

The Reversed Field Pinch toward magnetic order: a genuine self-organization

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Bonfiglio, Escande, Guo, and the RFX team

CNR - CONSORZIO RFX Associazione Euratom-ENEA sulla Fusione - PADOVA - ITALY

THEORY OF FUSION PLASMAS 2008

JOINT VARENNA - LAUSANNE INTERNATIONAL WORKSHOP

Varenna, Italy, August 25 – 29

1. Introduction

- Self-organization and RFP dynamo
- Simple kink-type deformation of plasma column provides the RFP dynamo :
laminar dynamics & magnetic topology order
genuine self-ORGANIZATION

2. MHD modelling

- H number – transition diagram
- SH - QSH - MH dynamic regimes features

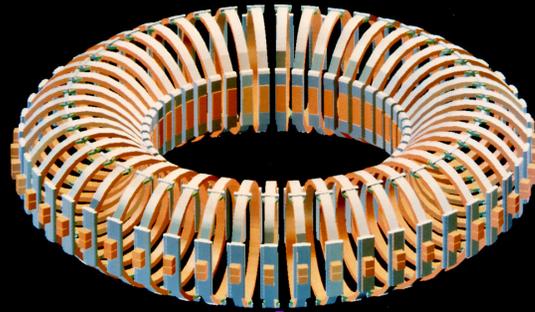
3. Experiments :

- high current operation 1.5 MA – 1.2 keV , and/or
- OscillatingParallelCurrentDrive operation

4. Summary open issues

RFP configuration

RFX coils



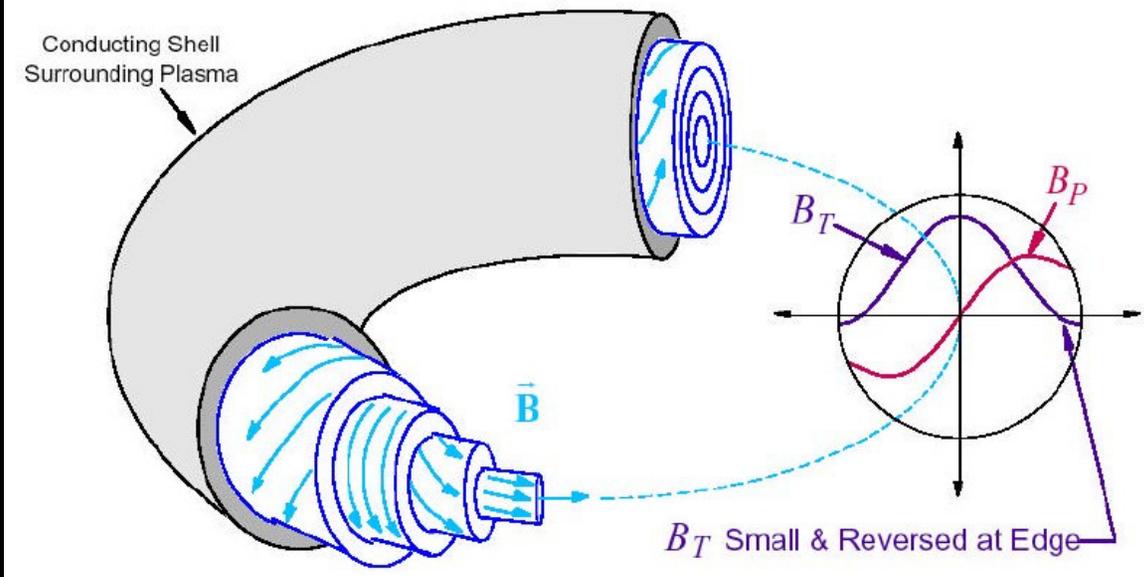
toroidal magnetic field



poloidal magnetic field

induction of plasma current

The RFP



mean
magnetic field
radial profiles

What we mean with “RFP dynamo effect”

1/2

Bodin et al. REVERSED-FIELD PINCH

⇒ Ohm's law

$$\mathbf{E} + \mathbf{V} \wedge \mathbf{B} = \eta \mathbf{J}$$

at reversal

$$E_{\vartheta} = \eta J_{\vartheta} + V_r B_z$$

⇒ Induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \wedge \mathbf{E}$$

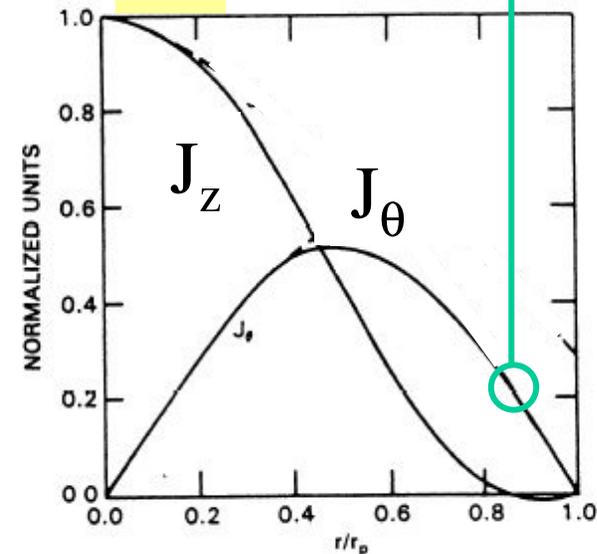
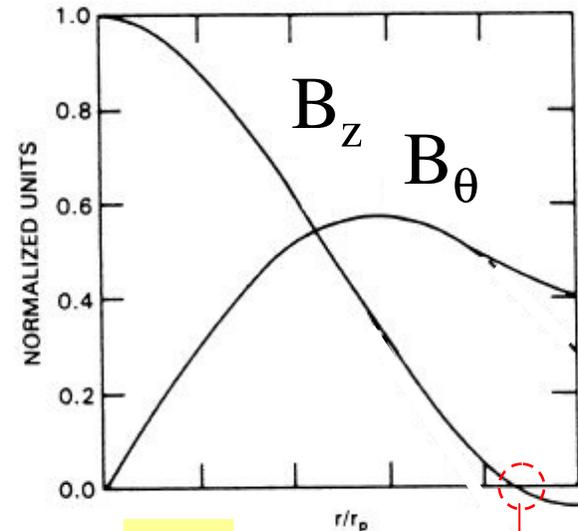
$\frac{\partial}{\partial t} = 0 \rightarrow$
stationarity

$$E_{\vartheta}(r) = 0$$

$$J_{\vartheta}(r) = 0$$

$$J_{\vartheta}(r) \neq 0$$

!! inconsistency



What we mean with “RFP dynamo effect” :

2/2

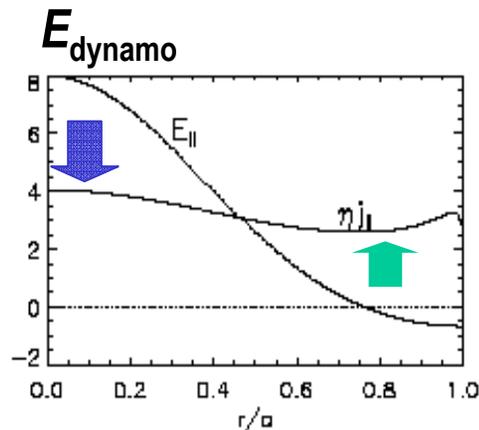
to resolve the previous inconsistency we need an “additional” mean electric field

with respect to the one provided by mean B and mean v fields, i.e. -within resistive MHD- the contribution by coherent modulation of B and v:

$$E_{\text{dynamo}} = \langle v \wedge B \rangle$$

$$\langle E_{\vartheta} \rangle = \langle \eta J_{\vartheta} \rangle + \langle V_r \rangle \langle B_z \rangle - \langle \tilde{V} \wedge \tilde{B} \rangle_{\vartheta}$$

In other words:



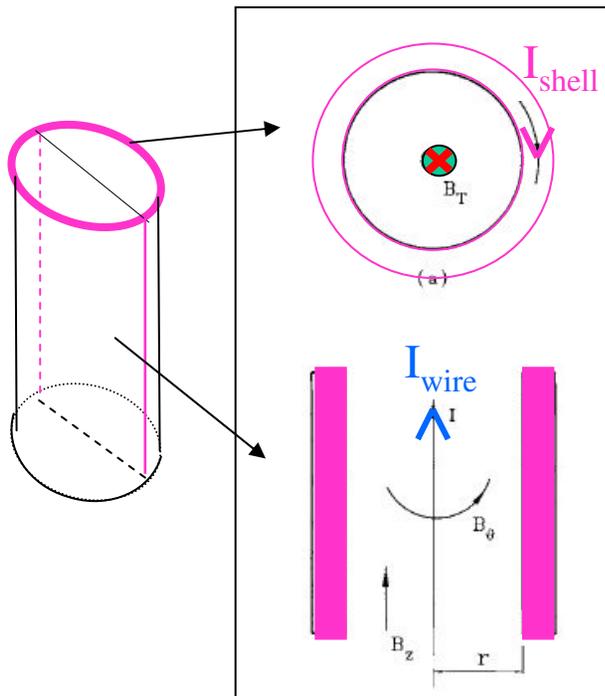
E_{dynamo} allows us to balance Ohm's law justifying that in stationary conditions:

- less mean J_z is driven in the core
- more mean J_{θ} is driven in the edge

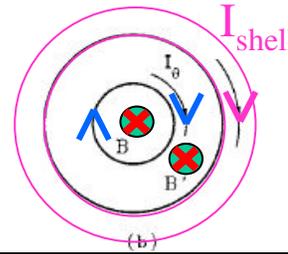
then expected by externally applied E.

Toy (wire) model : the simplest scheme of “RFP” dynamo

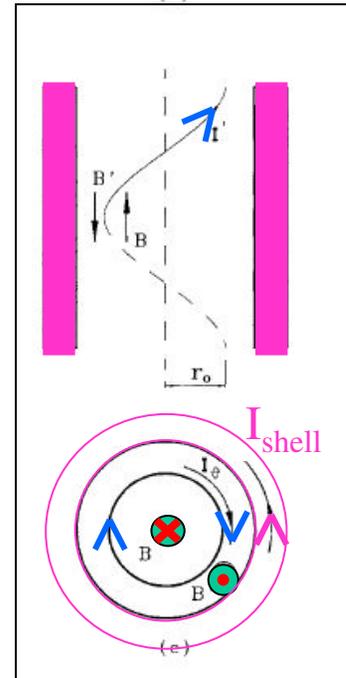
1) Wire (I_{wire}) on the axis of a flux conserver unstable



2)



The wire kinks



3)

Kinked wire at
Equilibrium when:

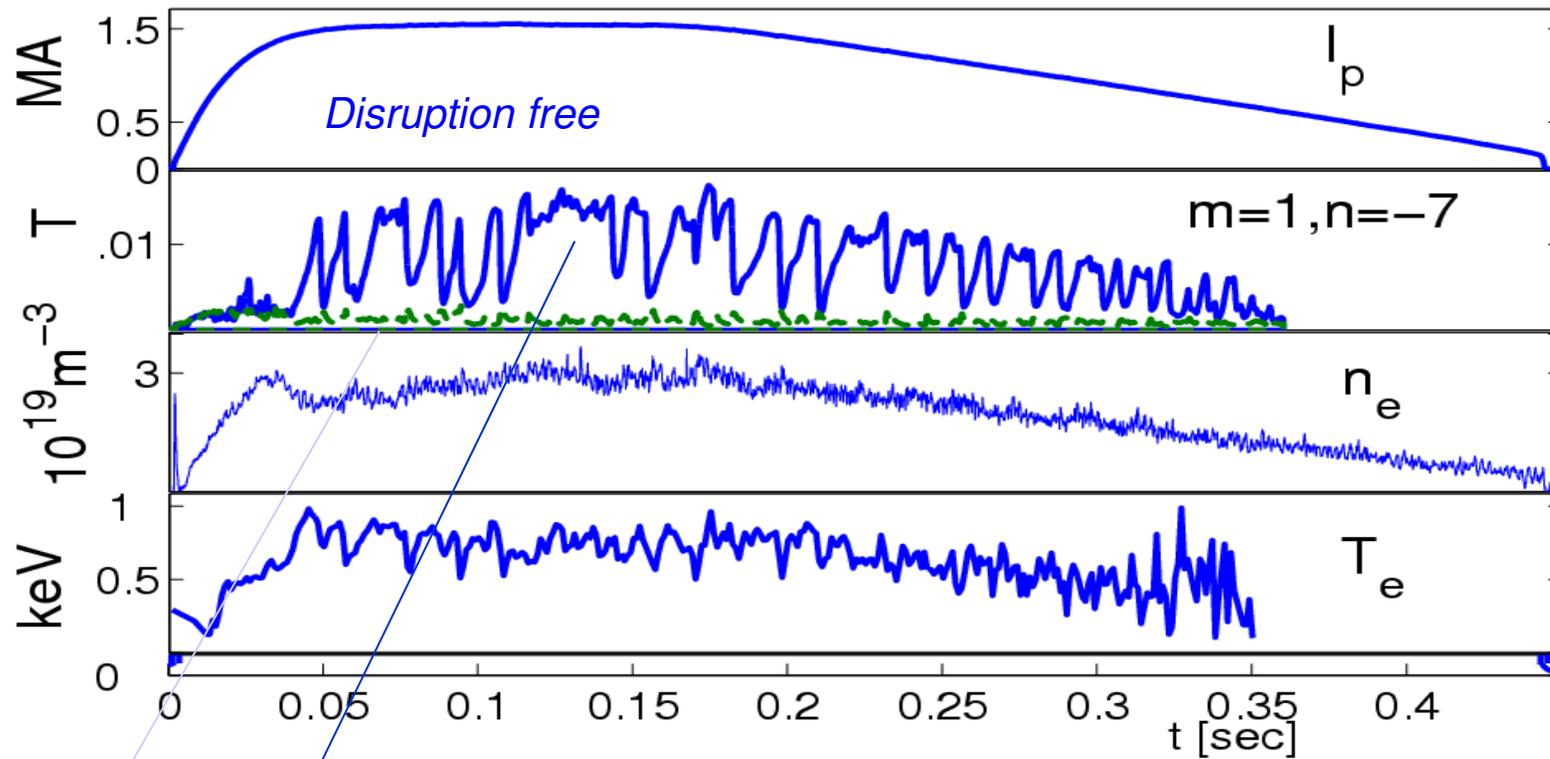
Field reversal by
solenoidal effect

Axial component of current decrease
Azimuthal component increase ... RFP dynamo

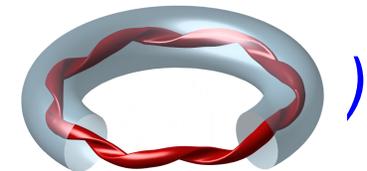
RFX-mod recent results

Valisa RFX team. invited EPS 08
to appear in PPCF 2008

Quasi Helical Regimes develop spontaneously at high Ip



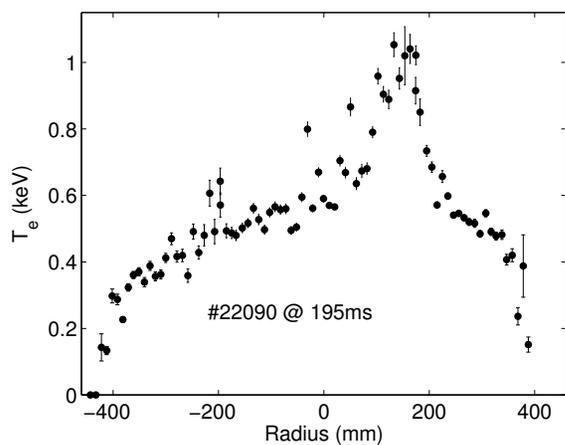
Dominant mode (helical amplitude)



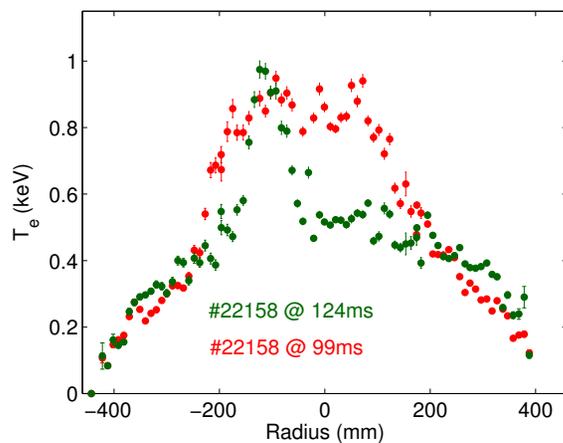
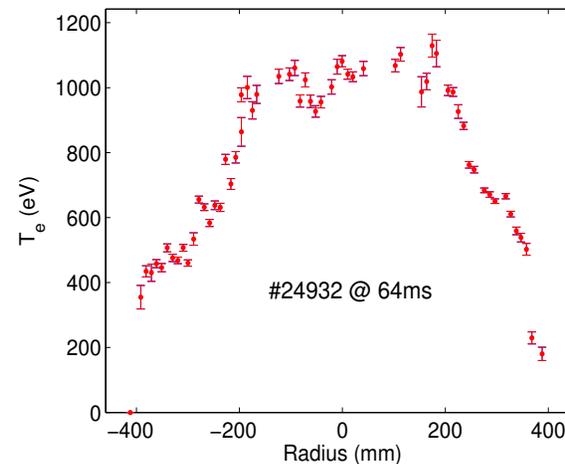
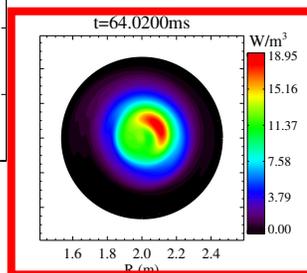
Secondary modes

RFX-mod recent results

Electron Temperature up to 1.2 keV- steep gradients

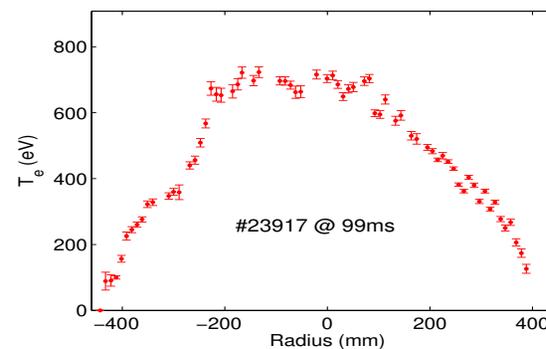


SXR
tomography



Bonomo Franz et al.
EPS 2008

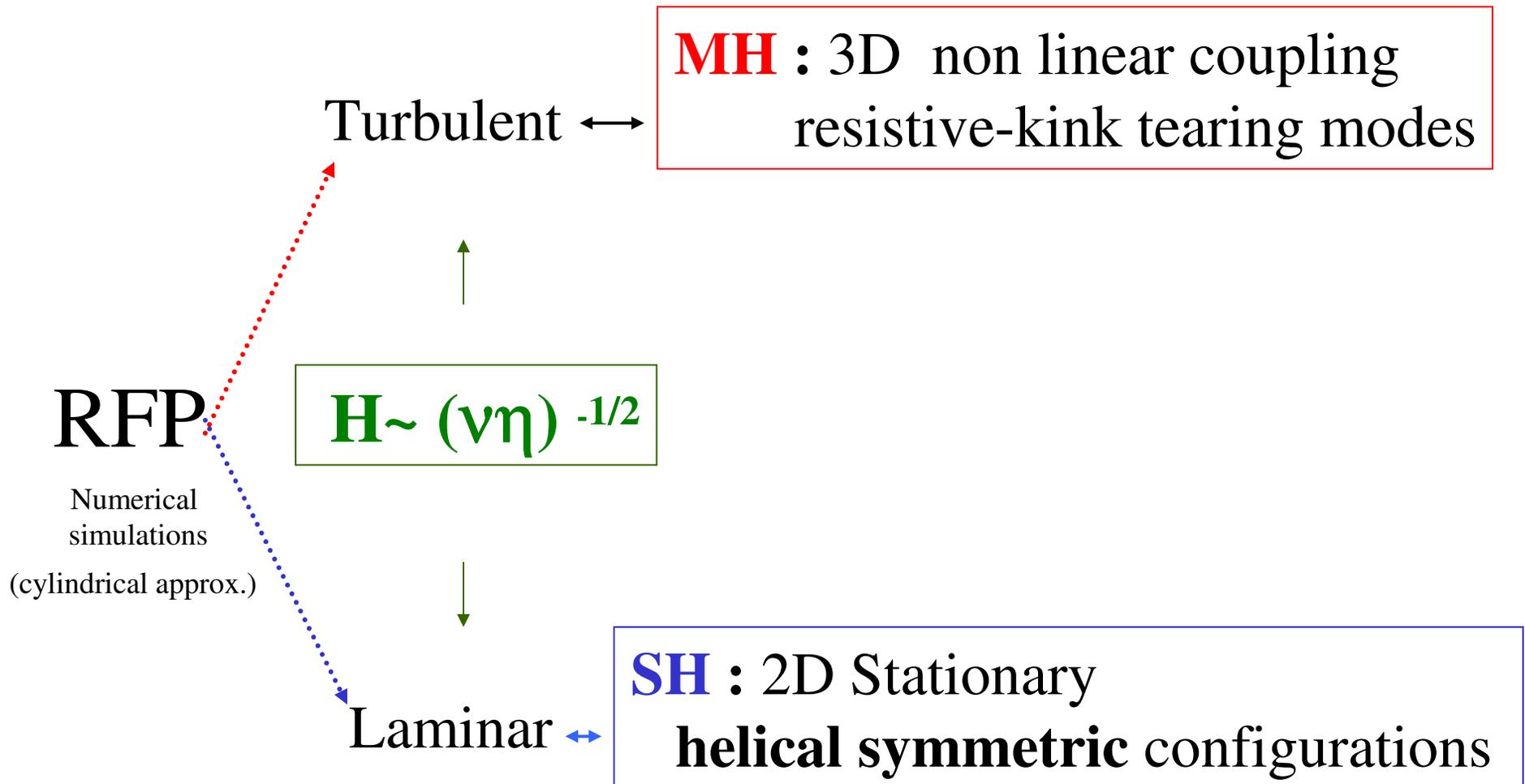
Alfier et al.
PPCF 2008



RFP self-organization and dynamo

MHD numerical modelling

MHD Numerical simulations



Model equations

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

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

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

3D MHD nonlinear code SpeCyl

Cappello & Biskamp
Nucl. Fus. 1996

$$\eta = \tau_A / \tau_R$$

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

$$\nu = \tau_A / \tau_v$$

simple visco - resistive
approximation

(ideal boundary)

re-scaling :

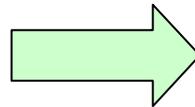
$$t \rightarrow \bar{t} = \sqrt{\frac{\eta}{\nu}} t$$

$$v \rightarrow \bar{v} = \sqrt{\frac{\nu}{\eta}} v$$

Model equations

... re-scaling : $t \rightarrow \bar{t} = \sqrt{\frac{\eta}{\nu}} t$ $\mathbf{v} \rightarrow \bar{\mathbf{v}} = \sqrt{\frac{\nu}{\eta}} \mathbf{v}$

(η, ν)



(H, P)

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

highlighted before

*by D. Montgomery et al. PPCF 92-93
and Tebaldi, Ottaviani JPP 99 (linear stab.)*

magnetic Prandtl: $\mathbf{P} = \nu / \eta$

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

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

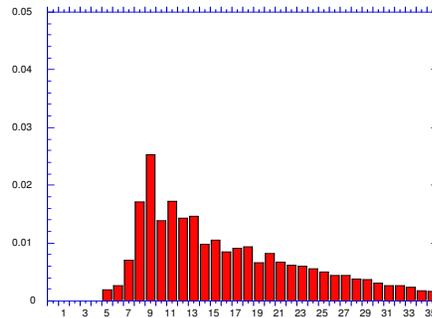
$$\rho \equiv 1, p \equiv 0$$

**“H” is the important parameter
when inertia is negligible !**

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

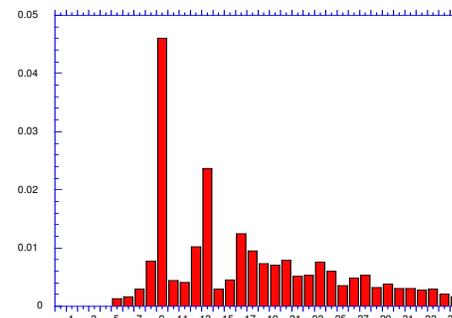
δB
 $m=1, n$

MH



n

QSH

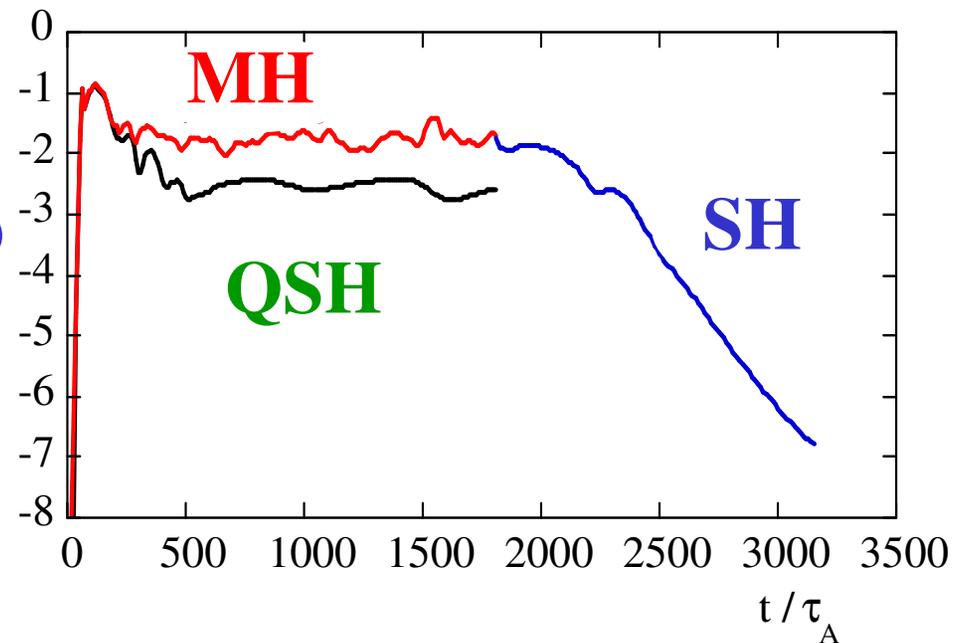


n

numerical results

$\log \delta E$
 $m=0$

$m = 0$ modes are
a good indicator 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

$$\Theta = 1.9$$

$$E^M_{m=0}$$

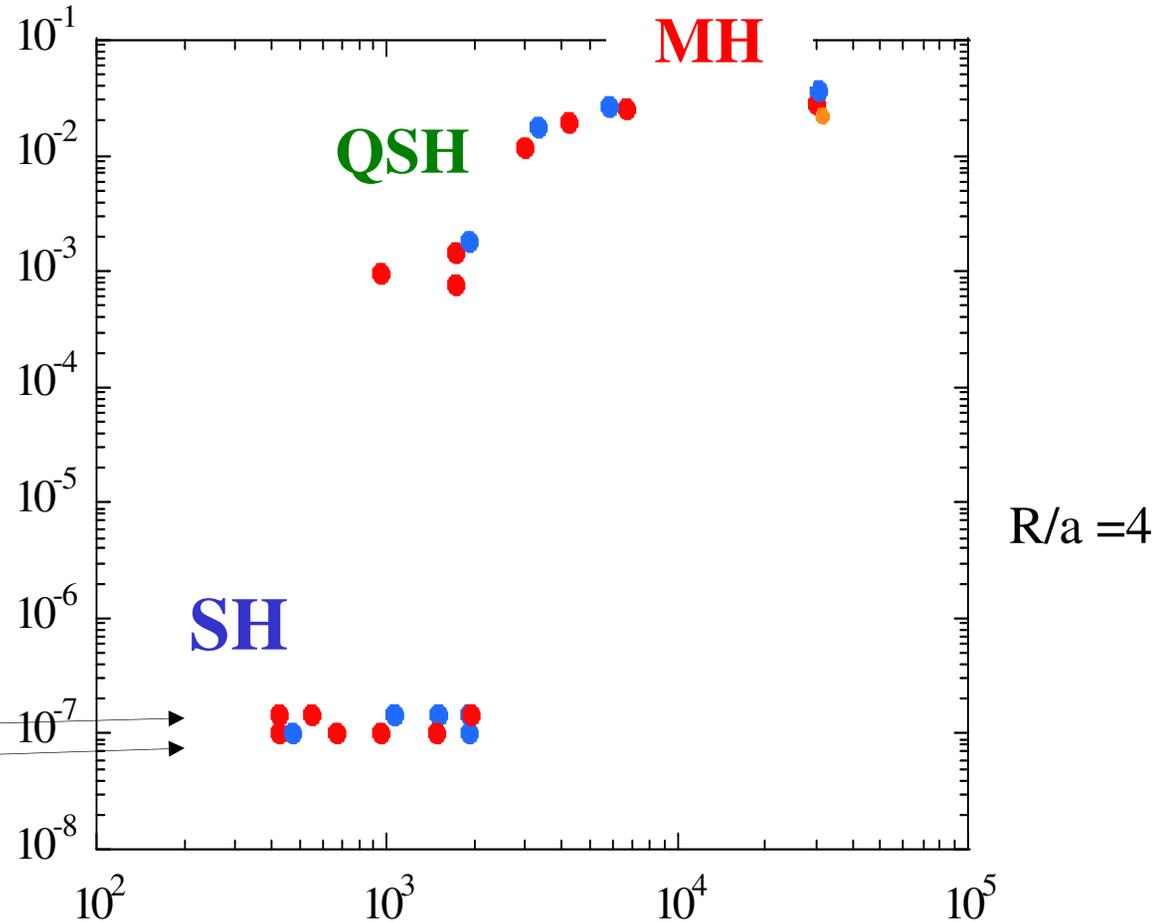
$S=3.3 \times 10^3$ (P: 2/3-10)

$S=3.0 \times 10^4$ (P: 1-5000)

$S=10^5$ (P = 10)

Two Single Helicity basins:

m/n	1/-12
	1/-11



$$H = 1/(v\eta)^{1/2}$$

Cappello & Escande PRL 2000

Cappello PPCF 2004

SH regime

Simple ohmic helical equilibrium

When **laminar** SH states are achieved and persist in a stationary way, as seen in numerical simulations,

the **electric field is entirely electrostatic** :

$$\nabla \wedge E = 0$$



in such conditions we have

$$E = -\nabla \phi \quad (+ E_{loop})$$

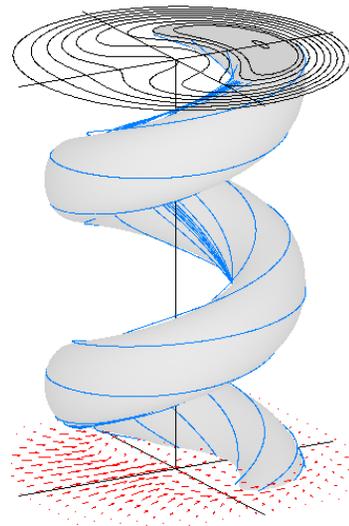
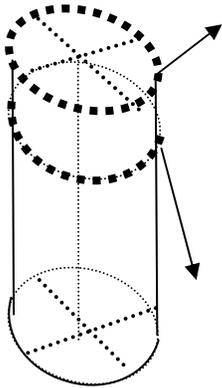
a **laminar electrostatic dynamo ...**
with perfectly conserved magnetic surfaces



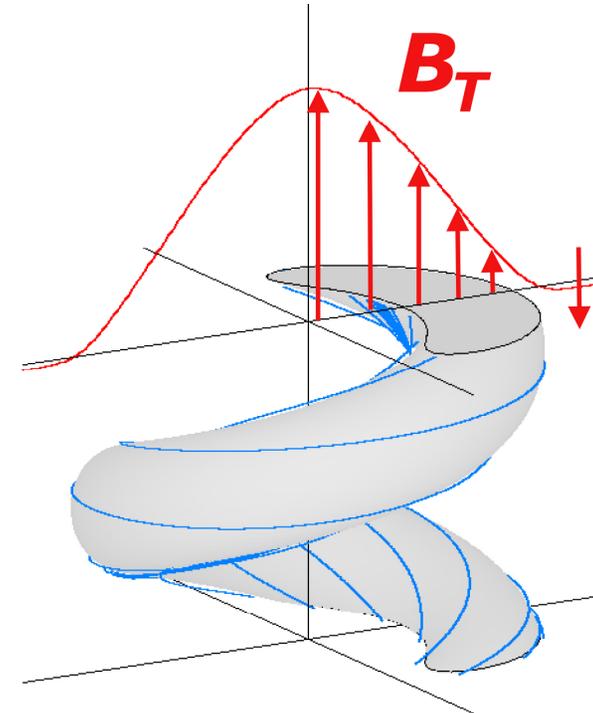
constant uniform applied E_{loop}

SH regime: “ the simplest RFP dynamo ”

Magnetic flux surfaces - field lines



... and corresponding mean profile of B_T



Helical Pinch Velocity

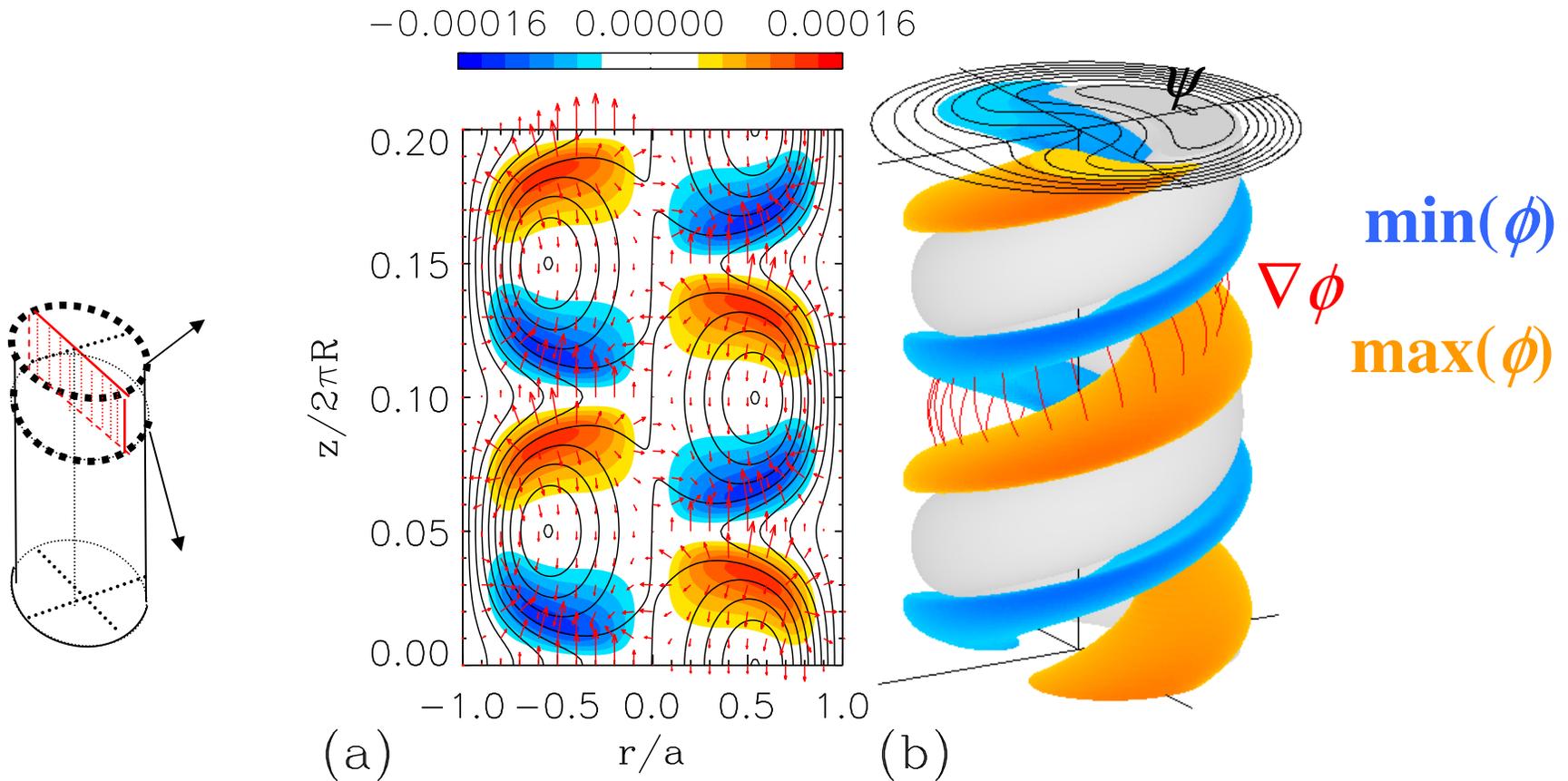
→ drift velocity induced by the electrostatic potential ...

SH regime

Electrostatic field $\nabla\phi$

ϕ : dipolar helical structure

$-\nabla\phi$: core helical capacitor



SH regime

perpendicular Ohm's law

$$E = E_{loop} - \nabla\phi = \eta J - v \times B$$

dynamo
velocity field

$$v_{\perp} = \frac{E_{loop} \times B}{B^2} - \frac{\nabla\phi \times B}{B^2} - \frac{\eta J \times B}{B^2}$$

paramagnetic
pinch

v_{loop}

v_{ϕ}

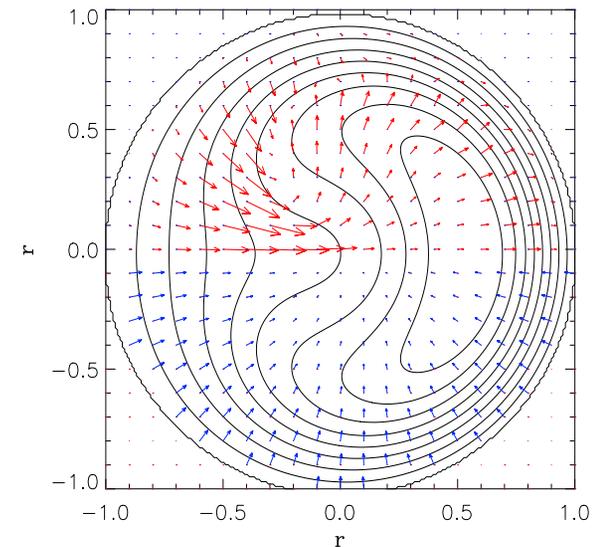
electrostatic
drift

dynamo velocity field \cong electrostatic drift

v_{total}

$\approx v_{\perp}$

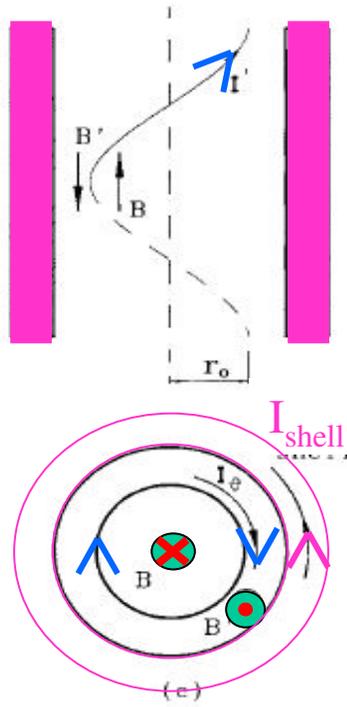
$\approx v_{\phi}$



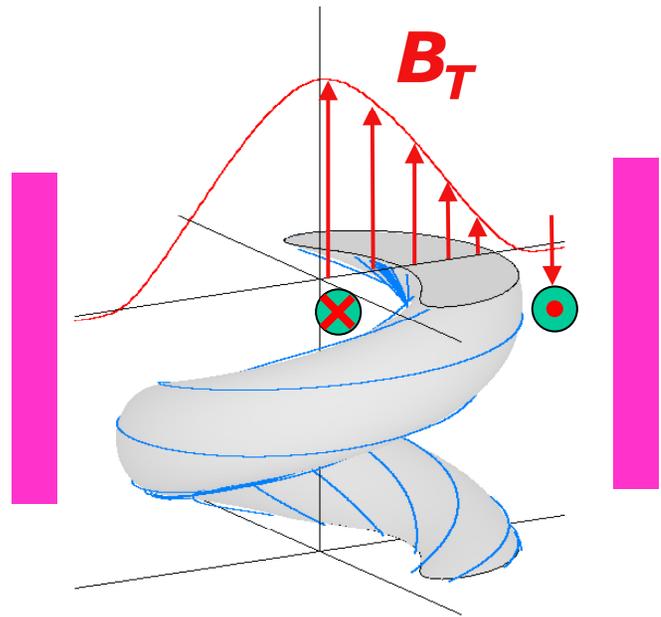
electrostatic nature of the RFP dynamo

Bonfiglio, Cappello, Escande Varenna 2006

Toy (wire) model and SH dynamo in MHD



kinked wire



SH in viscoresistive modelling

QSH regime:

$E_{m=0}$

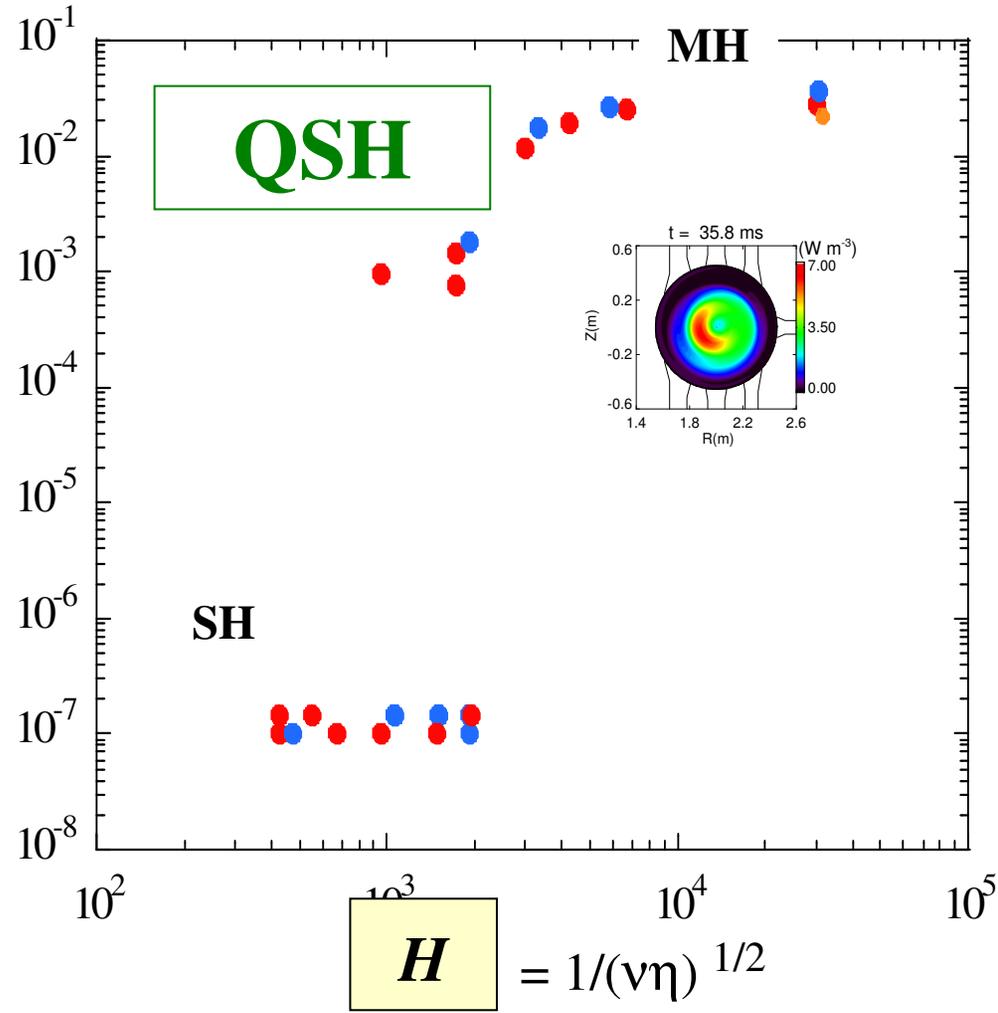
$(\Theta = 1.9)$

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

- 1/-12
- 1/-11

Numerical results

$\Theta = 1.9$

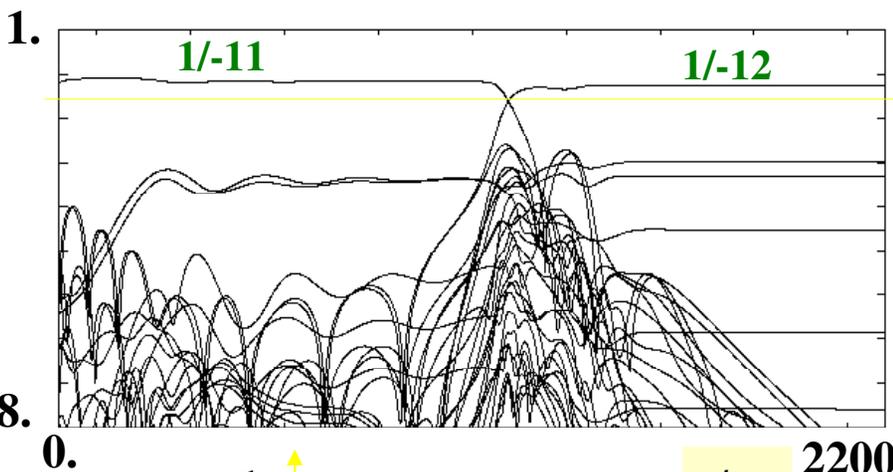


QSH regime:

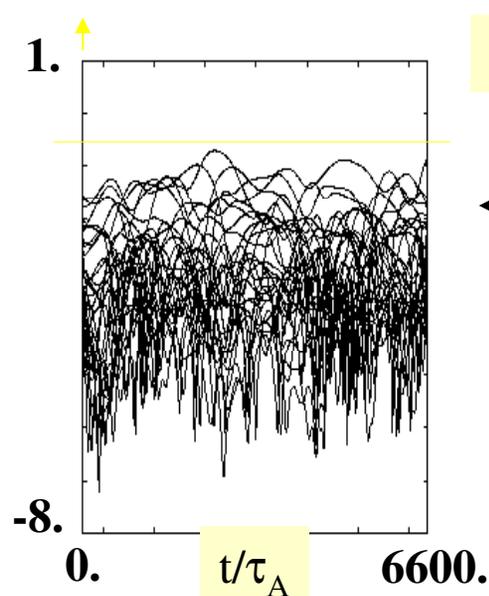
- some helicities persist for long time intervals,
- sensitivity to initial conditions,

QSH →

Log E_{m=1, n}



MH →



$H=3 \times 10^3$
($S=3 \times 10^4$, $P=100$)

QSH regime:

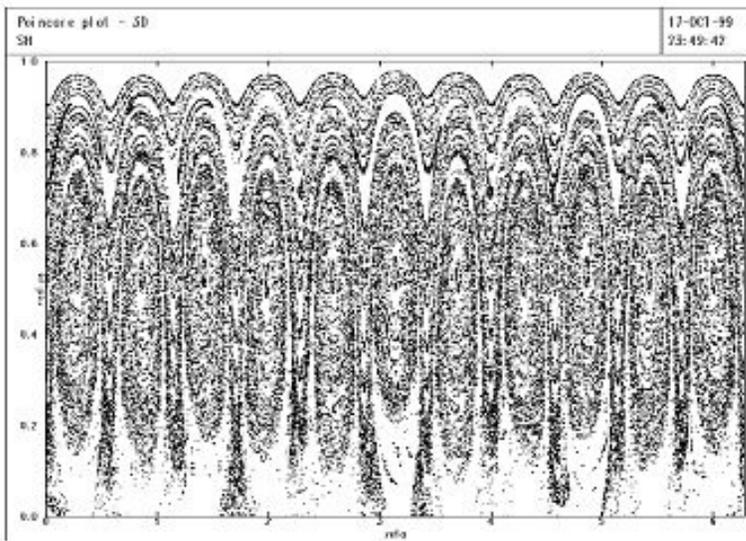
Poincaré plot in QSH regime

high amplitude

dominant helicity

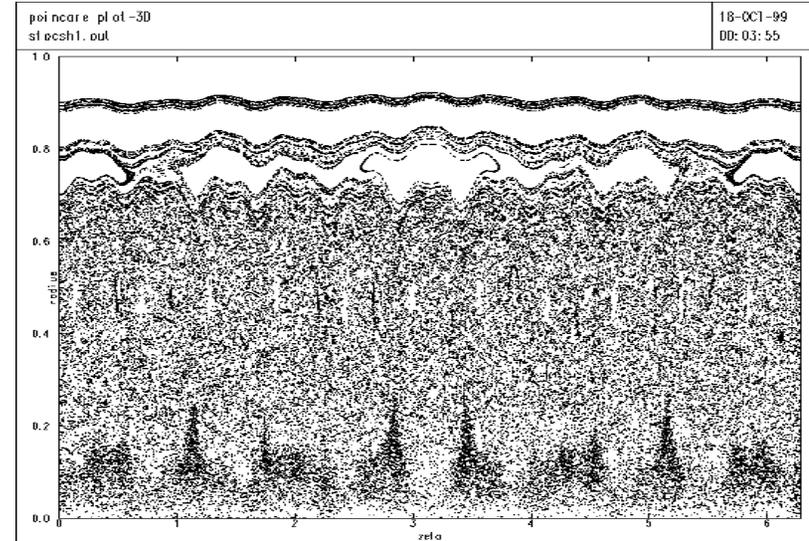
reduced amplitude

conserved helical structure

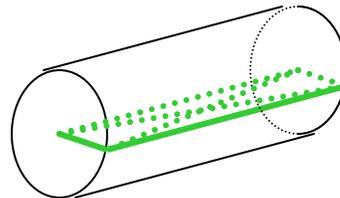


no separatrix – single helical axis

no order



with separatrix - island



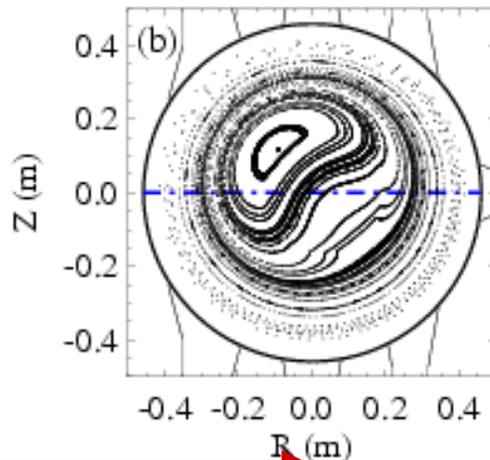
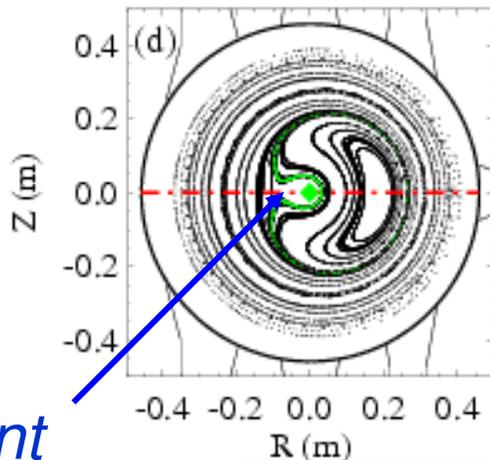
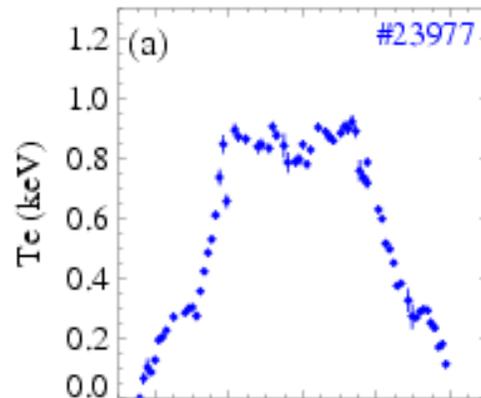
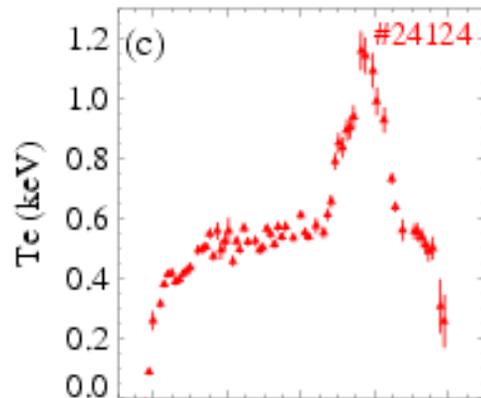
RFX-mod: topology reconstruction & T_e profiles

QSH

Island

SHAx

(Single Helical Axis)



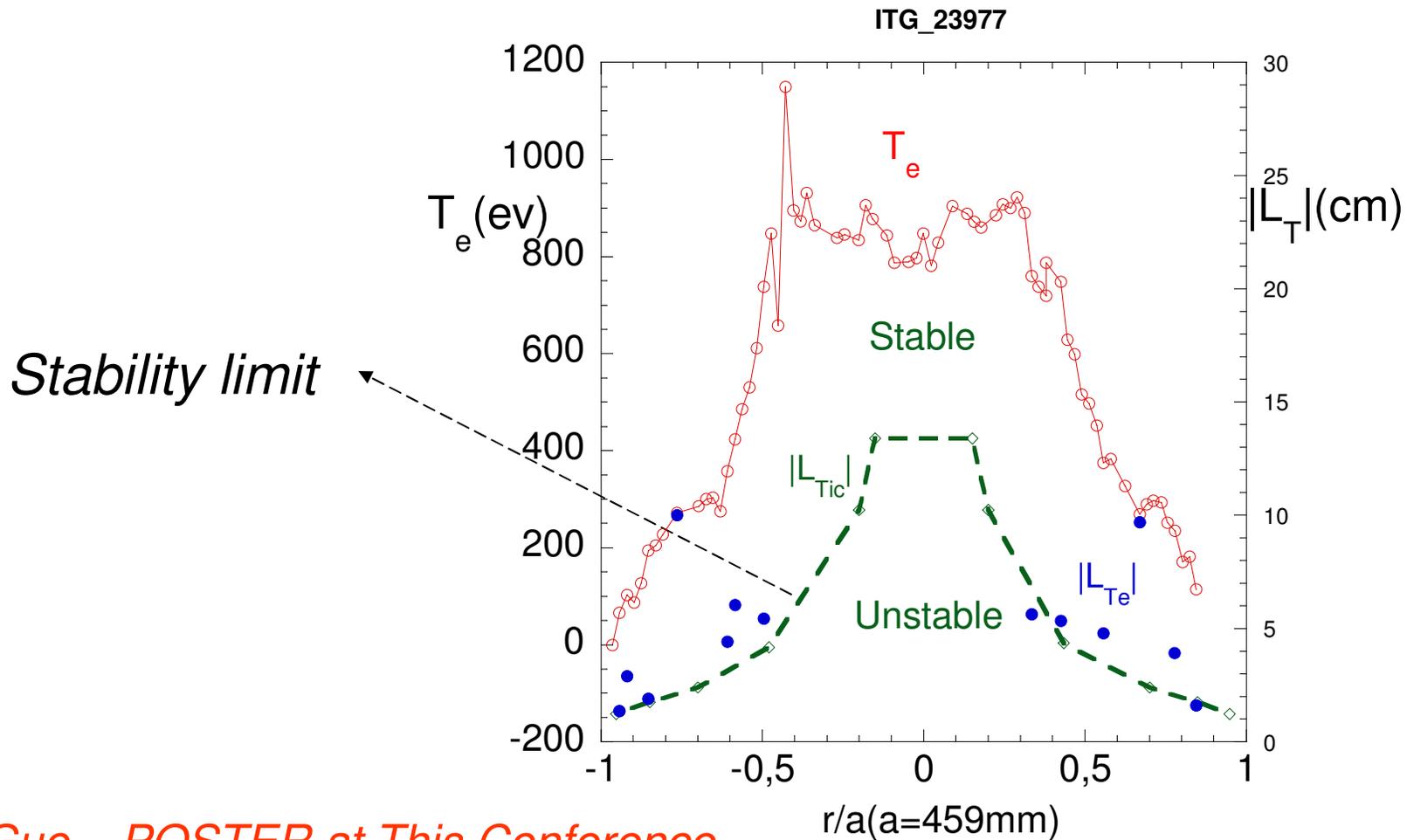
X point

b_{dom} / b_{sec} increases

expulsion of the separatrix : resilience to chaos potentially driven by residual perturbations

*Escande et al PRL 2000
Lorenzini et al PRL 2008*

Experimental gradients marginal stable for Ion Temperature Gradient modes (assuming $L_{Ti}=L_{Te}$) Possible role in transport in SHAx state (magnetic chaos healing)



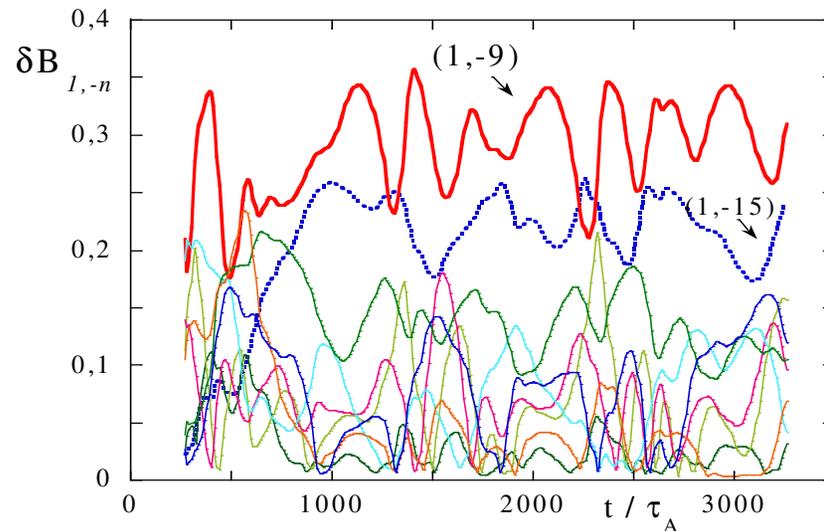
Guo – POSTER at This Conference
Gobbin, Guo et al. EPS 2008 P5.035

QSH regime:

The transition is rather continuous:

Less pure QSH are found in simulations

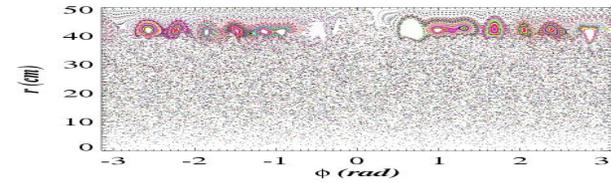
(similarly to experimental intermediate QSH)



Dominant mode with little energy separation

MH regime:

Spizzo Cappello Cravotta Escande et al. PRL 2006



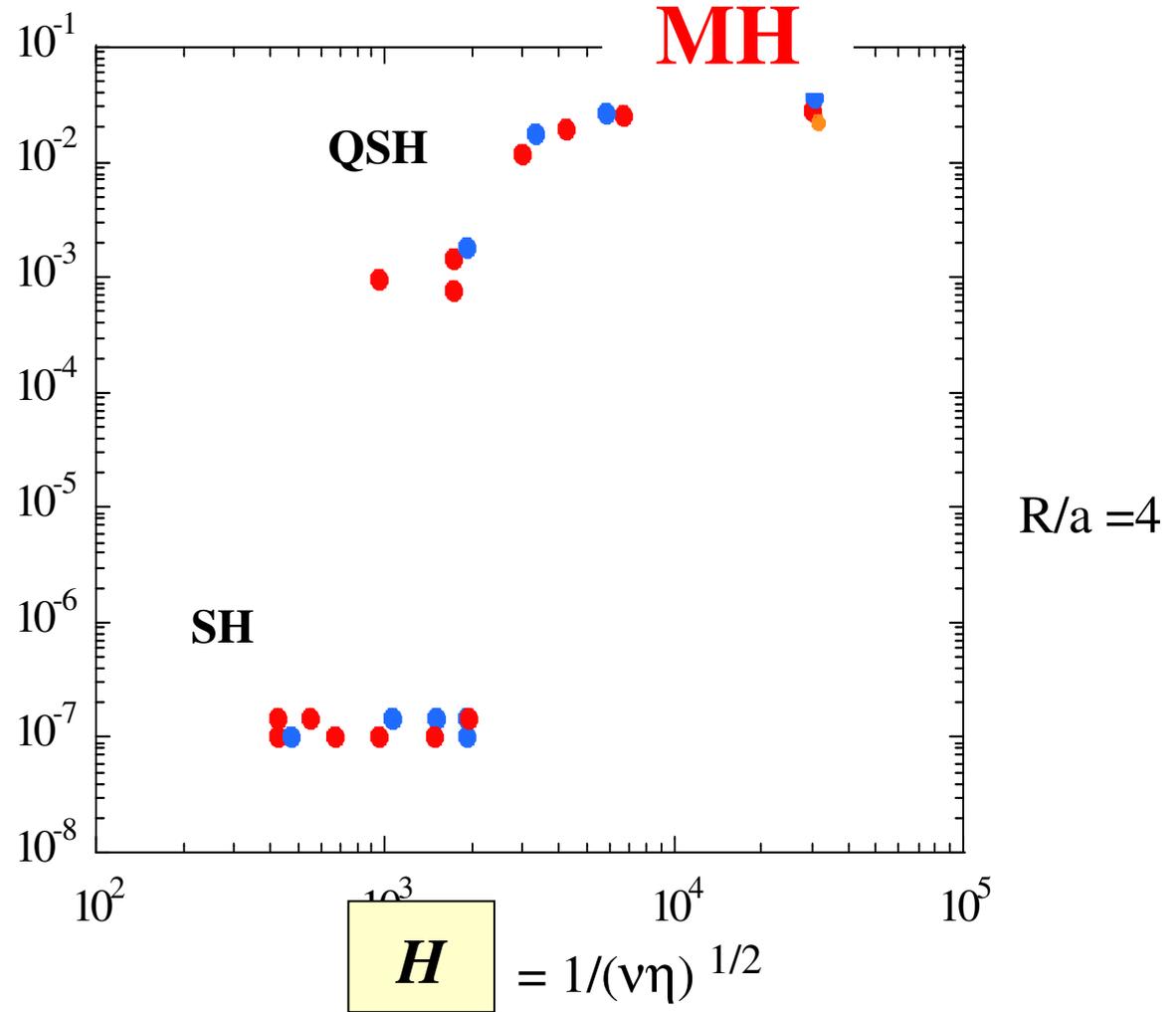
$\Theta = 1.9$

$E_{m=0}$

$(\Theta = 1.9)$

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

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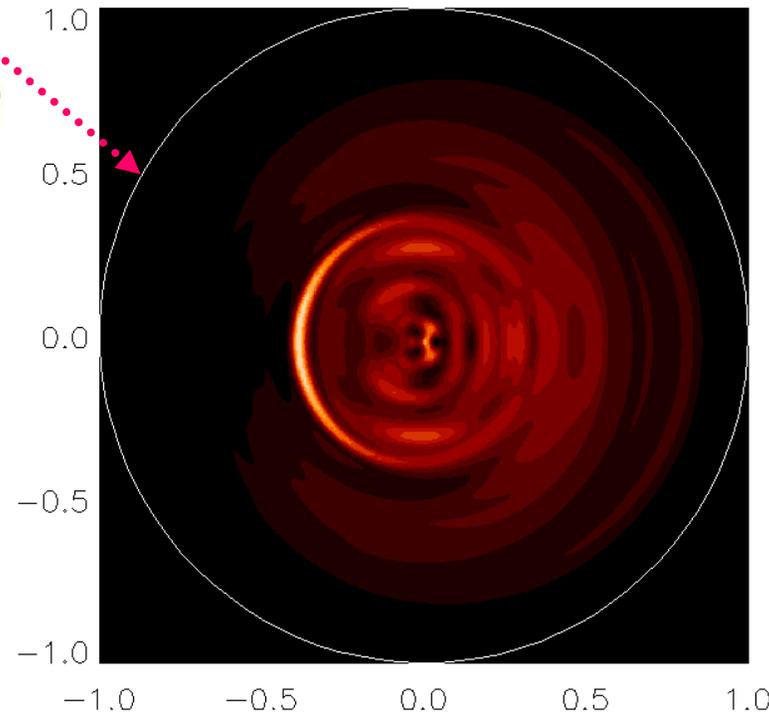
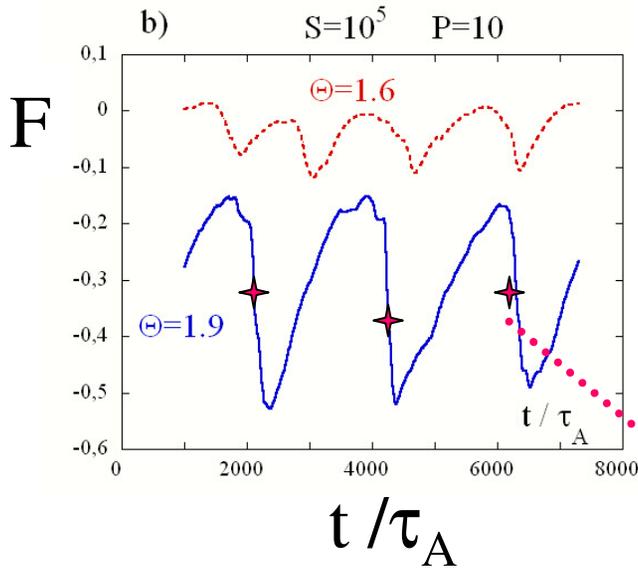


MH regime:

Nearly-periodic relaxation events

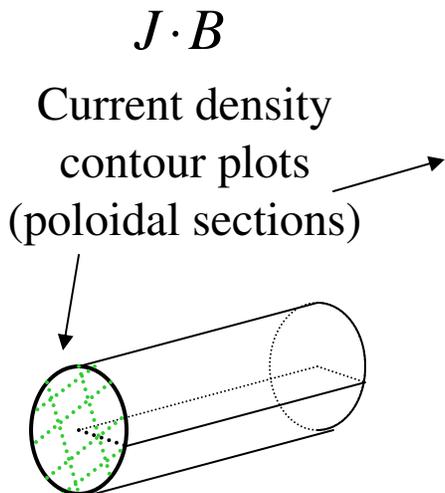
(similarly to experimental observations)

with formation of current sheets



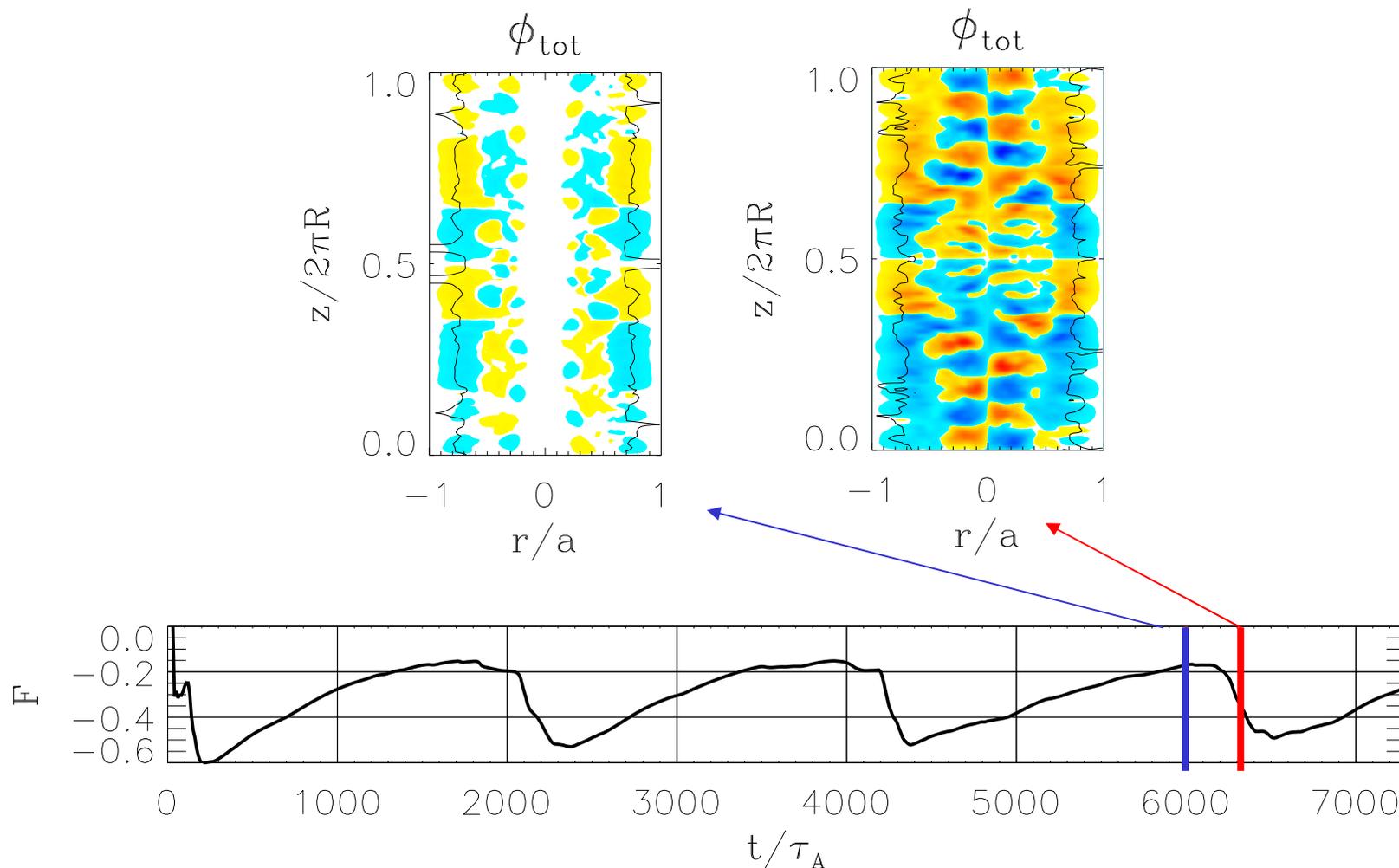
(3D: all of the modes contribute)

Bright colour => high current



MH regime:

The **electrostatic potential** (in addition to a $m=0$ component), especially during dynamo relaxation events, is dominated by **$m \geq 1$ component** and qualitatively similar to the SH one (**quasi-helical dipolar distribution**).



RFP dynamo in experiments

RFX-mod

with “Clean Mode Control” of magnetic boundary

Zanca et al. Nucl Fus. 2008

- **QSH is the most preferred regime :**

At high current (I_p up to 1.5 MA) (T_e up to 1.2 keV)

- **QSH systematic :**

With “Oscillating Parallel Current Drive” action (OPCD)

Terranova et al. PRL 2008

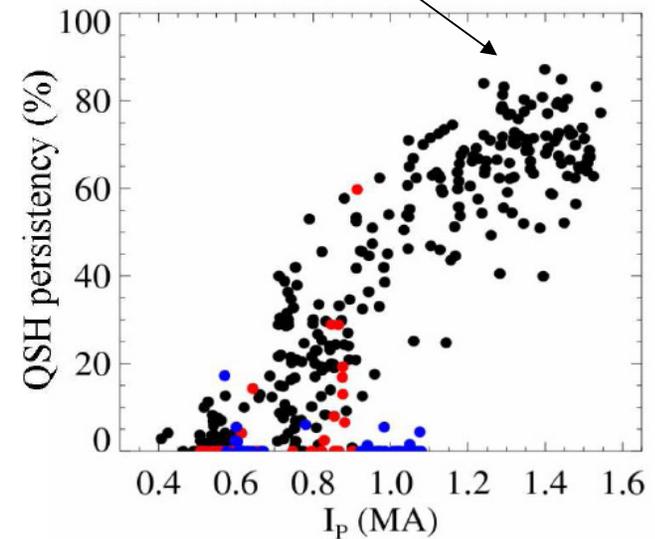
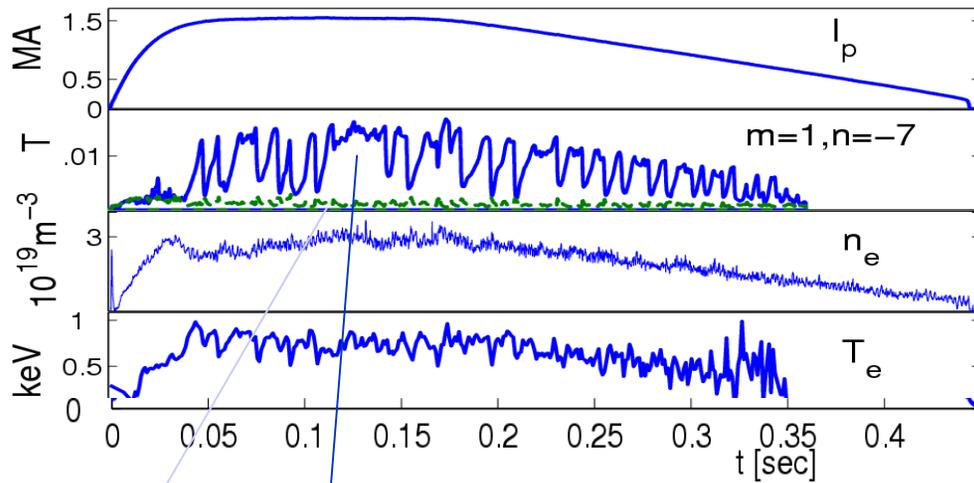
OPCD : Periodical pinching of plasma column induced by an oscillation of the toroidal flux

Valisa RFX team EPS 2008

RFX-mod

Quasi Helical Regimes develop spontaneously at high I_p

QSH persistency increases with current: up to 85% of flat top



Piovesan EPS08 O4.029

Dominant mode

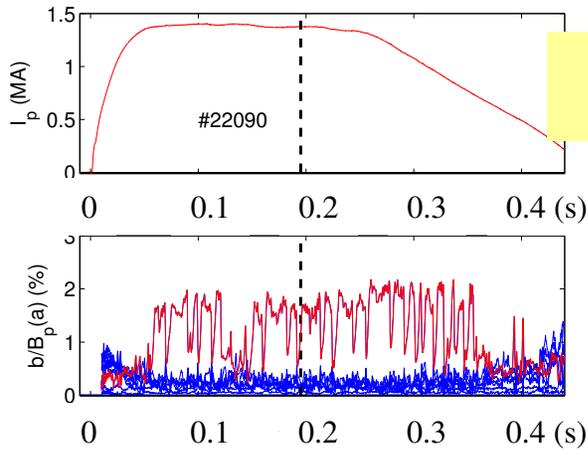
Secondary modes

*Valisa RFX team. invited EPS 08
to appear in PPCF 2008*

RFX-mod: QSH

- High current
- OPCD action stimulates systematic (pulsed) QSH

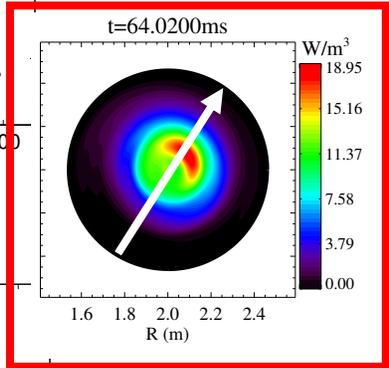
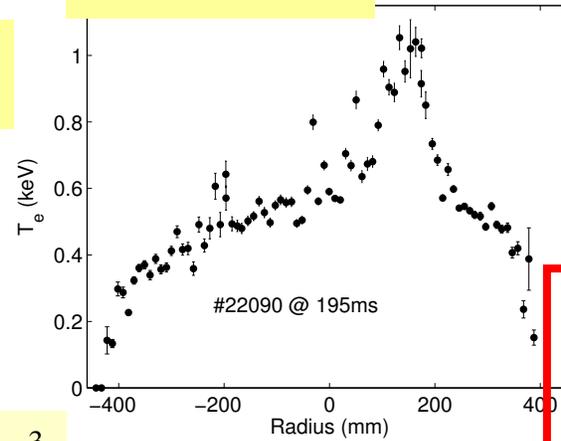
spontaneous QSH



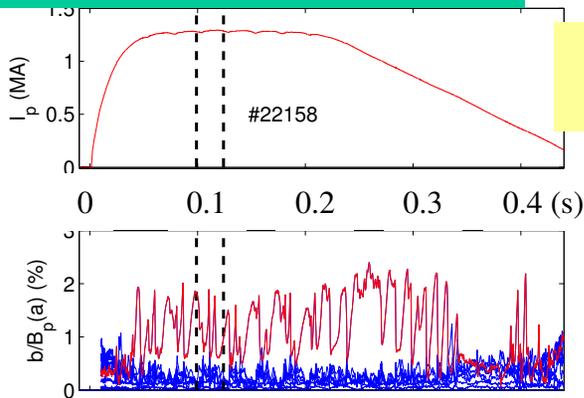
1.4 MA

$n \sim 4 \cdot 10^{19} \text{ m}^{-3}$

1 KeV

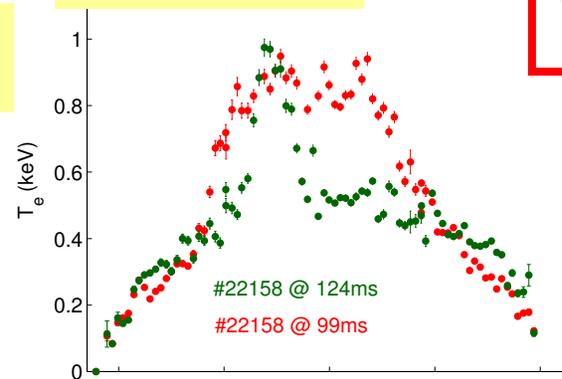


OPCD stimulated QSH



1.3 MA

1 KeV



Alfier et al.
PPCF 2008

Amplitude helical component

Temperature profile (Thomson scattering)

Summary and open questions (1 /2)

Viscoresistive MHD numerical modelling

Transition obtained in simple visco-resistive MHD

the **TURBULENT-LAMINAR** transition depends essentially on the strength of dissipative forces : **Hartmann number**

This is difficult to match with the experimental evidence that QSH is the most frequent state at high current ... unless postulating a strong increase of effective viscosity with plasma current : need to extend MHD modelling

Anomalous viscosity ...

Terranova et al PPCF 2000

McDevitt&Diamond 2006

RFP dynamo \Leftrightarrow simple kink of current channel

the saturated kink may be considered the RFP reference equilibrium
intuitive description of the RFP dynamo

... no need of MHD turbulence to sustain the configuration

Summary and open questions (2 /2)

QSH residual intermittency

- **Impact of more general modelling**

*Finite β – transport effects
toroidal effects*

PIXIE3D (L. Chacon)

- **How to better comply self-organization in experiment**

Why opcd so effective ?

- **Optimization of feedback control**

Transport in SHAx states (chaos healing)

- **What the dominant mechanism then ?
drift turbulence : ITG TEM ...**

TRB – GS2 – GYRO

- **Issue of density refuelling to enter the transport barrier**

RFX-mod **Aim : 2MA - low magnetic chaos - high confinement**