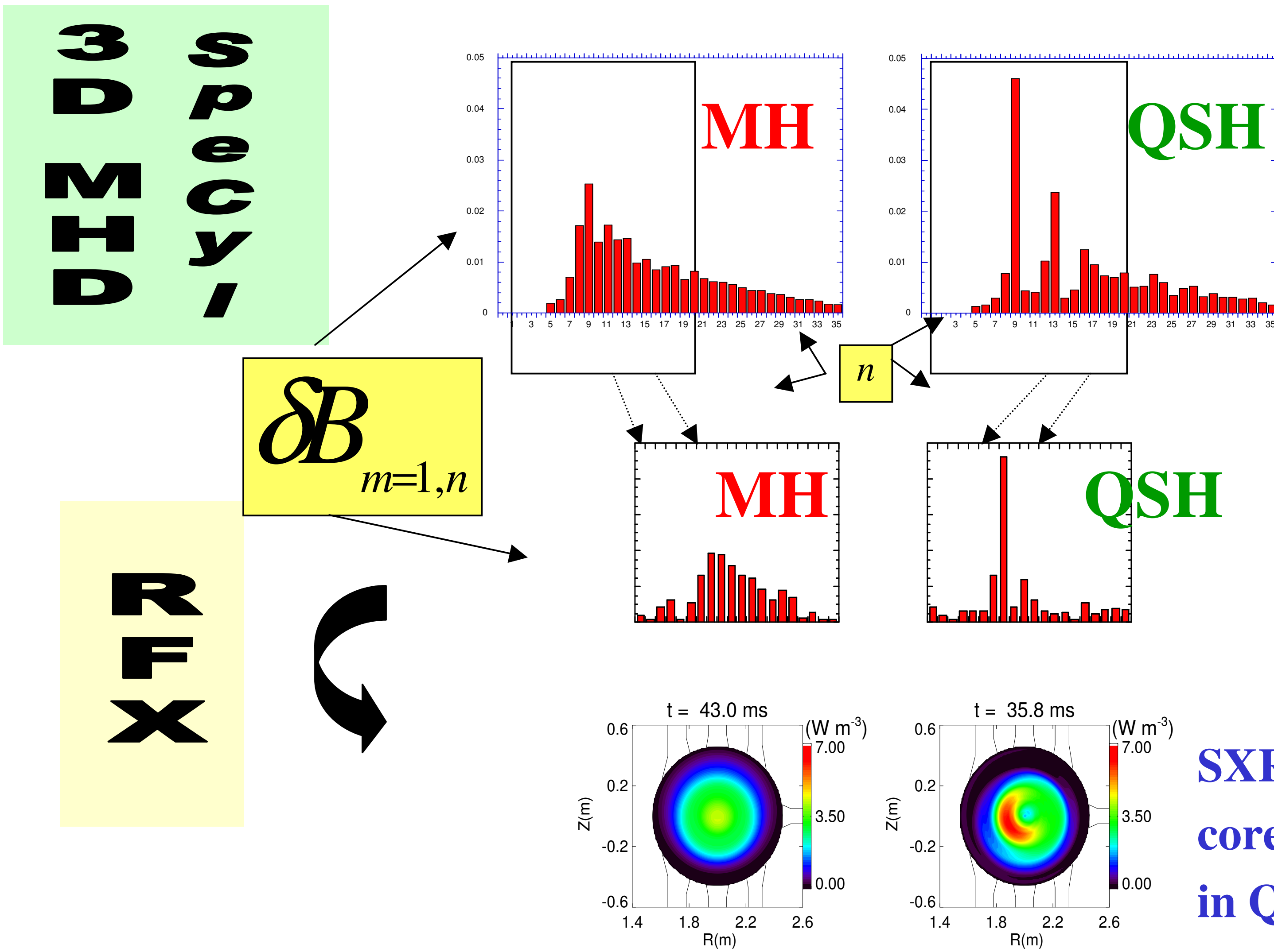
$$\frac{1}{P}\frac{d\bar{\mathrm{v}}}{d\bar{t}} = \bar{J} \wedge \bar{B} + \nabla^2 (H^{-1}\, \bar{\mathrm{v}})$$

$$\rho \equiv 1, p \equiv 0$$

“H” is <u>the</u> important parameter when inertia is negligible !

Simulations and Experiment:

magnetic perturbation at the plasma edge



SXR imaging:

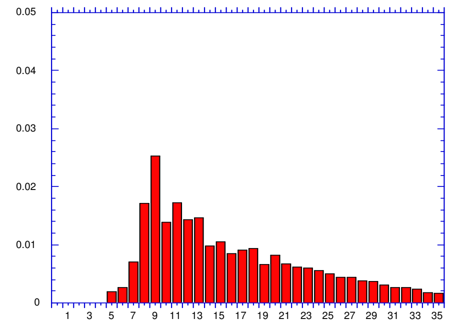
core helical structure

in QSH states

The m=1 modes drive nonlinearly the m=0 modes

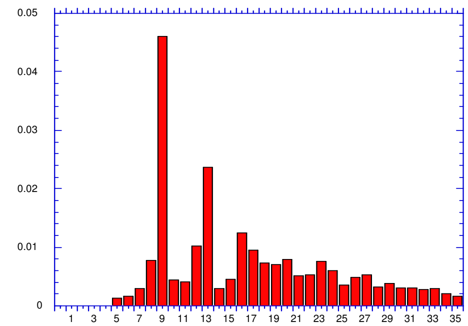
$\delta B_{m=1,\, n}$

MH



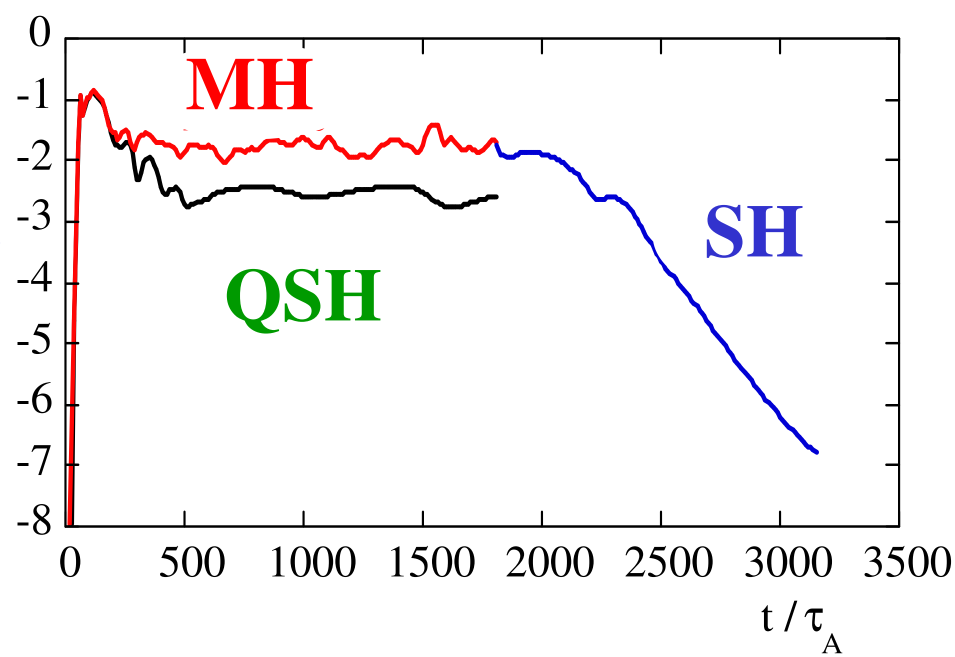
n

QSH



n

$\log \delta E_{m=0}$



m=0 modes are a <u>good indicator</u> of the dynamical regime

next slide :

RFP transition diagram

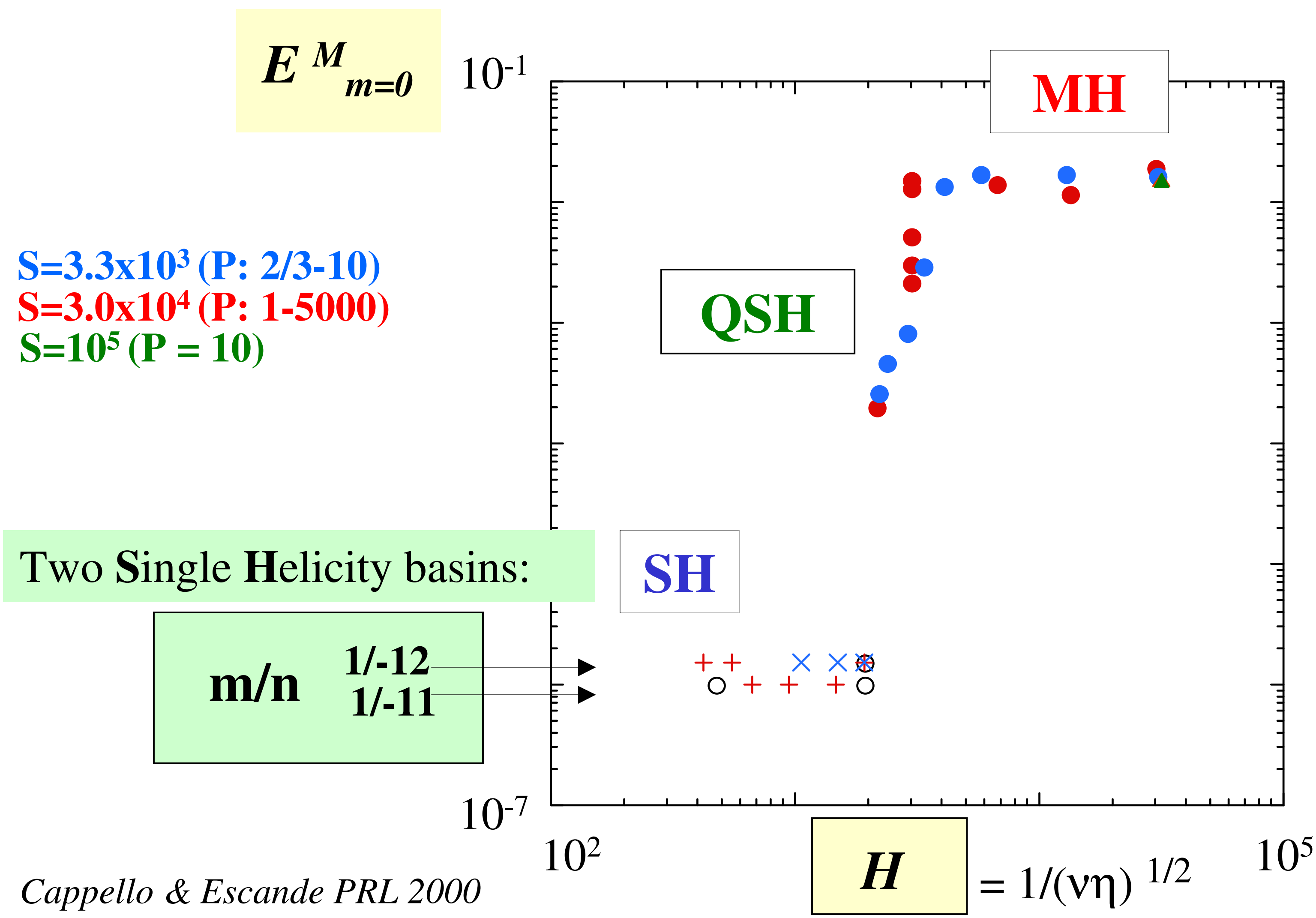
m=0 mode energy

vs.

Hartmann number

Dynamical regimes in the RFP : SH - QSH - MH

Numerical results



$\Theta = 1.9$

R/a =4

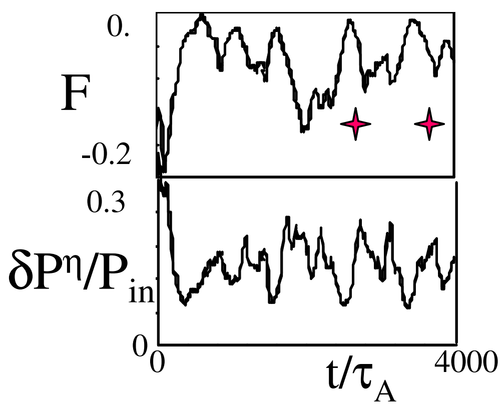
Cappello & Escande PRL 2000

MH regime:

MHD Reconnection and scaling laws

Cappello & Biskamp Nucl Fus 1996

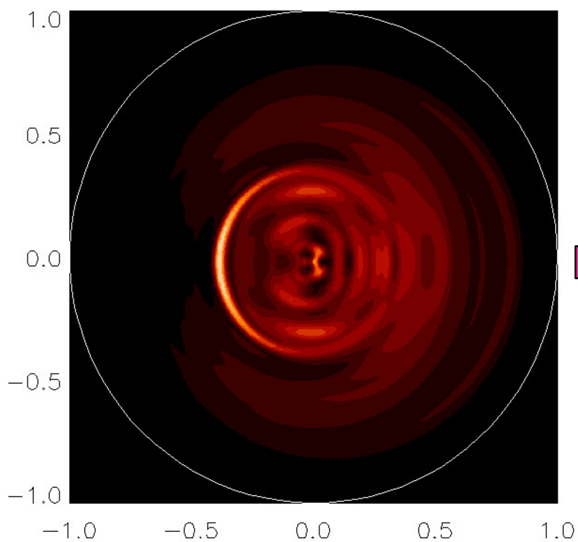
(P =1) $S = 3 \times 10^4$

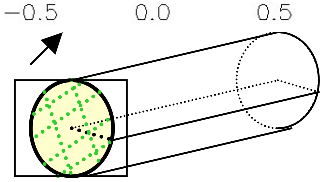


Quasi-periodic relaxation events
with formation of current sheets (3D)

NUMERICAL scaling law → $\delta B \sim S^{-0.22}$ **(P = 1)**

$\delta B \sim S^{-1/4}$ $(= H^{-1/4})$ (at constant P)





$J \cdot B$

ARGUMENT:

Sweet-Parker reconnection

$(\delta v_{perp} / \delta B = S^{-1/2})$

dominates RFP dynamics

$(S^{-1} J_{\theta 0} = < \delta v \times \delta B >_{\theta \text{ at reversal}})$

... $P \neq 1$ ...
+
RFX data
➔
ITG turbulent viscosity may characterize the RFPs

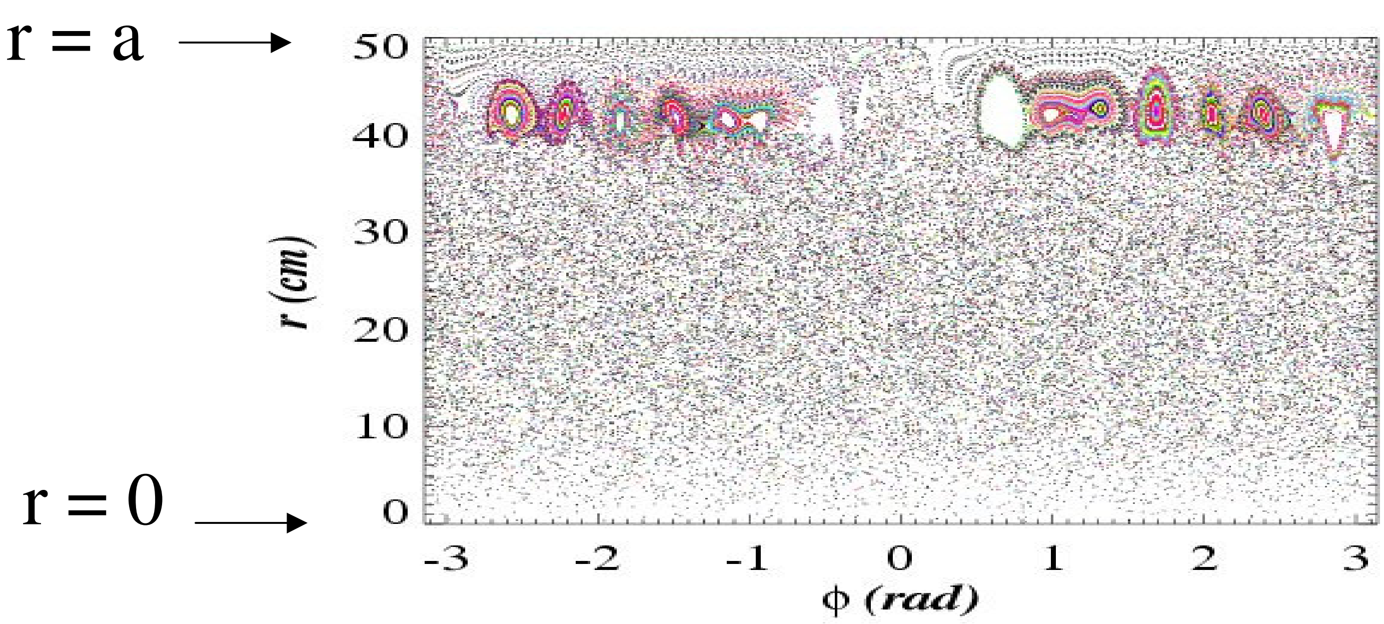
Terranova et al. PPCF 2000

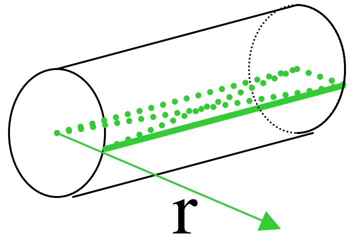
MH regime:

Poincaré plot in MH regime

role of m=0 modes and reversal region :

persistence of insulating islands

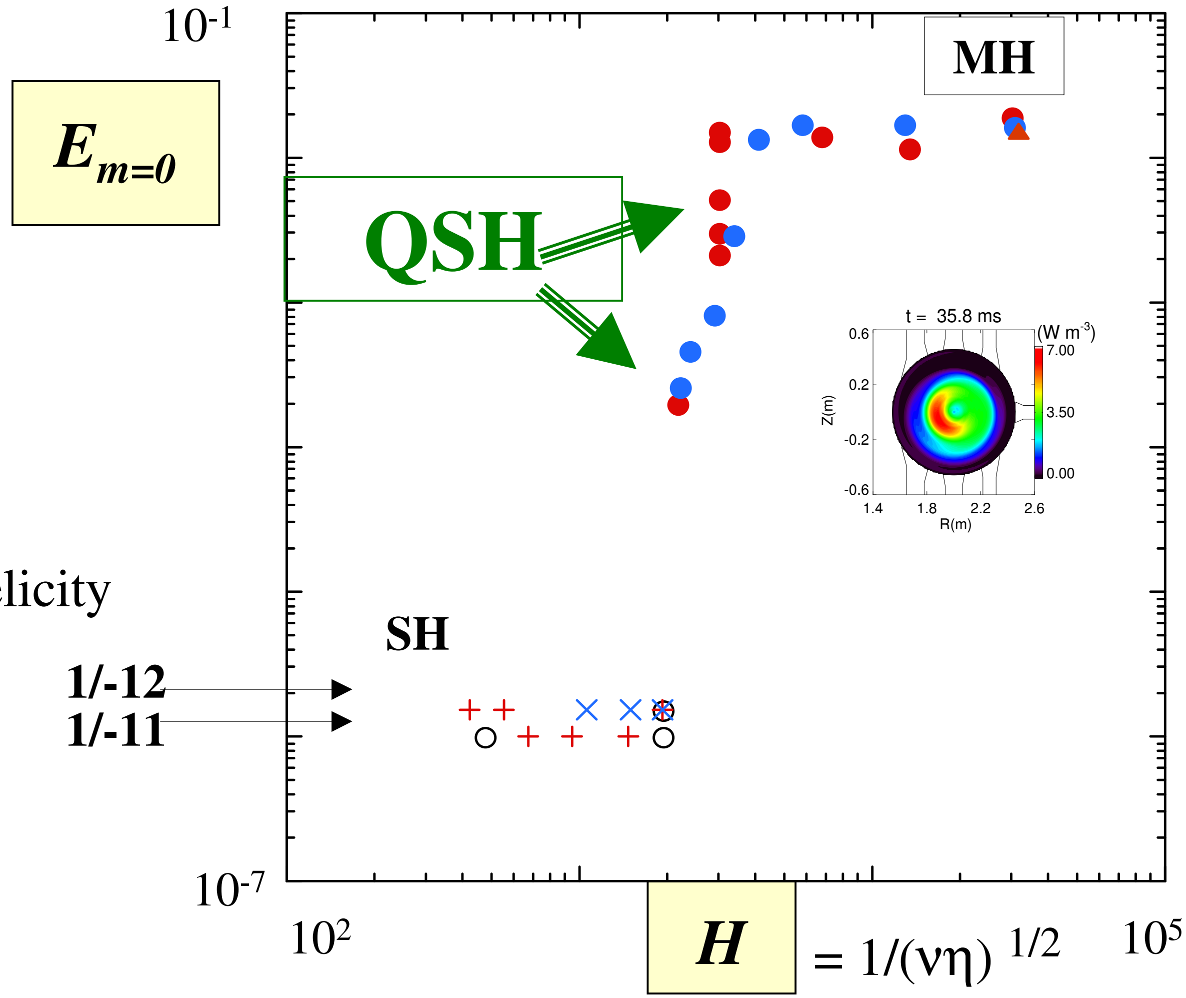




- Cravotta et al. Poster P2-107
- Frassinetti et al. Poster P1-111 this conference

QSH regime:

Chaos healing …



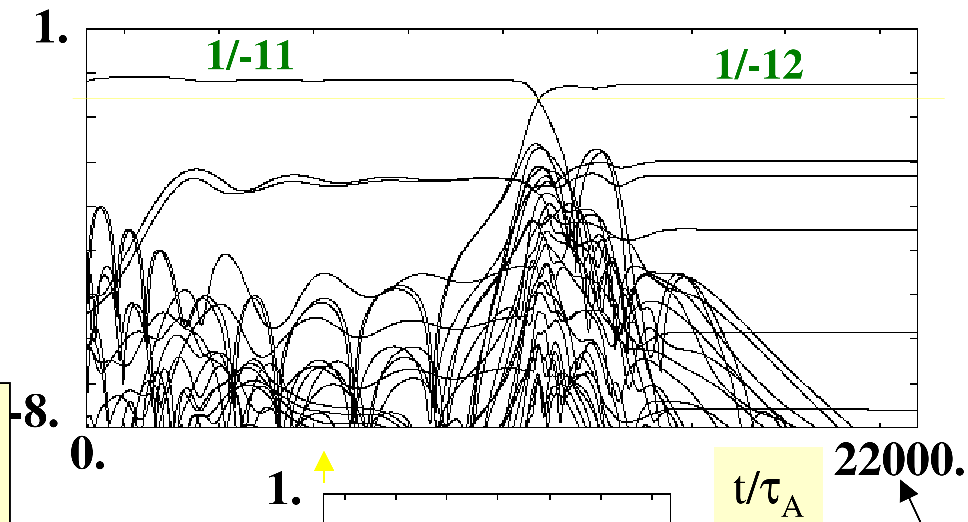
(Θ = 1.9)

Two **S**ingle **H**elicity basins **m/n** :

QSH regime:

- **some helicities persist for long time intervals,**
- **sensitivity to initial conditions,**

QSH

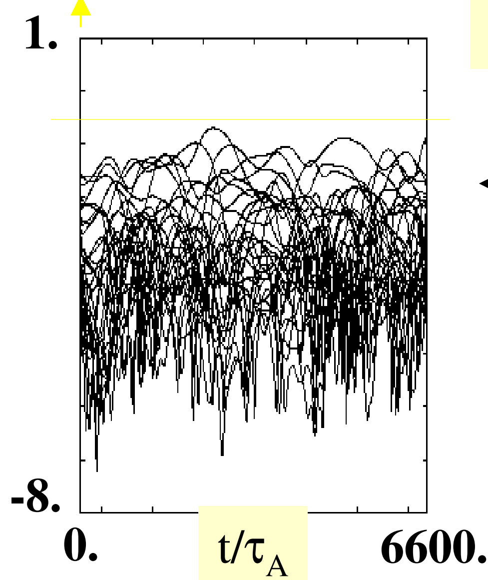


Log $E_{m=1,\,n}$

$H=3x10^3$

($S=3x10^4$,P=100)

MH

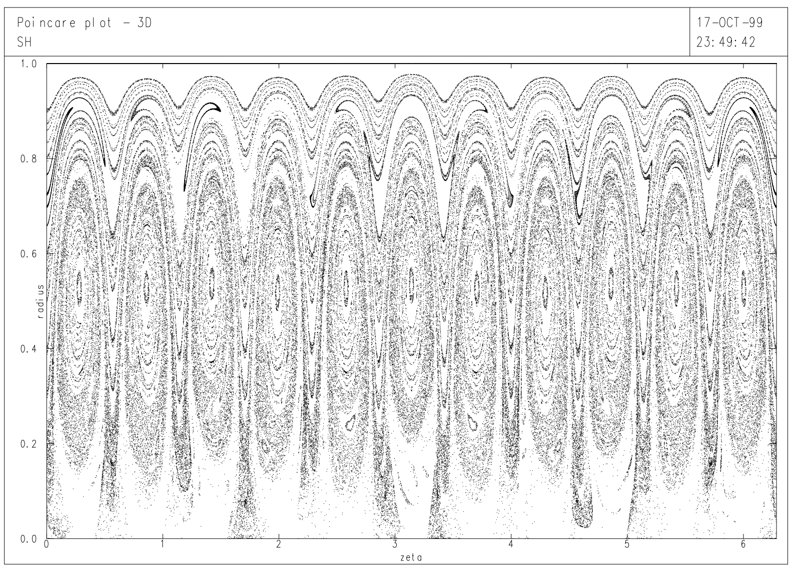


QSH regime:

Poincaré plot in QSH regime

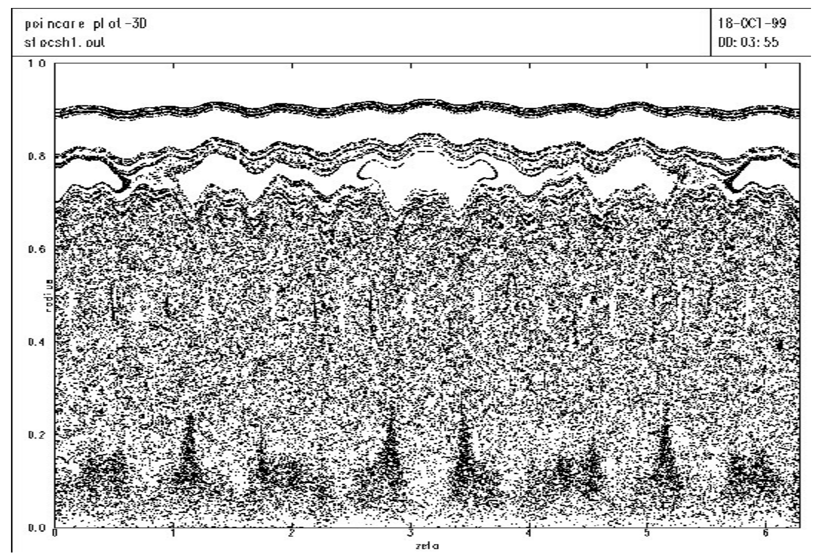
high amplitude ← **dominant helicity** → **reduced amplitude**

conserved helical structure



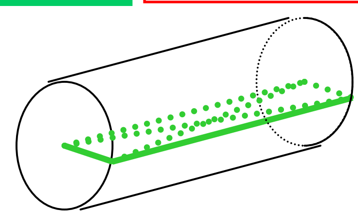
no separatrix

no order

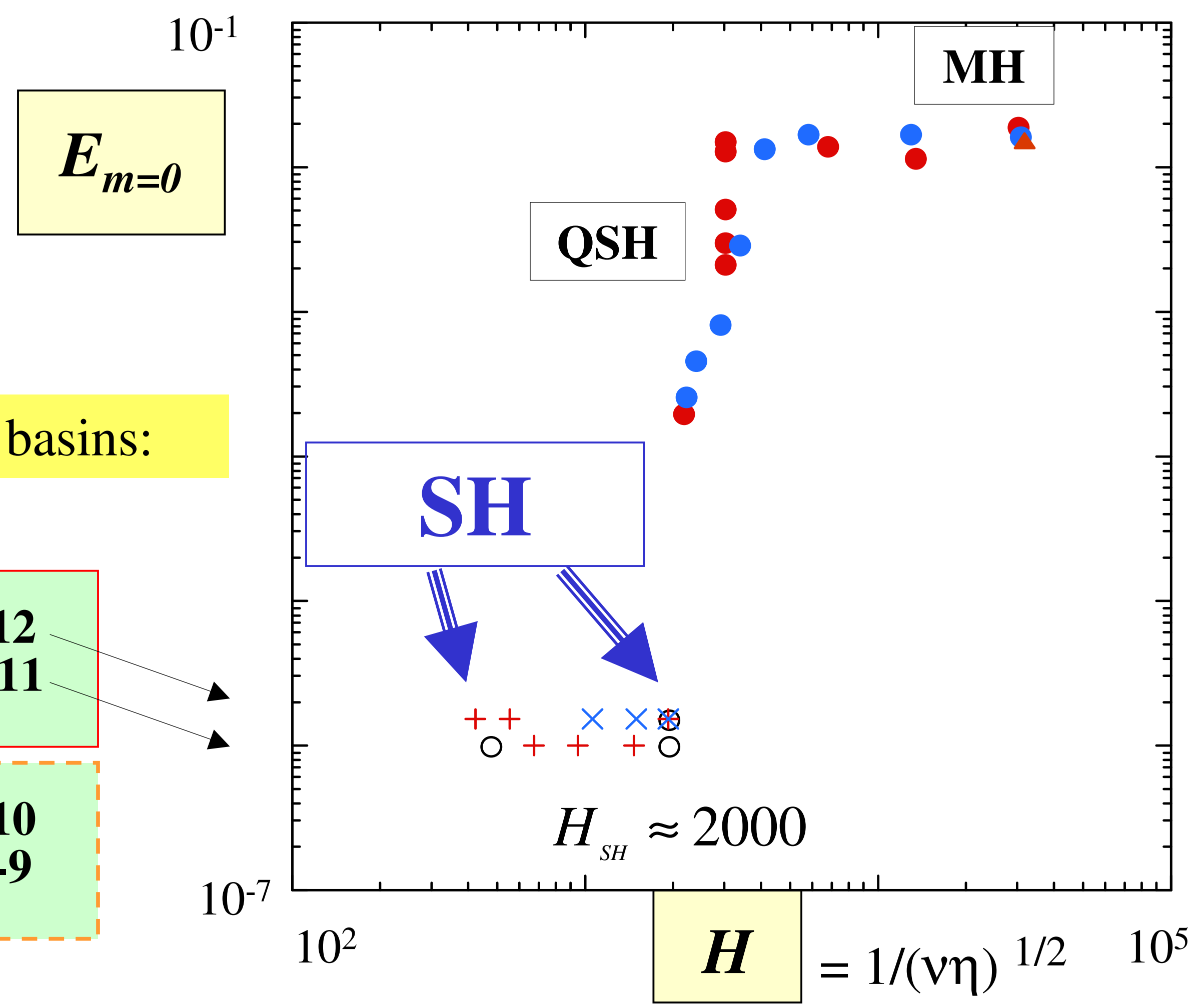


with separatrix

Escande,Paccagnella et al. PRL 2000



SH regime: **Simple ohmic helical equilibrium**



Two **S**ingle **H**elicity basins:

$\Theta = 1.9$

m/n **1/-12** **1/-11**

m/n **1/-10** **1/-9**

$\Theta = 1.6$

SH regime:

Escande, D'Angelo, Preti et al. PPCF2000

- … solution of ohmic equilibrium problem
  pressure is necessary for SH
- and saturation of kink instability.

When **laminar** SH states are achieved and persist

in a stationary way, as seen in numerical simulations,

the **electric field is entirely electrostatic** :

$$\nabla \wedge E = 0$$

$$\downarrow$$

$$E = -\nabla\Phi$$

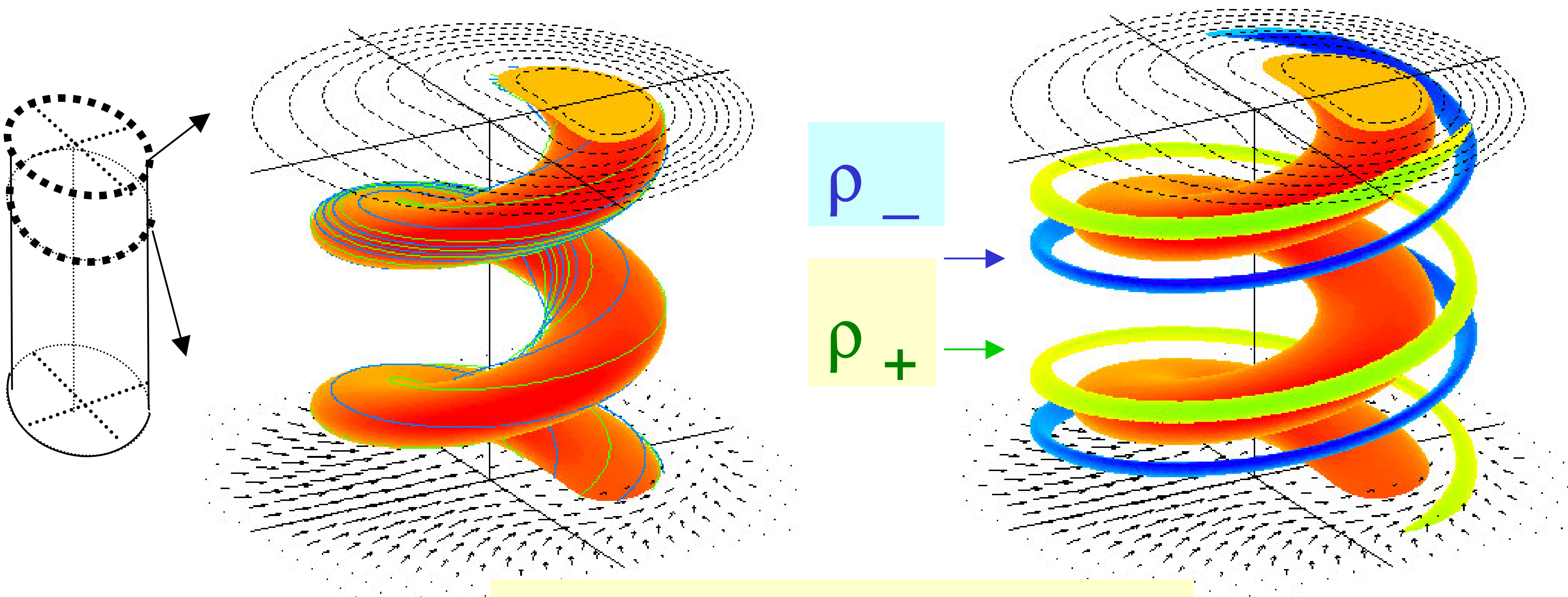
in such conditions we have

a **laminar electrostatic dynamo…**

SH regime: “ the simplest **RFP** dynamo ”

Magnetic flux surfaces and field lines

small charge separation double helix:
(consistent with quasineutrality!)



Helical Pinch Velocity

➔ drift velocity corresponding to the electrostatic potential

Bonfiglio, Cappello, Escande RFP WS 2004

Summary and open questions (**1** /4)

Transitions from turbulent to laminar regimes:

The **Hartmann number *H***

is the most important physical parameter in deciding the

Stability, robustness and accessibility of QSH-SH regimes,

-*numerical result of visco-resistive nonlinear MHD*

(-- benchmarked with :
DEBS code with resistive boundary conditions
NMROD with toroidal effects)

- *seen also by scaling argument, when inertia is negligible or large P,*

Summary and open questions (**2** /4)

Transitions from turbulent to laminar regimes:

- **Impact of more general MHD modeling**:

- finite β,
- non collisional terms like Hall and diamagnetic terms ….
- more accurate modeling of transport coefficients
for example : $\eta = \eta(T)$, $\eta(\psi)$,
- complete stress tensor may be important, as well as
inclusion of anomalous terms...

- **RFX data indicate ITG anomalous viscosity may be active,**
- **need for experimental estimates !**

Available estimates of the experimental H value suggest
H increases with plasma current *(dissipation decreases with current),*
yet the most robust QSH regimes have been achieved
in the last generation RFP experiments, (quasi - stationary in RFX)

Summary and open questions (**3** /4)

Transitions from turbulent to laminar regimes:

Boundary conditions:

• External action on selected Fourier components

may help in inducing a SH-QSH regime;

…Recent successful simulations (R. Paccagnella with DEBS)

New RFX assembly

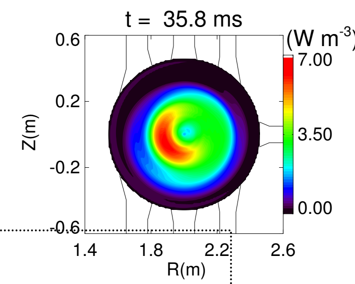
with flexible **set of active coils**

will allow experiments in these directions

Summary and open questions (**4** /4)

Magnetic chaos and transport:

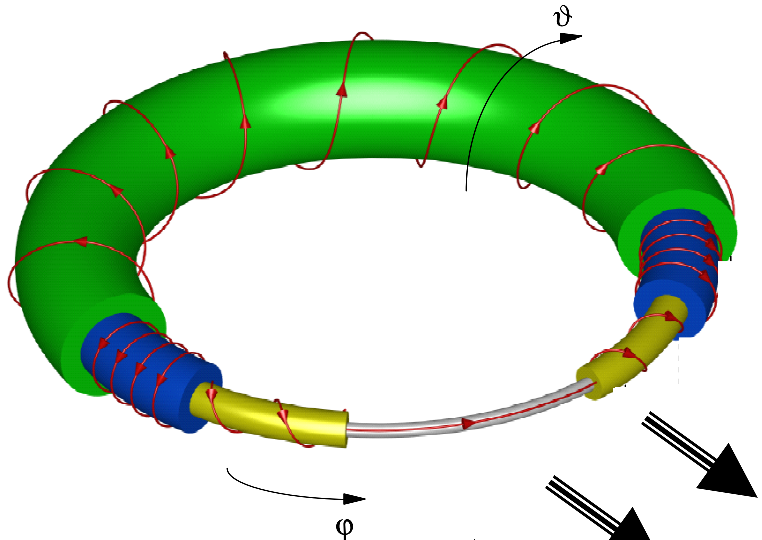
Onset of **QSH states with suitable amplitude** (large!) of the dominant helicity **may explain** the **experimental** observation of helical structures in **SXR tomography**,
(**separatrix expulsion ➔ chaos healing**)



Still to clarify the requirements for full exploitation of **confinement improvement** by onset of QSH/SH regimes,

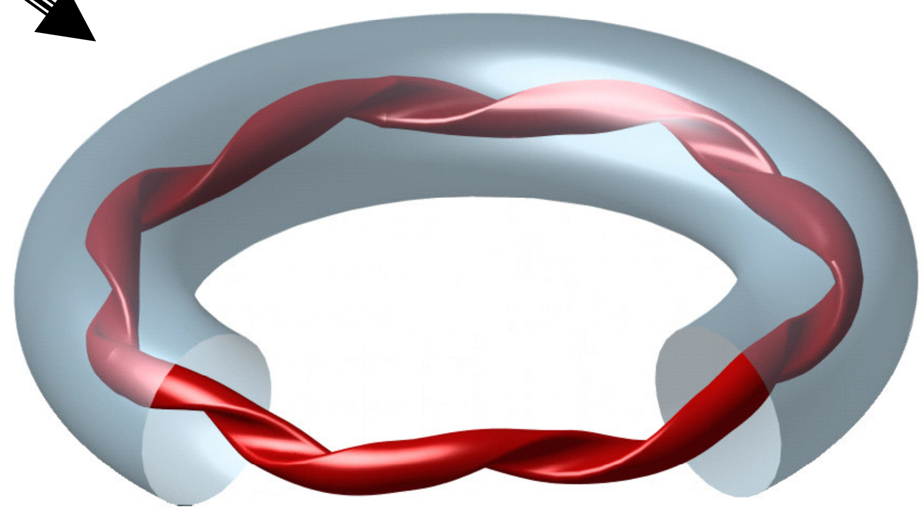
An assessment of the transport properties of SH and QSH states has been undertaken

Predebon et al.,
poster P2-112
this conference



Think kink !

Stable helical equilibrium



Opens new
perspective for the RFP

but also yields
better “zero order” description of conventional RFP.