Theory and Advanced Simulation

The Reversed-Field Pinch case

Helical Self-Organization processes

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Theory and Simulation physics group of Consorzio RFX

Consiglio Nazionale delle Ricerche – CNR – ISTP (Istitute for Plasma Science and Technology)
CONSORZIO RFX
Associazione Euratom-ENEA sulla Fusione - PADOVA - ITALY
partnership of CNR, ENEA, INFN, Padova University and Acciaierie Venete spa

Preliminary considerations, a few slides:

RFP and RFX in Italy,
Theory-Simulation EUROFusion context.

Consorzio RFX: hosted in National Research Council - Research area in Padova

"Palazzo della Ragione"

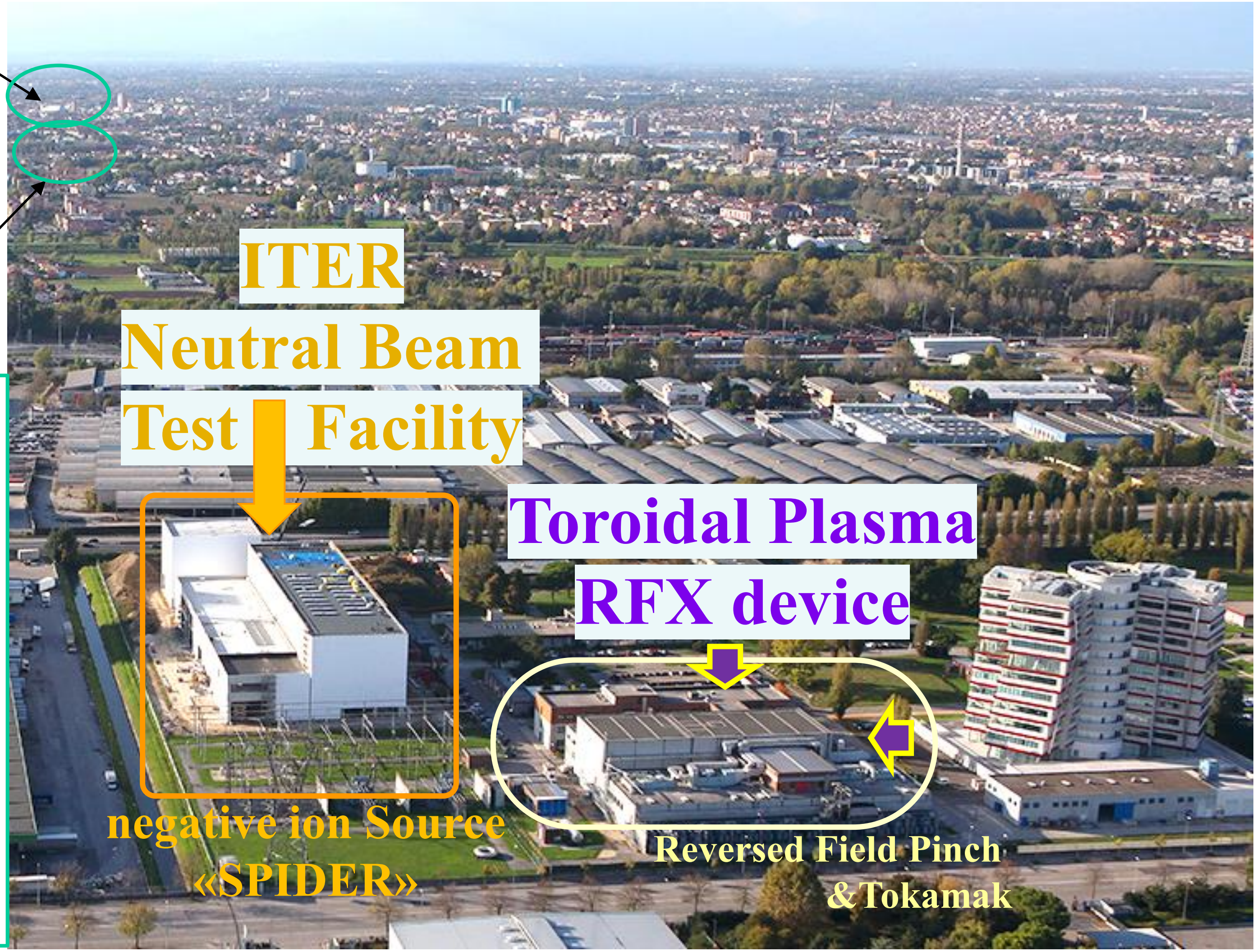
From the web

https://en.wikipedia.org/wiki/Palazzo_della_Ragione,_Padua

Padova University historical site

From the web

https://en.wikipedia.org/wiki/University_of_Padua



Reversed Field Pinch, RFP, partners:

USA - Sweden - Japan – China

RFX experimental infrastructure funded by Italian Ministry of University and Research **MUR**

*High priorities infrastructures in Italy (for Fusion): **DTT** (ENEA) and **RFX** (CNR)*

NRRP (National Recovery and Resilience Plan):

project "*NEFERTARI*" based upon the **RFX** Research_Infrastructure

Project title: '**NEFERTARI**'
(**N**ew **E**quipment for **F**usion **E**xperimental **R**esearch & **T**echnological **A**dvancements with **R**fx **I**nfrastructure)

Project aim: innovation of **experimental equipment** and **diagnostic systems** for RFX-mod2

Duration: 30 months (**2022 – 2025**) *with a perspective scientific exploitation for the next 10 years*

EUROfusion welcomes alternative approaches and intellectual diversity

The Reversed Field Pinch research is an example

EUROfusion welcomes alternative approaches and intellectual diversity

The Reversed Field Pinch research is an example

EUROPEAN RESEARCH ROADMAP

(2018 revision, FP9: 2021-27,
after first release in 2013, FP8: 2014-20)

https://euro-fusion.org/wp-content/uploads/2022/10/2018_Research_roadmap_long_version_01.pdf

Preface by T. Donnè & W. Morris - page 3:

“ The strategy of the fusion roadmap is built on three main pillars:

- the international ITER tokamak
- a fusion neutron source facility for materials development and qualification
- demonstration power plant DEMO

In addition, a strong **research and innovation programme is needed** **supporting these** and looking towards commercial fusion power plants.
Parallel research and innovation programmes … include **alternative approaches**, notably the stellarator.
In pursuing this goal, Europe should seek all the opportunities for international collaborations for mutual benefit from the **intellectual diversity** of the whole fusion community and from the sharing of resources and facilities. ”

https://art.torvergata.it/retrieve/e291c0d5-855c-cddb-e053-3a05fe0aa144/JG12.356-web.pdf (2013 first Eurofusion Roadmap release by F. Romanelli et al)

Magnetic Configurations for fusion energy

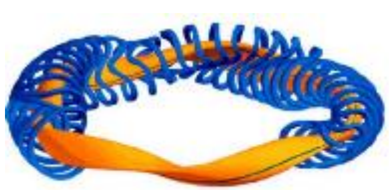
*The RFP magnetic configuration is produced mainly **by plasma current itself***
In principle, no additional heating system appears necessary

Stellarator | Tokamak | RFP

Increasing plasma current

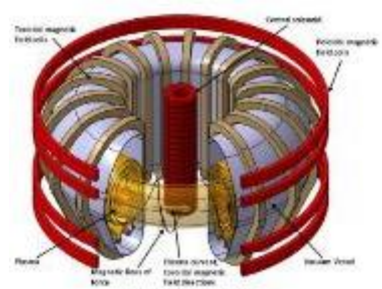
Global Helical self-organization

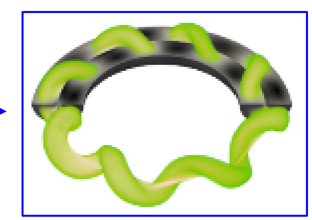
	Stellarator	Tokamak	RFP
🙂	Steady state	Confinement	Light Tech expected
😠	Coils Complexity	Disruption risk	Confinement



[*]

FIG. 1.14. Schematic of stellarator magnetic field coils and plasma configuration (Ref. [1.62]).





R = 5.5 m W7-X

(R = 3.9 m LHD)

R = 1.65 m AUG

R = 3 m JET

(R = 6.21 m ITER)

R = 2.0 m RFX

(1.5 m MST USA
1.4 m KTX Hefei China)

https://doi.org/10.1088/1741-4326/abe06c

[*] Fusion Physics IAEA 2012

[**] Marrelli et al 2021 Nuclear Fusion

Magnetic configurations for fusion energy despite the differences
display several **common physics issues**

.

Transition low–high confinement regimes
Transport barrier formation
Magnetic relaxation
RFP dynamo/Flux pumping effect
Density limit
Isotopic effect
"Anomalous" ion heating (like in Solar Corona?)
…

proficuous **challenge** for <u>theories, models, understanding</u> !

EUROfusion E-TASC groups TSVV & ACH *aim at "validated predictive capability"*

Eurofusion Theory and Advanced Simulation Coordination effort (E-TASC):

https://iopscience.iop.org/article/10.1088/1361-6587/ac44e4

X. Litaudon et al PPCF (2022)

*" Therefore, it is timely to prepare this transition with a **coordinated**, comprehensive:*

Theory, Simulation, Verification and Validation programme

TSVV

to maximize the benefit delivered from investment in large facilities.
*This aspect is recognized in the revised version of the Research Roadmap for the Realisation of Fusion Energy (Donné et al 2017, European Research Roadmap to the Realisation of Fusion Energy 2018) which states 'For all the missions, a **theory and modelling effort integrated tightly with the experimental programme will be crucial in providing the capability of extrapolating the available results to ITER, DEMO and commercial fusion power plants through carefully validated models and codes**'. An empirical approach will not be sufficient to bridge the gap between an experimental facility like ITER and a demonstration facility-like DEMO as stated in the EUROfusion 25 Research Roadmap '*
It has become clear that a strong theory and modelling programme is essential because empirically-based predictions are uncertain in unexplored environments like ITER and particularly DEMO, and this will be a stronger focus than foreseen earlier.
*It will make use of **Advanced Computational techniques and High performance computers**.' "*

AC-Hubs

EUROfusion E-TASC groups: TSVV & ACH

EUROfusion
FUSION SCIENCE DEPARTMENT
E-TASC KOM

TSVV — Develop state-of-the-art codes for the WPs to also be used for ITER and DEMO

ACH — Support the TSVVs in code development

E-TASC KOM: Introduction | April 23, 2021

***TSVV*: Theory, Simulation, Verification and Validation**

***ACH*: Advanced Computing Hubs**

https://indico.euro-fusion.org/category/279/attachments/1700/3352/ETASC-KOM-Intro_Naulin_Jenko.pdf

On a smaller scale, RFP research is a *proficuous* place for training and practicing *TSVV*:

"*Theory, Simulation, <u>Verification & Validation</u>*"

Verification and validation are defined in the DOE Defense Programs (DOE/DP) program plan for the Strategic Computing & Simulation Validation & Verification Program [1] as:

> **Verification** – The process of determining that a computer simulation correctly represents the conceptual model and its solution.
>
> **Validation** – The process of determining the degree to which a computer simulation is an accurate representation of the real world.

Am I solving the model correctly?

Am I solving the proper model?

… Benchmarking against
- analitycal solutions
- different codes

… Tight connection and comparison with experiments

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“*Theory, Simulation, Verification & Validation*”

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“ Newcomers ”

Uncertainty Quantification (UQ) VVUQ…

Sensitivity Analysis (SA)

https://pmc.ncbi.nlm.nih.gov/articles/PMC9232142/

While scientific computing has undergone extraordinary increases in sophistication, a fundamental disconnect exists between simulations and practical applications. While most simulations are deterministic, engineering applications have many sources of uncertainty arising from a number of sources such as subject variability, initial conditions or system surroundings.

https://pmc.ncbi.nlm.nih.gov/articles/PMC7304739/

https://www.sciencedirect.com/science/article/pii/S0017931022003957

Some links/references (for those who are interested)

2021
https://indico.euro-fusion.org/category/279/attachments/1700/3352/ETASC-KOM-Intro_Naulin_Jenko.pdf

2024
https://finnfusion.fi/app/uploads/2024/06/mantsinen_c.pdf

Advanced Computing Hubs within EUROfusion E-TASC programme
Mervi Mantsinen
ICREA and Barcelona Supercomputing Center (BSC)
FinnFusion Annual Seminar, Helsinki, Finland, 27-28 May 2024

- (2016) https://geodynamics.org/resources/301/download/Oberkampf_Webinar_CIG-2016.pdf
Dr. William L. Oberkampf Sandia National Laboratories (retired)
Verification, Validation, and Predictive Capability: 2021 What's What?

- (2010) M. Greenwald *Verification and validation for magnetic fusion* Phys. Plasmas 17, 058101;
https://doi.org/10.1063/1.3298884

- (2008) P. W. Terry, M. Greenwald, J.-N. Leboeuf, G. R. McKee, D. R. Mikkelsen, W. M. Nevins, D. E. Newman, and D. P. Stotler, *Validation in fusion research: Towards guidelines and best practices* Physics of Plasmas 15, 062503
https://doi.org/10.1063/1.2928909

- (1998). AIAA. "Guide for the Verification and Validation of Computational Fluid Dynamics Simulations." American Institute of Aeronautics and Astronautics, AIAA-G-077-1998 https://arc.aiaa.org/doi/book/10.2514/4.472855

Preliminary considerations summary:

- Consorzio RFX site
- RFX high priority national infrastructure (NEFERTARI project)
- EUROFUSION welcomes:

  alternative approaches – parallel research – intellectual diversity
- DIFFERENT configurations for Magnetic Confinement Fusion: Stellarator Tokamak RFP
- COMMON PHYSICS issues: challenging for theories models understanding
- Theory, Advanced Simulation, Verification & Validation and EUROFUSION: E-TASC
- RFX-RFP research:

  Proficuous place for training and practicing Theory, Simulation, V & V …UQ

Theory and Advanced Simulation

<u>The Reversed-Field Pinch *case*</u>

Helical Self-Organization processes

tightly integrated to past and future experimental programme:
- RFX / RFX-mod /
- RFX-mod2 device

(1992 – 1999)

RFX

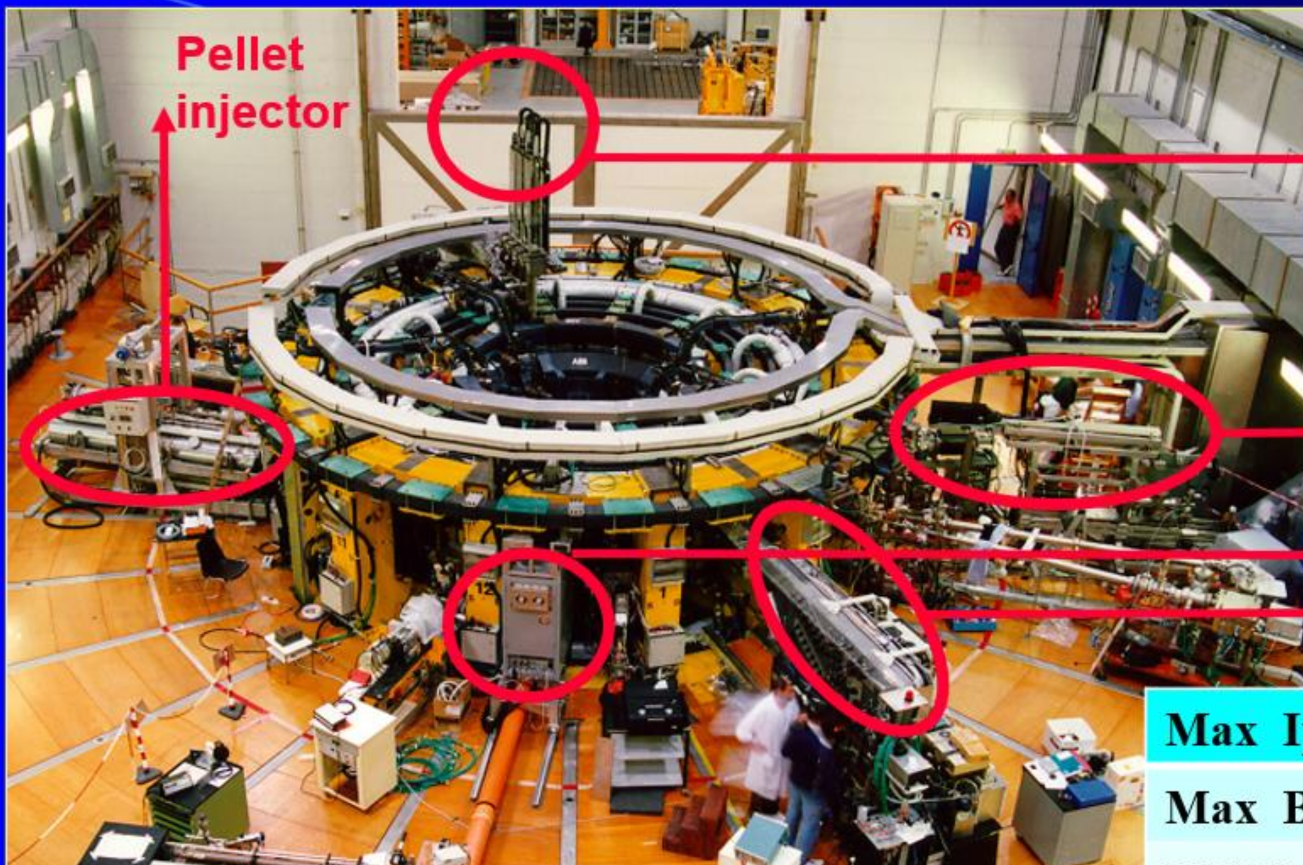
(2004 – 2015)

RFX-mod

(2026 …)

RFX-mod2

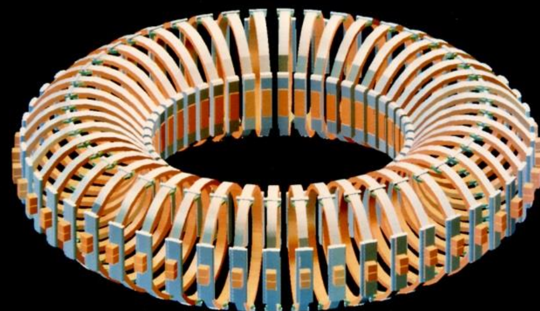
(MIAIVO project
PNRR NEFERTARI project)



Max Ip	2 MA
Max Bz	0.7 T
RFP Pulse duration	0.6 s
Tokamak Pulse	1 s

Pinch device - plasma self-squeezes due to plasma current I

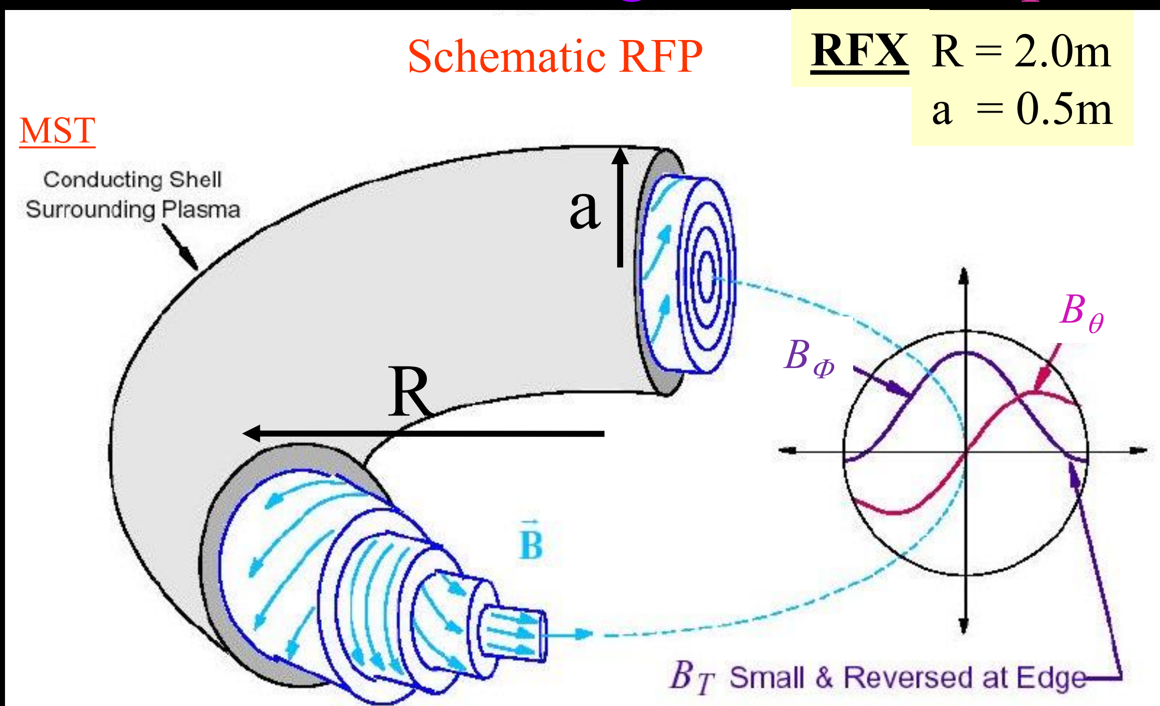
RFX device coils



toroidal magnetic field

poloidal magnetic field

induction of plasma current



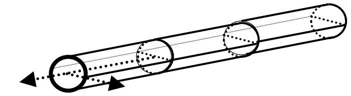
mean magnetic field radial profiles

Courtesy of MST team

Schematic B(r)

axisymmetric components

Tokamak and RFP

Periodic cylinder: 

common approximation of the torus.

Usual coordinates:

given $B_\phi(r=0)$ and plasma radius "a"

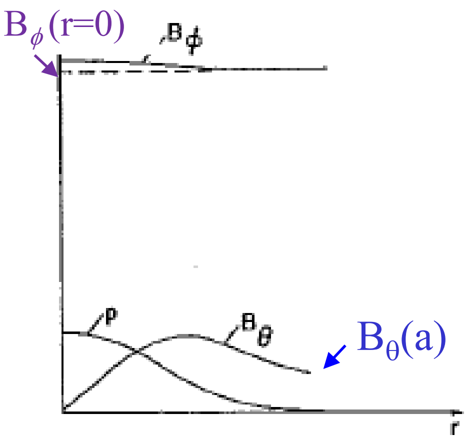


Figure 6.10. Typical radial profiles for an ohmically heated tokamak.

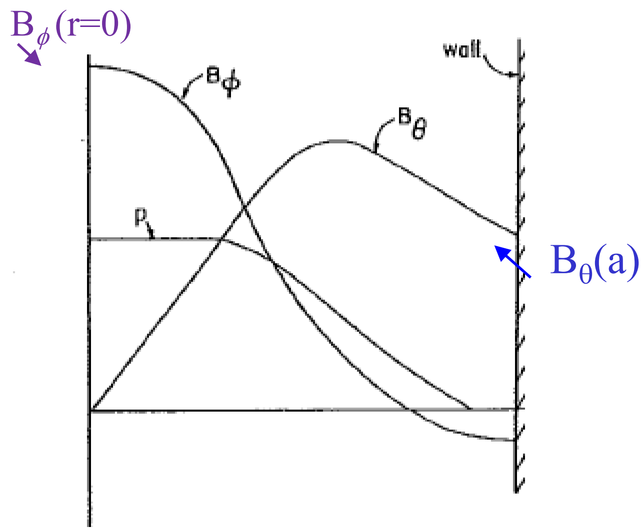
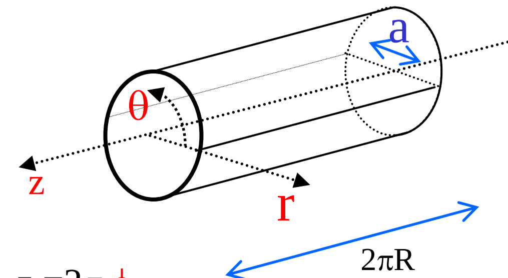


Figure 6.5. Schematic diagram of the B_ϕ, B_θ, and p profiles providing radial pressure balance in an RFP.

Ideal MHD – J. Freidberg 1987



$z = 2\pi\ \phi$

Poloidal angle θ
and
z toroidal like, or ϕ

Schematic B(r)

axisymmetric components

Tokamak and RFP

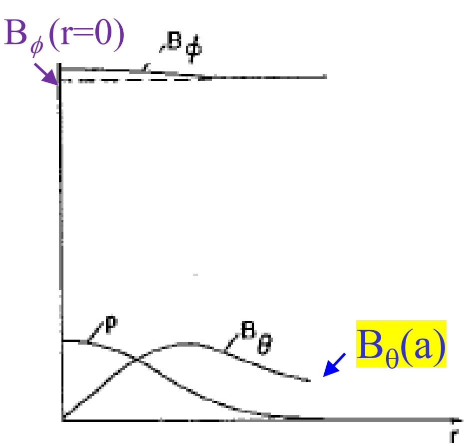
RFP much larger plasma current I

$$\nabla \wedge \mathbf{B} = \mu_o \mathbf{J}$$

given $B_\phi(r=0)$ and plasma radius "a"

$$aB_\theta(a) \sim Ip$$

$$\int_S d\mathbf{S} \cdot \nabla \times \mathbf{A} = \oint_C d\mathbf{l} \cdot \mathbf{A}$$



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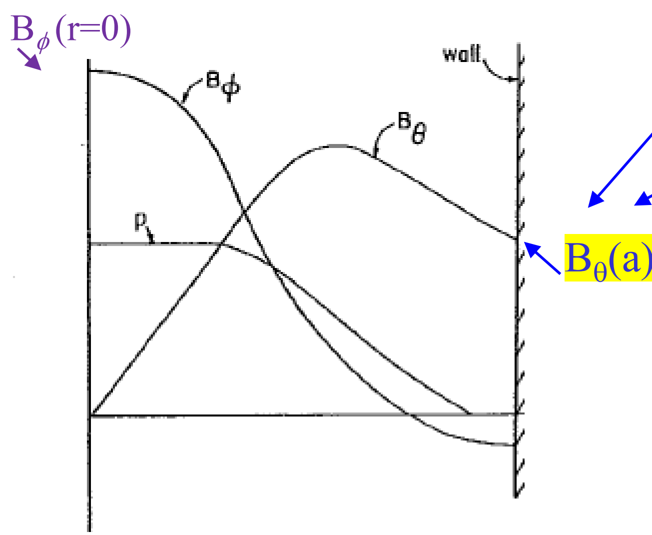
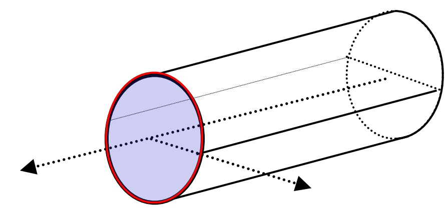


Figure 6.5. Schematic diagram of the B_ϕ, B_θ, and p profiles providing radial pressure balance in an RFP.



Reversal, **F,** and Pinch, **Θ,** parameters:

$$F \equiv \frac{\mathbf{B}_z(a)}{<\mathbf{B}_z>} \qquad \Theta \equiv \frac{\mathbf{B}_\vartheta(a)}{<\mathbf{B}_z>} \sim \frac{Ip}{\Phi}$$

Safety factor: $$q(r) = \frac{d\,\Phi}{d\,\psi} \sim \frac{r\,B_z(r)}{R\,B_\theta(r)}$$

F has a similar relevance as q(a) in Tokamak "vocabulary"

Let's enter a little bit more into the RFP world

Right from its origin (‘50), the RFP placed puzzling issues.

The configuration was discovered in early pinches when pushing plasma current to high enough values

1. B_Z self-reversal was **unexpected**,

   ... associated quiescent regime: **unexpected**

2. Call for an «*RFP dynamo*»

1. Quiescent regimes associated with B_Z field reversal

Historical observations ('*50ties* several toroidal pinches) ZETA machine (UK):
Pushing plasma current above "threshold" → toroidal Bz self-reversal

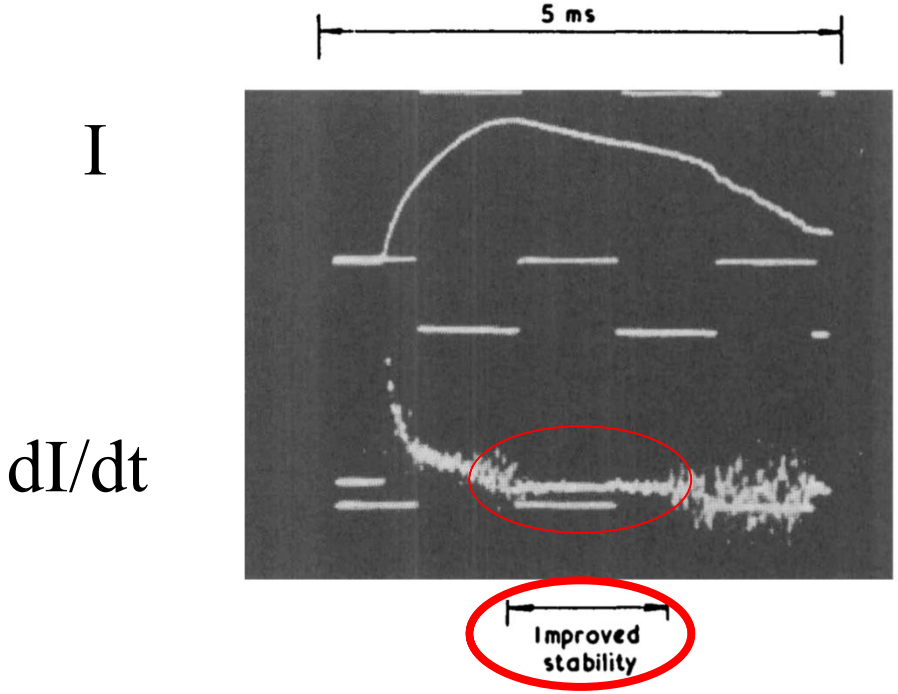


FIG.2. Oscilloscope record of ZETA discharge lasting 5 ms. Top trace is gas current I, reaching a maximum here of 420 kA, while lower trace is rate-of-change of current dI/dt and exhibits period of quiescence subsequently associated with magnetic-field reversal.

Figure from: Bodin, Evans, Nuclear Fusion 1985 *«Reversed-field pinch research in the United Kingdom»*

1. Quiescent regimes associated with B_Z field reversal

A few lines about Taylor's relaxation theory for the RFP.
It was inspired by astrophysical dynamo theories

1. Quiescent regimes associated with B_Z field reversal

A few lines about Taylor's relaxation theory for the RFP.
It was inspired by astrophysical dynamo theories

Taylor's relaxation theory for the RFP [*]
boosted the RFP reseach due to its ability to provide a first understanding…

Taylor's conjecture can be considered a "weak formulation" of Woltjer theorem (1958) proposed to describe astrophysical magnetic fields of celestial bodies: ***astrophysical dynamo***… in particular ***turbulent dynamo***

It considers a variational principle:
- search for the minimum of magnetic energy,
- compatible with a given conserved topological complexity (magnetic helicity).

(The topological complexity is an ideal invariant, due to the frozen-in law of magnetic field in perfectly conducting fluids… Alfvén theorem).

[*]
J. B. Taylor PRL 1974
J. B. Taylor Rev. Mod Phys. 1986

1. Quiescent regimes associated with B_Z field reversal

By solving the variational problem casted by Taylor's relaxation theory one finds "relaxed states" with field reversal for $\Theta \geq 1.2$

The theory gained a great success, providing a first way to understand the experimental observations

… despite quantitative differences, significant in the external region around reversal…

Bessel analytical solutions

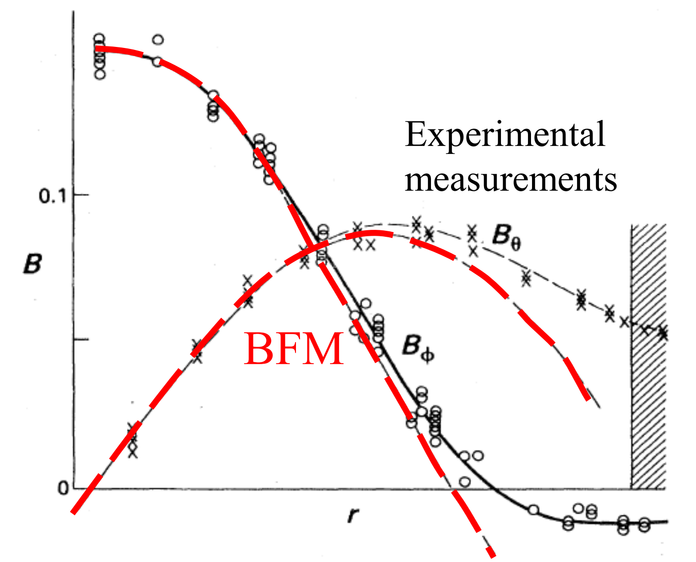


FIG. 2. Experimental and theoretical magnetic field profiles. HBTX-1A (from Bodin, 1984).

Rev. Mod. Phys., Vol. 58, No. 3, July 1986

Bessel Function Model (BFM)

[*]
J. B. Taylor PRL 1974
J. B. Taylor Rev. Mod Phys. 1986

For those interested in the Taylor Relaxation Theory: come to my office. I can suggest some material.

2. "RFP dynamo effect " needed … let's recall the equations for conducting fluid:

Ohm's law

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

(simple form for conducting fluid)

Induction equation

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

2. "RFP dynamo effect " needed … let's recall the typical B and J profiles:

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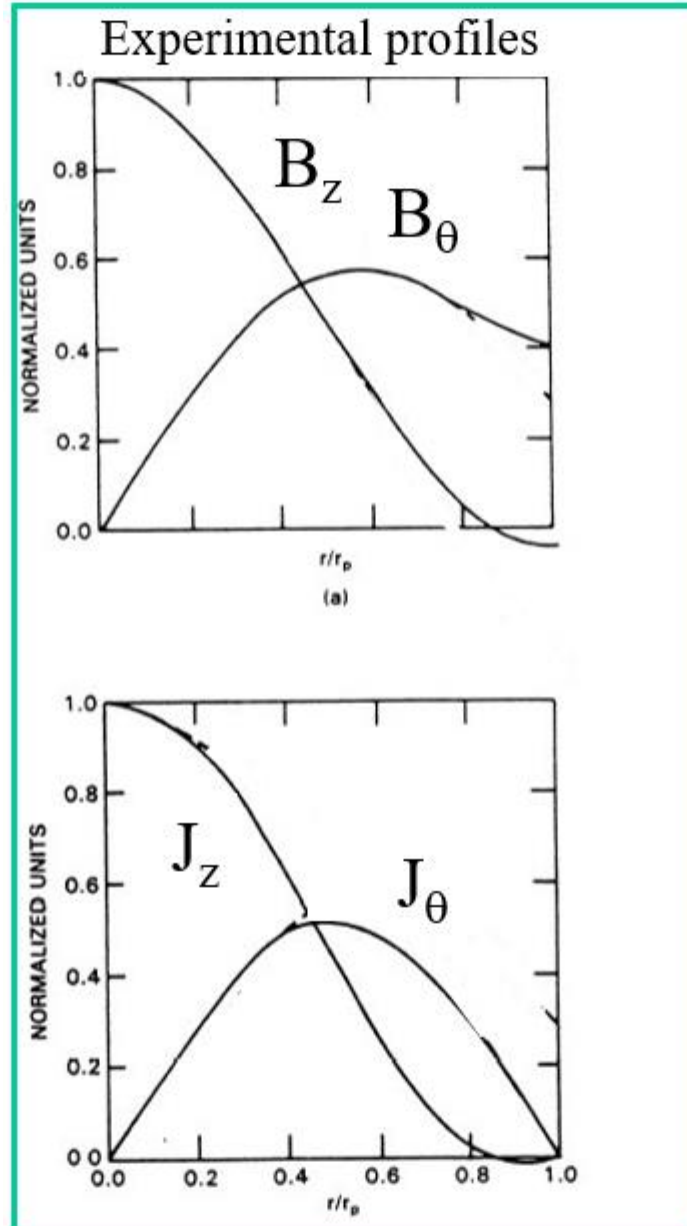

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Ohm's law

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

Induction equation

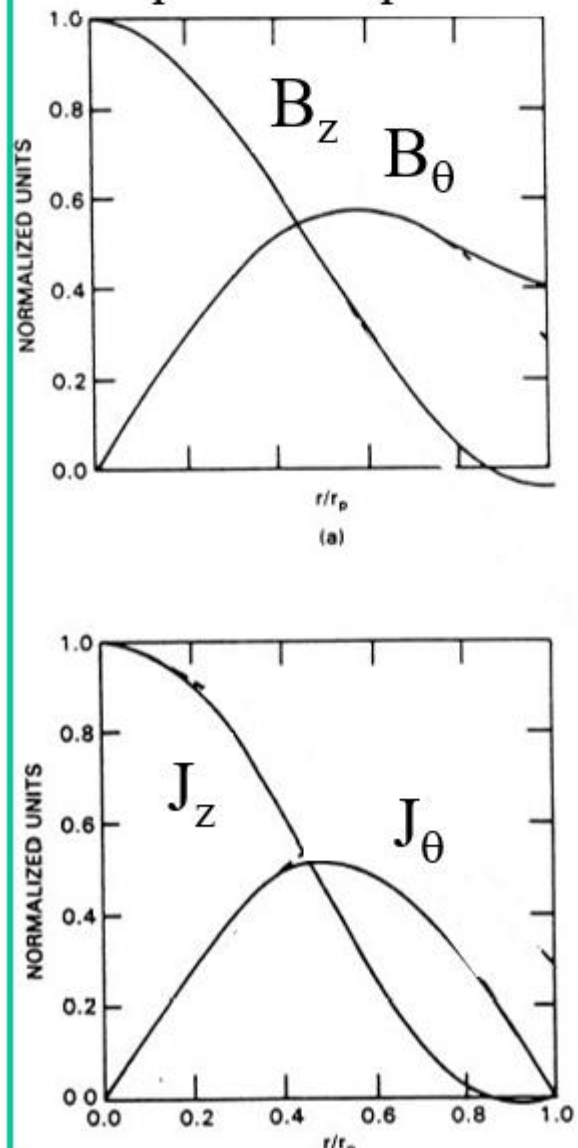
Consider stationary fields

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

stationarity $\frac{\partial}{\partial t} = 0 \rightarrow \left\{ \begin{array}{l} \boxed{E_\theta(r) \equiv 0} \\ E_Z(r) \equiv E_o \end{array} \right.$

(Applied Voltage)

Experimental profiles



2. “RFP dynamo effect ” needed !! Inconsistency

Project along poloidal coordinate

Ohm’s law

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

at reversal $B_z = 0$

$$\boxed{E_\theta(r) = \eta\, J_\theta + \cancel{V_r\, B_z}}$$

$$J_\vartheta(r) = 0\ !\quad !$$

Induction equation

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

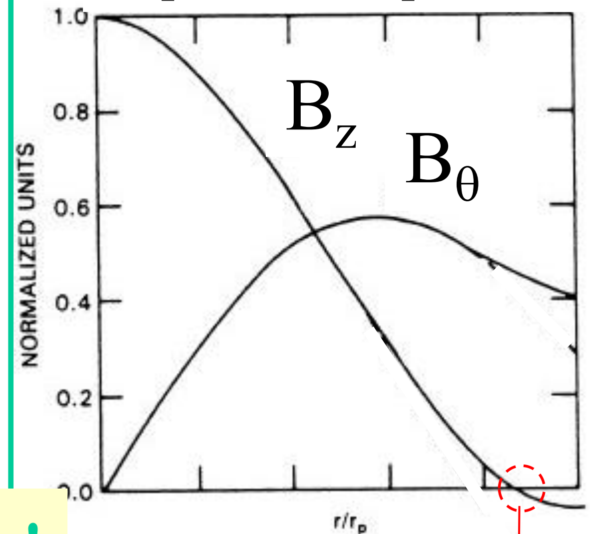
stationarity $\frac{\partial}{\partial t} = 0 \rightarrow$

$$\boxed{E_\theta(r) \equiv 0}$$

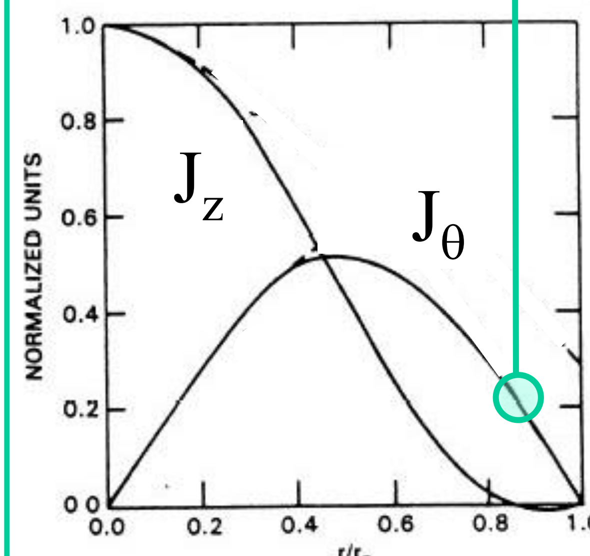
$$E_Z(r) \equiv E_o$$

(Applied Voltage)

Experimental profiles



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



2. “RFP dynamo effect ” needed

an additional “dynamo” electric field is needed with respect to the one provided by axissymmetric B and v fields in order to balance Ohm’s law if a finite J_θ is present at reversal radius:

within resistive MHD such a contribution comes through a coherent modulations V^1, B^1 on top of the axisymmetric components V, B

$$\boxed{E_\theta(r) = \eta J_\theta + Vr\,Bz \; < V^1 \wedge B^1 >_\theta}$$

E_{dynamo}

Thus, inspired by astrophysical studies, and supported by Taylor Relaxation Theory, a small scale turbulence has been deemed as necessary to get RFP dynamo effect …

*We shall see that a laminar –steady- macroscopic helical dynamo can also be a solution of **3D nonlinear MHD** simulations for cylindrical RFP.*

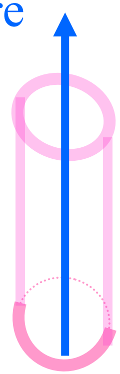
The toy model:
intuitive and simplified understanding of self-reversal
(schematic and intuitive RFP)
… and of the global helical self-organization

Toy model (1): a kink deformation of the current "path" pumps toroidal B-flux

Think of a current carrying wire in a flux conserver:

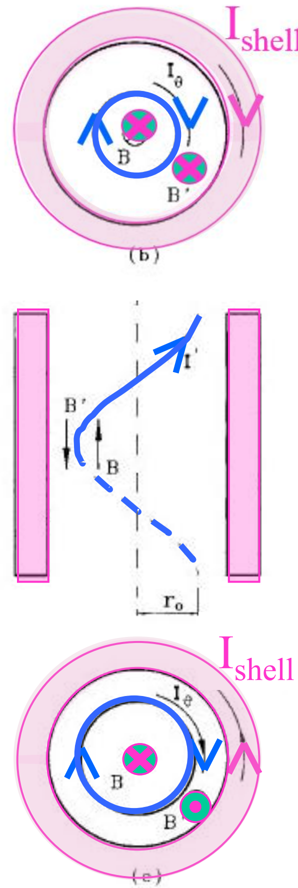
Kink unstable

I_{wire}



$\Phi_{B\text{-flux}}$ conserver (shell)

Iwire & Ishell attract each other



solenoidal effect by the wire itself:
- core B increase

by flux conservation:
- edge B decreases ..

Kink saturates when/if reversal of edge field is achieved

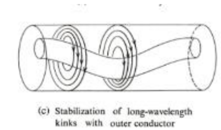
Early elements:
Verhage-Furzer-Robinson NF 1978
Kadomtsev 1992 (Sawer PoF1959)

Elaborated in:
Benisti Escande EFTC 1998
Escande et al. PPCF 2000

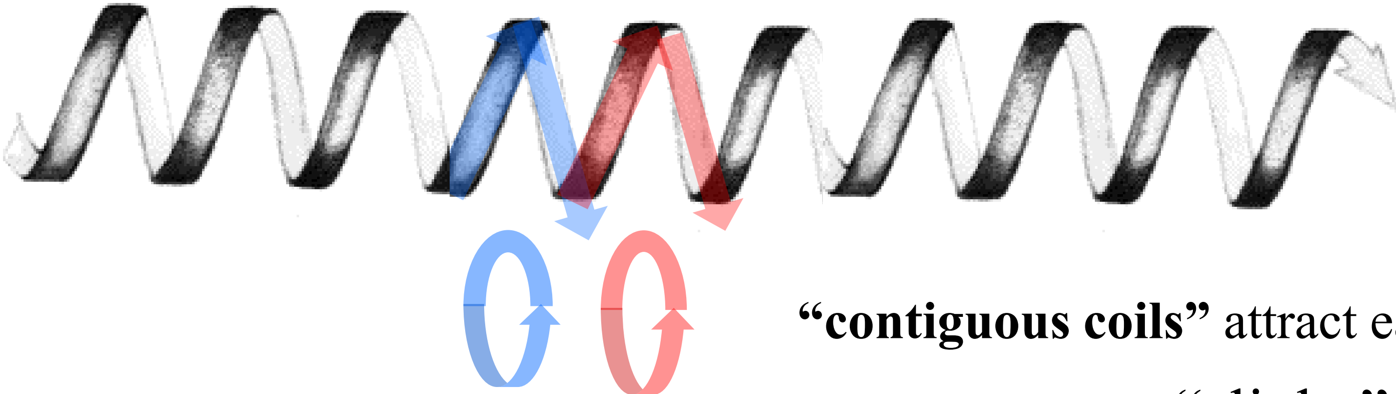
See also Cappello et al Varenna 2008

$r_0 \rightarrow 1$ (disruption) for too small $\frac{I_{wire}}{\Phi}$
(Tokamak case)

Toy model (2): the kink deformation is subject to a secondary instability



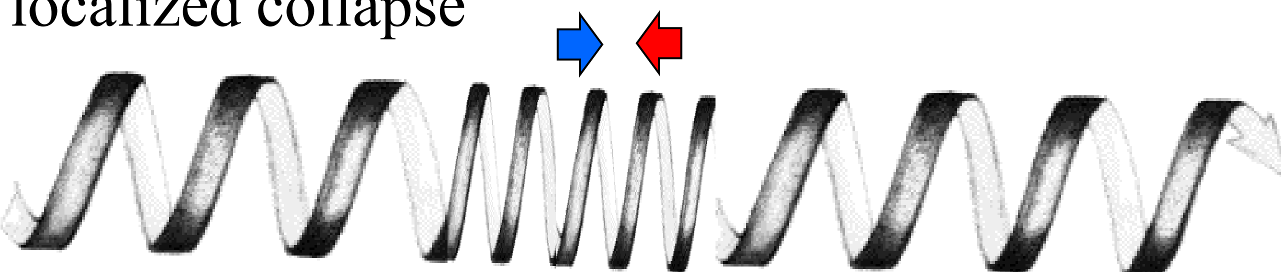
After kinking …

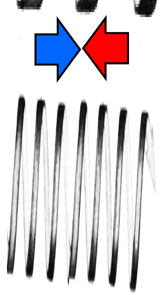


“contiguous coils” attract each other …

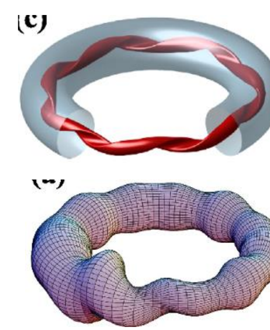
…“slinky” instability

… localized collapse





plasma buldging-collapse
at a toroidal location,
similarly in experiments
and nonlinear modeling…



Cappello et al., Theory of Fusion Plamas - Varenna 2008

Summary of first steps in RFP theory, modeling and understanding :

- ZETA experiment puzzling: quiescent regime & reversal of magnetic field (‘60)
- Taylor relaxation theory (‘70):
  - analytical «relaxed» solutions with Bz reversal
  - need for additional dynamo Electric field (small scale turbulence deemed necessary)
- Toy model schematic intuitive description of reversal effect (flux pumping by global kink)

Modern era - **Helical self-organization processes**

- Overview of RFX observations

- Description from **nonlinear MHD model:**

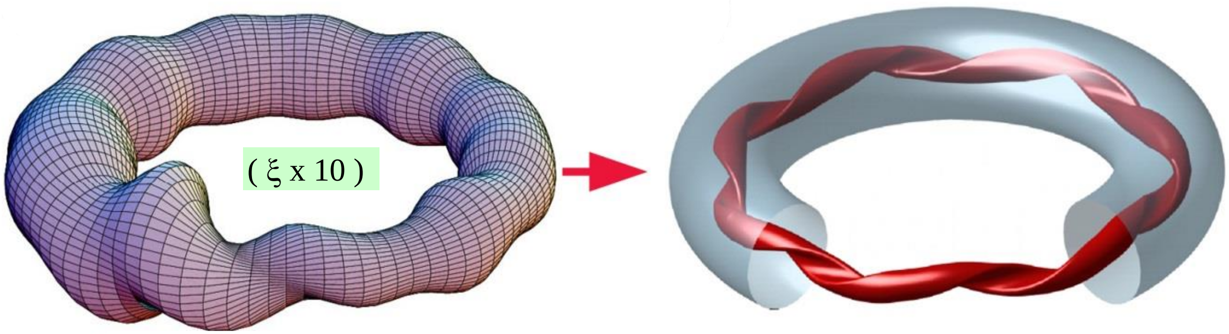
  3D Numerical Simulation

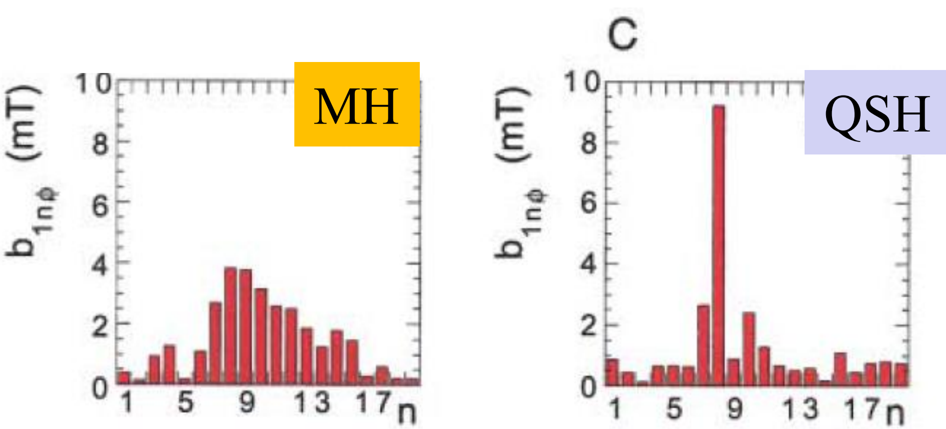
RFP self-organization in brief

RFX

RFP ↔ saturated KINKED plasma

for Ip above ~ 1 MA

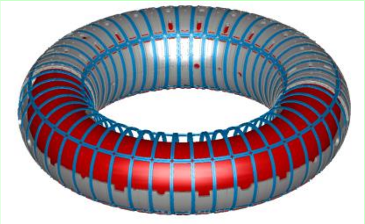




MHD spectrum: resistive kink-tearing modes

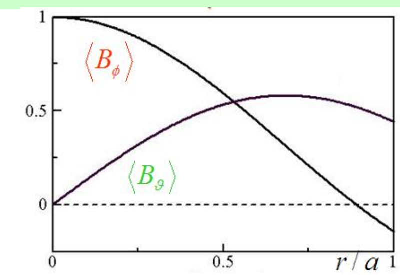
Advanced operation required in RFX-mod

CLEAN MODE CONTROL
and/or
NON-CONVENTIONAL SCENARIOS (PPCD-OPCD)



192 independent coils

Feedback coils system
Typical operation:
Ip ~ 1.7 MA
Te up to 1.2 keV

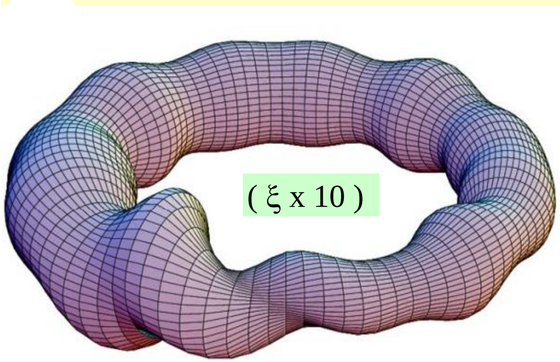


RFP self-organization in brief

RFX

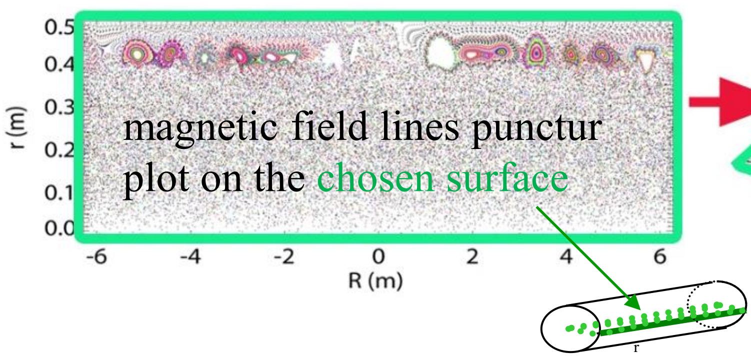
RFP ↔ saturated KINKED plasma

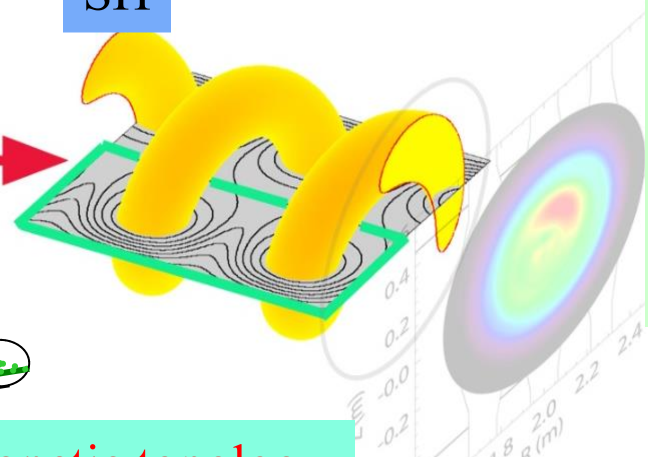
for Ip above ~ 1 MA



MH

SH





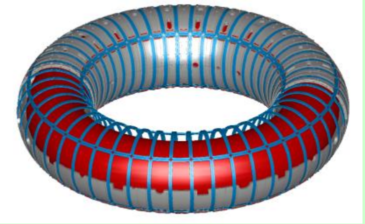
MHD spectrum impact on magnetic topology

Believed to rule transport properties in RFP

Advanced operation required in RFX-mod

CLEAN MODE CONTROL
and/or
NON-CONVENTIONAL
SCENARIOS (PPCD-OPCD)

RFX-mod

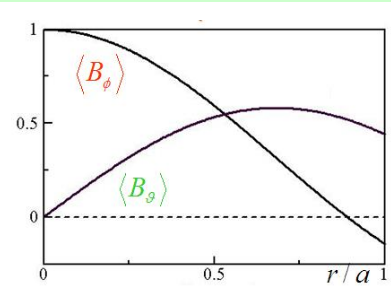


Feedback coils system

Typical operation:

Ip ~ 1.7 MA

Te up to 1.2 keV



RFP helical self-organization – Experimental overview

- **First observations: one single MHD mode emerging**
- **Statistical robustness of the helical self-organization**
- **Electron Temperature (and density) Internal Transport barrier – eITB**
  - Relation with safety factor profile
  - Temporal behavior
- Impurity screening effect
- Isotopic effect: better performances when running Deuterium discharges

RFP helical self-organization: several experiments RFX – TPE – MST –T2R

RFX

FIG. 3 (color). Schematic view of a $n = 7$ helical structure inside the RFX vessel.

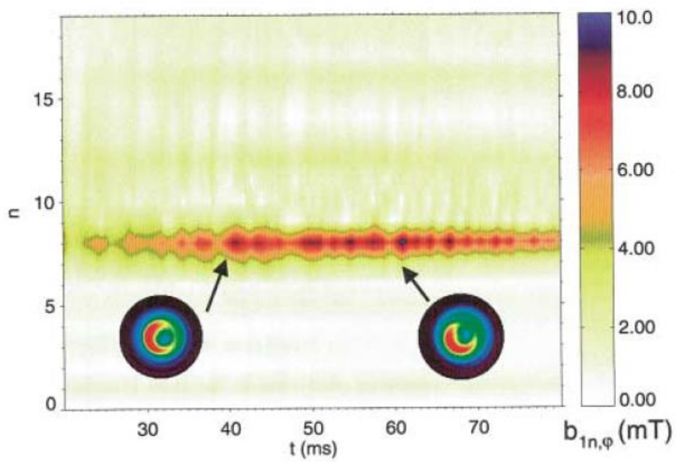
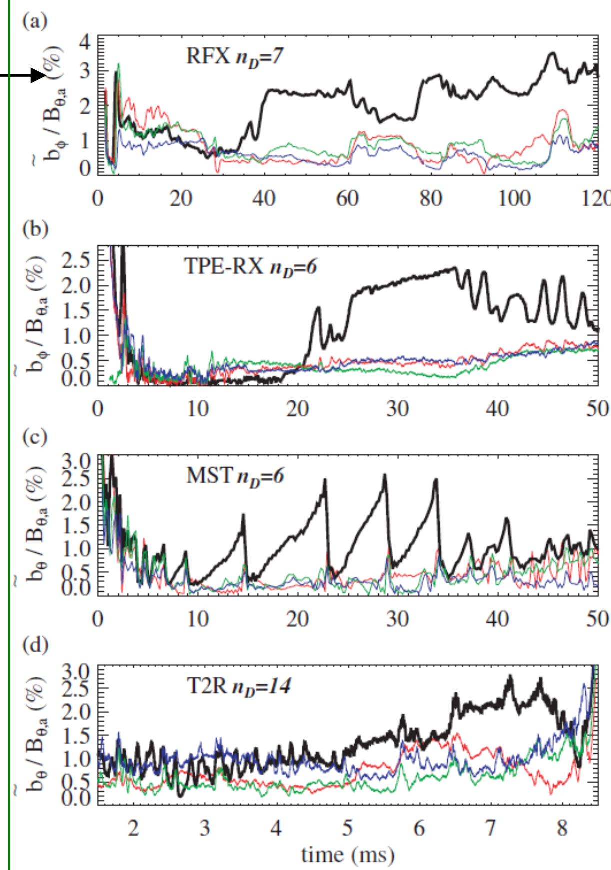


FIG. 5 (color). $m = 1$ modes n-spectrum vs time and SXR emissivity patterns at selected times ($t = 40$ ms and $t = 60$ ms) in a plasma (No. 11336) where the QSH state is permanent. The dominant mode in this case is $n = 8$.

Escande, Martin, Ortolani et al. PRL 2000



TPE-RX	Japan
MST	USA
T2R	Sweden

Martin, Marrelli, Spizzo et al. NF 2003

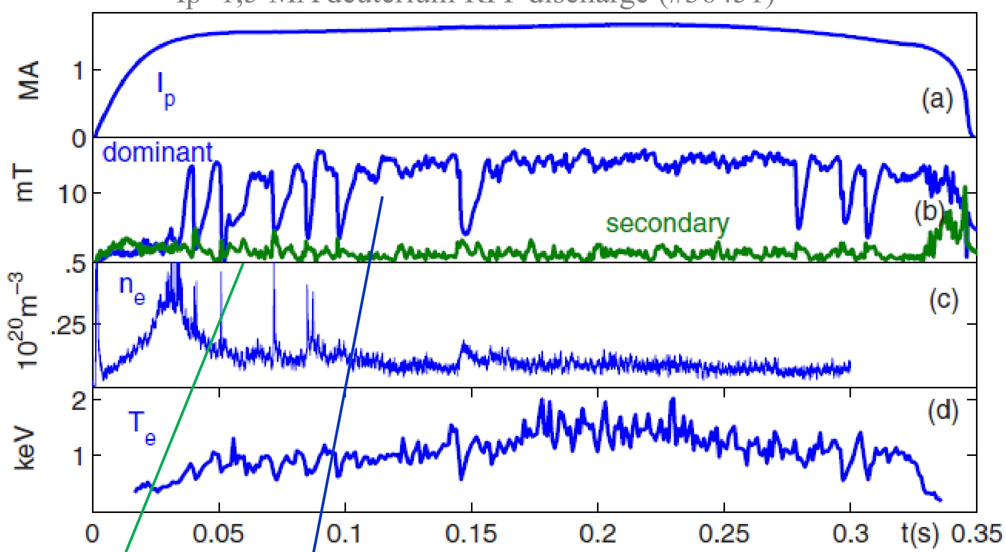
More recently also:
RELAX (Japan), KTX (Hefei- China)

RFP helical self-organization: a robust process

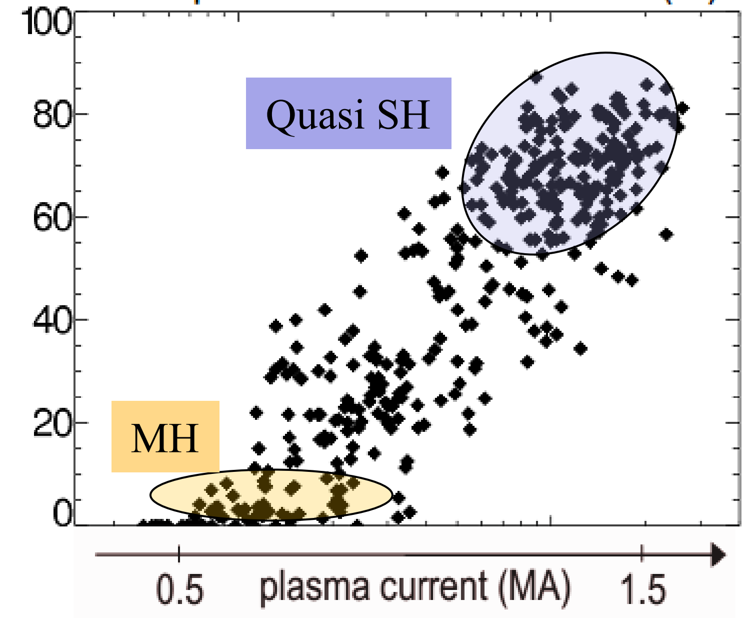
RFX -mod

HELICAL persistency increases with current - up to > 85% of flat top

Ip=1,5 MA deuterium RFP discharge (#36451)



Flattop fraction with helical state (%)



(hydrogen RFP discharges)

Dominant mode (internal)

ave secondary modes

Puiatti, Dal Bello, Marrelli et al. NF 2015

Piovesan, Zuin et al NuclFus 2009

Similar behavior in MST experiment:
- Chapman et al IAEA EX/P6-01 (2012)
- Sarff et al Nucl Fus (2013)

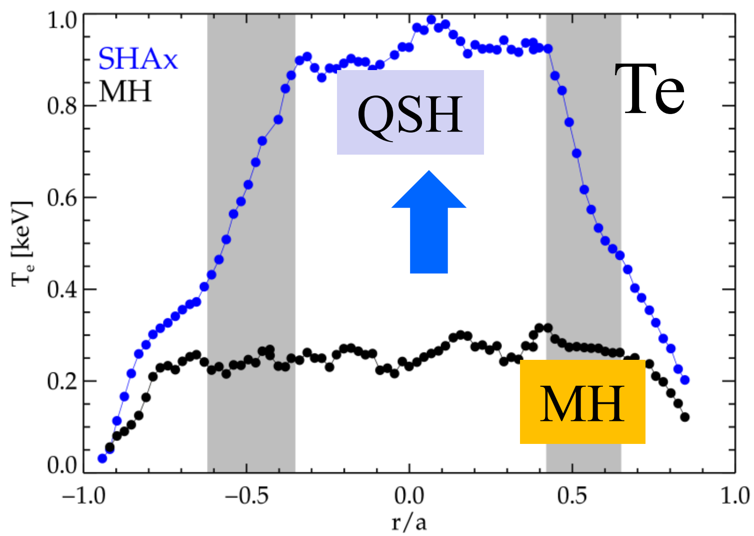
RFP helical self-organization: barriers formation

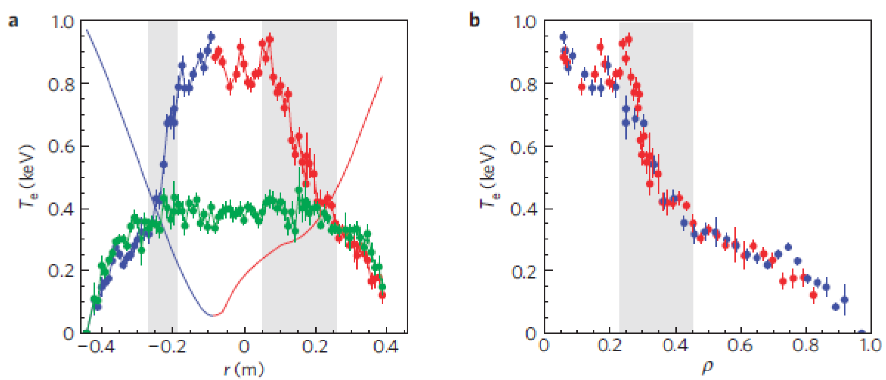
RFX -mod

Formation of e-Internal Transport Barriers

24598, 117ms
I_P=1.3MA
n/n_G=0.20

22201, 35ms
I_P=0.7MA
n/n_G=0.22





Barrier formation believed to be provided by magnetic chaos healing effect

Lorenzini, Martines, Piovesan et al NatPhys 2009
Piovesan, Zuin, Alfier et al NF 2009
Cappello et al Theory of Fusion Plasmas, 2008

Joint Varenna-Lausanne International Workshop

RFP helical self-organization – 3D nonlinear MHD modeling

- SpeCyl code
- Verification benchmark vs PIXIE3D (LANL code)
- Relevant dimensionless parameters in governing dynamical regime transition

  Resistivity η, Viscosity ν, and the Hartman number $(\eta\nu)^{-1/2}$
- Role of non-ideal Boundary Condition:

  Magnetic Perturbation (Resonant MP / Non-Resonant MP) and sawtooth pacing

…

- **Sensitivity Analysis** vs viscosity profiles
- Magnetic chaos healing, Lagrangian Coherent Structures detection

3D nonlinear MHD modeling

$B(r,\theta,z,t)$, $v(r,\theta,z,t)$

The "minimum" visco resistive 3D MHD approximation:

Induction equation: Faraday + Ohm's law

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

Momentum equation

more or less *Navier Stokes (– pressure + Lorentz)*

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

Implemented in the
SpeCyl numerical code

3D nonlinear MHD

SpeCyl code - simple visco-resistive approx.

Cappello & Biskamp Nucl. Fus. 1996

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

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

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

$$\nabla \cdot \boldsymbol{B} \equiv 0 \quad \nabla \wedge \boldsymbol{B} \equiv \boldsymbol{J}$$

$\eta = \tau_A / \tau_R$

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

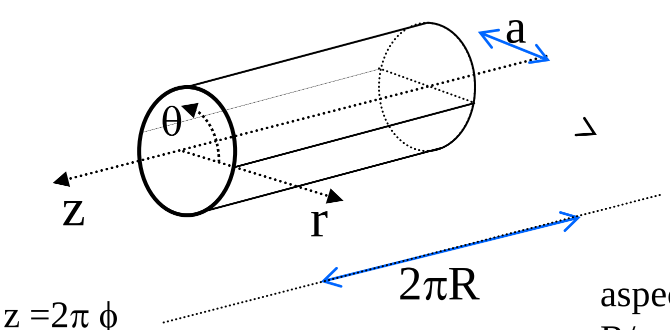
two dimensionless parameters with assigned radial profiles

Lundquist: $\mathbf{S = 1 / \eta}$

Viscous Lundquist $\mathbf{M = 1 / \nu}$

r	Finite difference
θ, ϕ	Spectral formulation
t	Predictor-corrector + semi-implicit

Geometry: periodic cylinder



aspect ratio
R/a= 4 (RFX)

3D nonlinear MHD

SpeCyl code - simple visco-resistive approx.

Cappello & Biskamp Nucl. Fus. 1996

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

$$\frac{\mathrm{d}\boldsymbol{v}}{\mathrm{d}t} = \boldsymbol{J} \wedge \boldsymbol{B} + \boxed{\nu}\, \nabla^2 \boldsymbol{v}$$

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

$$\nabla \cdot \boldsymbol{B} \equiv 0 \quad \nabla \wedge \boldsymbol{B} \equiv \boldsymbol{J}$$

$\eta = \tau_A / \tau_R$ two dimensionless parameters with assigned radial profiles

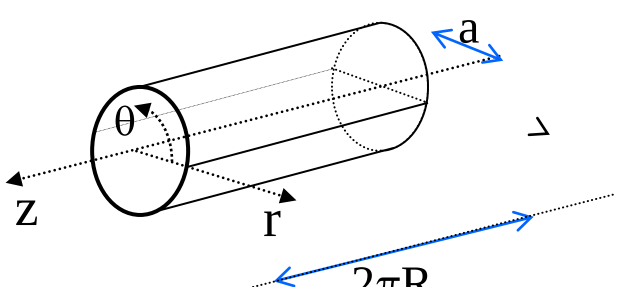
$\nu = \tau_A / \tau_v$

Lundquist: **$S = 1 / \eta$**

Viscous Lundquist **$M = 1 / \nu$**

r	Finite difference
θ, ϕ	Spectral formulation
t	Predictor-corrector + semi-implicit

Geometry: periodic cylinder



$z = 2\pi\, \phi$

aspect ratio
R/a= 4 (RFX)

"typical" boundary conditions:

- $B'_z = 0$ (**constant magnetic flux Φ**)
- Constant E_z (or constant I_p)

m,n
- Ideal boundary
- MP on $B_{r\, m,n}$ (~ 1%, 2%, 4 %...)
- Thin shell + vacuum layer +ideal wall

- velocity field: no slip/self consistent.

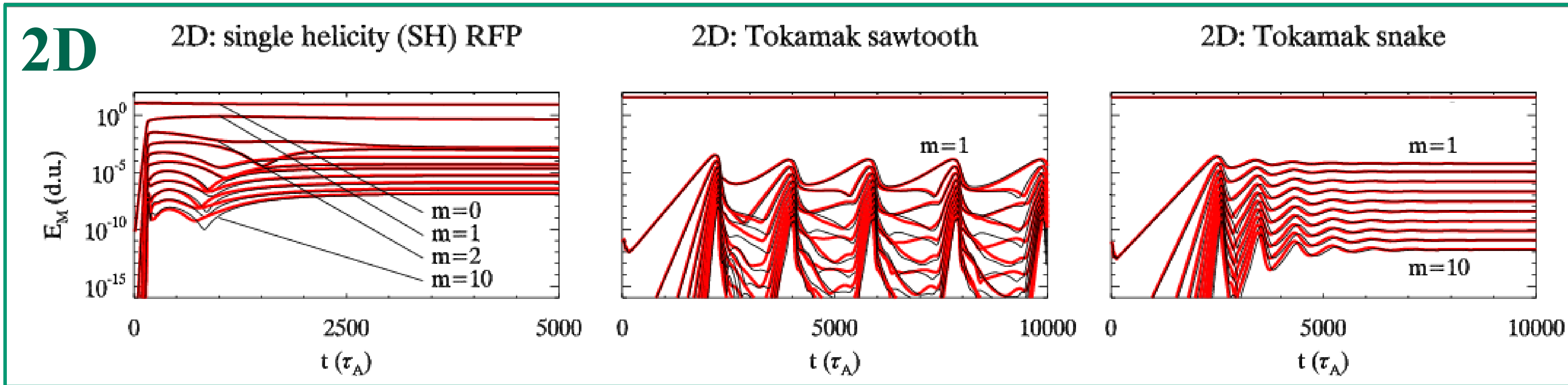
initial conditions define Φ, Iz

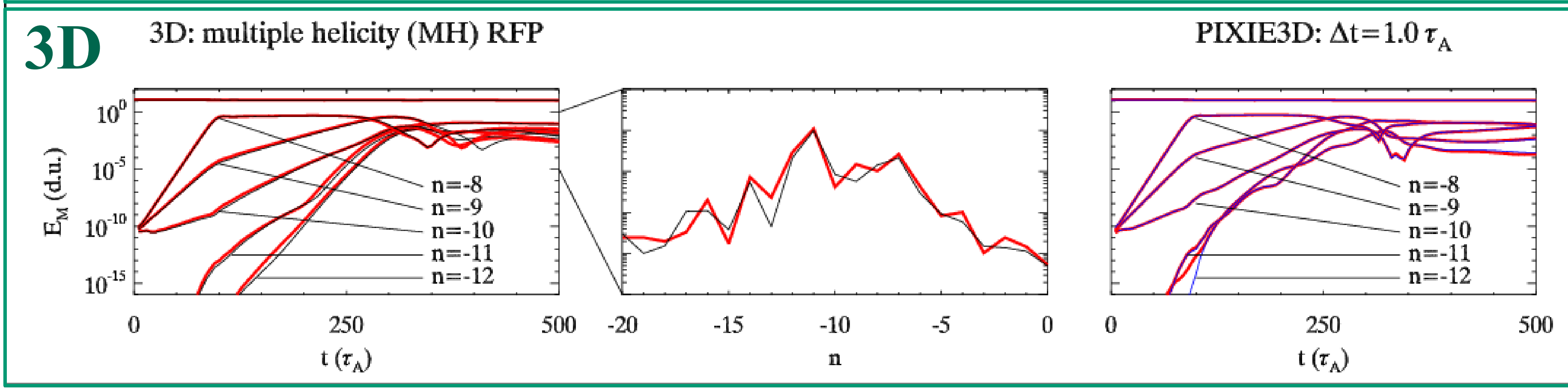
Nonlinear **verification** benchmark **SpeCyl** – **PIXIE3D**

PIXIE3D is a massively parallel code in arbitrary curvilinear geometry
conservative, solenoidal finite-volume discretization in space,
fully implicit temporal advance.

PIXIE3D: Chacòn ***CPC*** *2004,* ***PoP*** *2008,* ***Los Alamos NL -NM USA***

Bonfiglio, Chacòn, Cappello POP 2010
Spinicci, Bonfiglio, Chacòn, et al, AIP Advances 2023





Magnetic energy evolution from ***SpeCyl*** *and PIXIE3D (black and red curves respectively).*
Top panels 2D) *RFP and Tokamak.*
Bottom 3D) *left) RFP case,* *right) PIXIE3D with different time steps (red $\Delta t=5x10^{-3}$ blue $\Delta t=1$ τA)*

Model equations transformation

… re-scaling : $t \to \bar{t} = \sqrt{\frac{\eta}{\nu}}\, t$ $\quad \mathrm{v} \to \bar{\mathrm{v}} = \sqrt{\frac{\nu}{\eta}}\, \mathrm{v}$

(S , M) $\quad$ (η , ν) $\quad$ *(**H** , P)*

Magnetic Prandtl **P** = ν/η = S/M
Hartmann number **H** = (νη) $^{-1/2}$

Hartmann: **H= (νη) $^{-1/2}$**

highlighted in
D. Montgomery et al. PPCF 92-93 (applied to linearized equations)

magnetic Prandtl: **P= ν / η**

Whenever intertia is negligible and/or magnetic Prandtl is large:
the H number alone governs the solutions of the model equations

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

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

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

Cappello & Escande PRL 2000

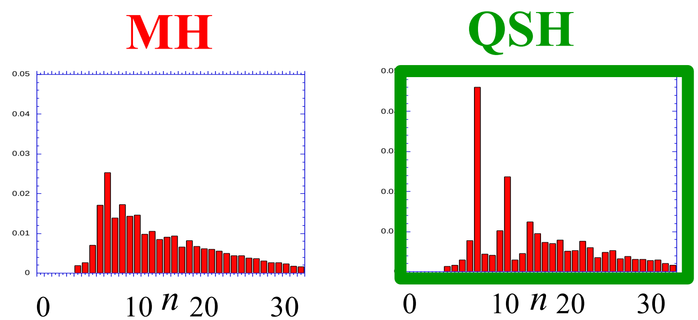
3D nonlinear MHD

Some examples of different regimes decided by *H*

Spectrum of MHD modes: m=1 resistive kink/tearing modes

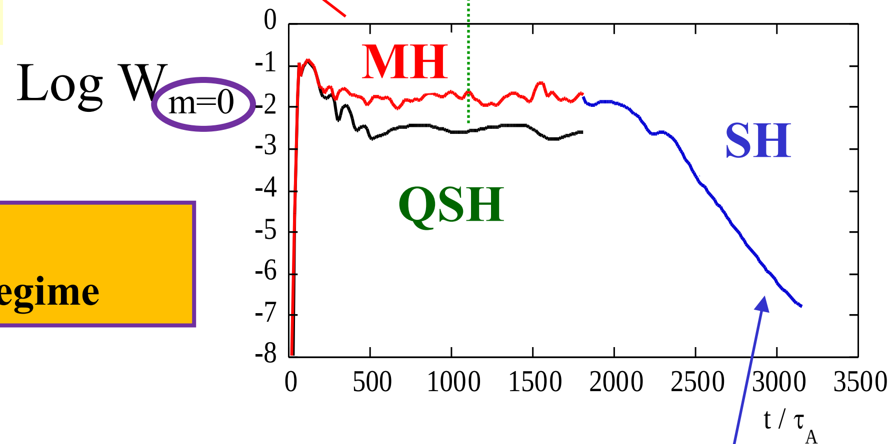
m=1 modes

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



m=1, n=1,2,…

m=1 modes
nonlinearly drive
m=0 modes



m=0, sum_n

m = 0 modes:
signature of the dynamical regime

Low H: **SH Single Helicity regime**
m=1 ONE single m=1 mode survives (and its hamonics)
m=0 modes decrease to vanishing values

3D nonlinear MHD

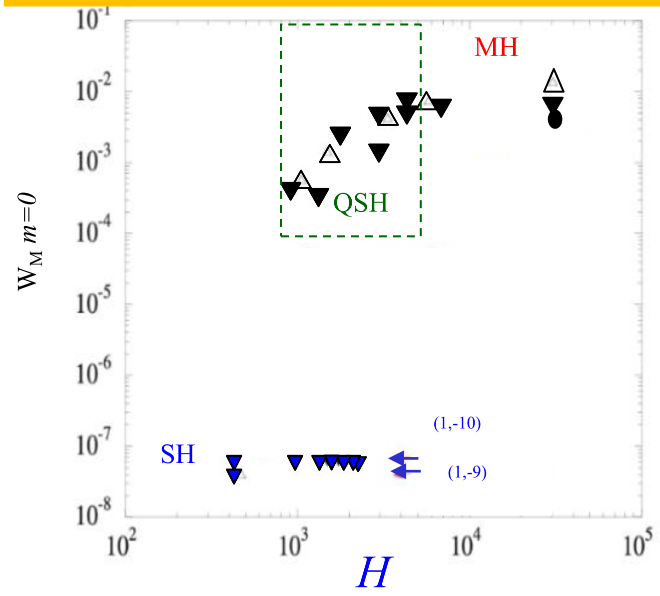
The transition to helical regimes

- is a continuous one ruled by: Hartmann number, H, ($\eta\nu$)$^{-1/2}$

m = 0 modes:
signature of the dynamical regime

A transition diagram can be drawn in terms of:
- Wm=0 mode -time averaged- energy (order parameter)
vs
- H artmann number

△ S=3.3x10³ (P: 2/3-10)
▼ S=3.0x10⁴ (P: 1-5000)
● S=10⁵ (P = 10)



Solutions with different values of the couple (S, P) lie on a single curve when plotted against H

SH
Wm=0 exponentionally decaying:
conventional finite value assigned in the plot

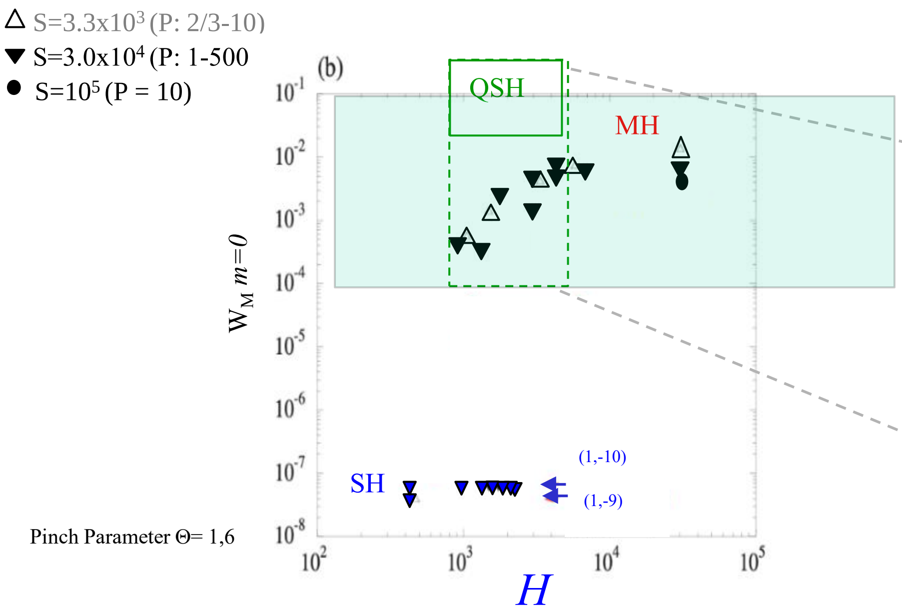
Pinch Parameter Θ= 1,6

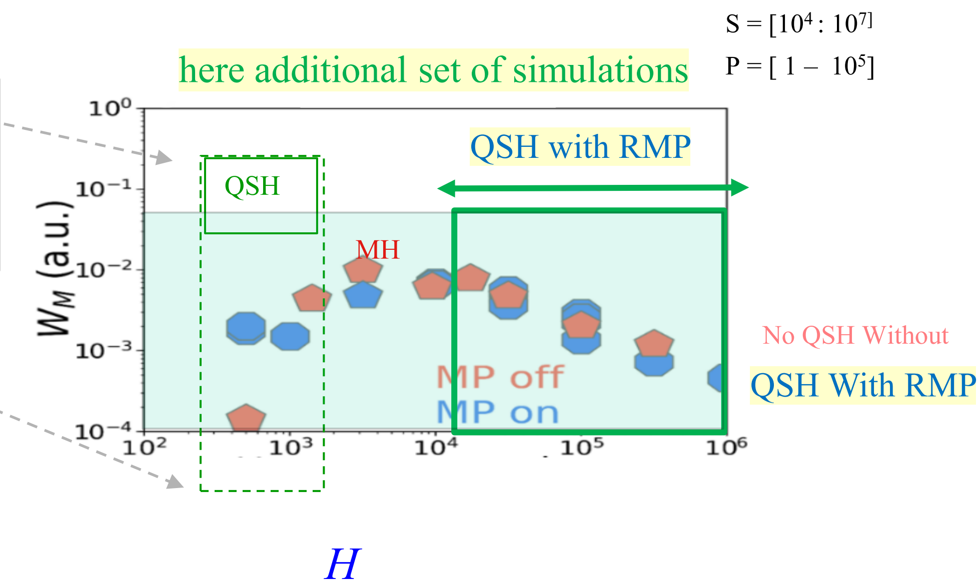
Cappello & Escande PRL2000
Cappello PPCF 2004

3D nonlinear MHD

The transition to helical regimes

- is a continuous one ruled by: Hartmann number, H, $(\eta\nu)^{-1/2}$
- is significantly favored by **seed** edge **Magnetic Perturbation**





The higher H (lower dissipation) the smaller the MP required to excite QSH regimes

Cappello & Escande PRL2000
Cappello PPCF 2004

Veranda, Bonfiglio, Cappello et al NF 2020

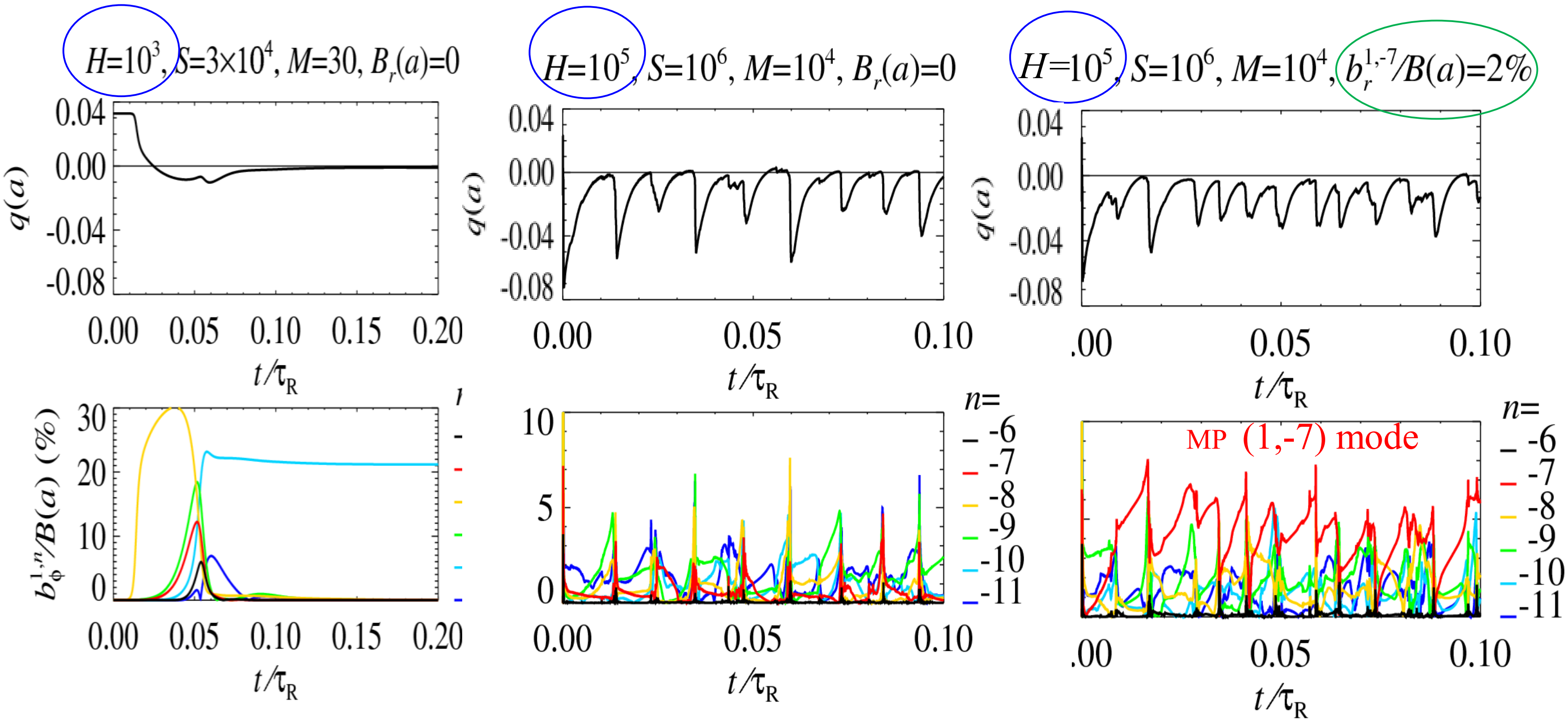
3D nonlinear MHD

RFP

Trend with increasing H and applying MP

RFP "sawtooth" cycle excitation

"sawtooth" cycle pacing and QSH excitation



Similar to RFX-mod at "intermediate" values of plasma current

Bonfiglio NF 2011
Veranda PPCF 2013
Bonfiglio PRL 2013

3D nonlinear MHD

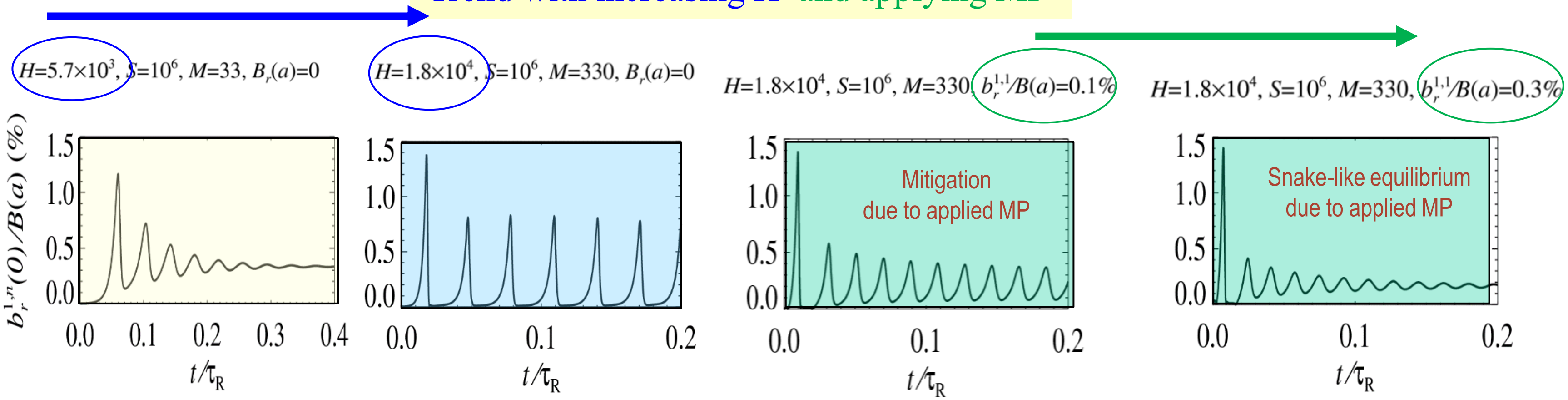
Tokamak

Circular tokamak in viscoresistive SpeCyl simulations: + MP (1,1)

Snake like (high dissipation) → periodic sawtoothing (low dissipation)

approaching snake (**same dissipation but MP applied**)

Trend with increasing H and applying MP



H & MP produce similar dynamical effects as in RFP

Bonfiglio, Chacon, Cappello PoP 2010
Bonfiglio, Escande , Zanca, Cappello NF 2011
Veranda, Bonfiglio Cappello et al EPS 2012
Bonfiglio, Veranda , Cappello et al PPCF 2015

3D nonlinear MHD

Remarks:

- 3D nonlinear MHD simulations at realistic values of Lundquist parameters remain beyond present capabilities,
- indeed, the estimate of a realistic viscous Lundquist, i.e. theory of momentum transport, is still an open issue,
- Uncertainty in the estimate of Ludquist number appears less problematic, yet some debate still pop up here and there;

3D nonlinear MHD

Summary of the presented hints from viscoresistive approximation of RFP description:

Large and medium scale resistive-kink/tearing modes yield field reversal (dynamo effect);

Resitivity and viscosity (the product of them - H) govern:

- the transition from magnetic chaos dominated to reduced chaos (QSH) regimes,
- the amplitude and frequency of sawtooting,

Magnetic Perturbations (MP):

- are capable of pacing sawtooth amplitude and frequency,
- favors the transition to QSH;

Summary and Concluding remarks

J. B. Taylor theory of RFP relaxation (‘70ties).

- Variational principle: provides analytical solutions of magnetic profiles similar to experimental measurements.

Toy model (‘60ties and modern *revival*).

- Schematic model provides intuitive description of macroscopic helical self-organization.

3D nonlinear MHD numerical simulations.

- Despite the simple approximation adopted in SpeCyl code implementation, several characteristic features observed in experiments find a useful description and inspires directions to be studied.

It still remains challenging to achieve a quantitative predictive capability, needed for fusion research.

Additional hints are available from viscoresistive approximation of RFP description, and are briefly presented in the following slides:

- Relaxation-reconnection events at sawtooth cycle
  - Magnetic into Kinetic energy conversion (possible ion heating?)
  - Current sheets formation – magnetic reconnection,
  - Mode phase locking, (toroidal collapse of the helix)
  - Excitation of Alfven waves

- Transport Barrier formation and Magnetic chaos healing

- Some open issues

next slides: relaxation-reconnection cycles features (only mention)

- Magnetic into Kinetic energy conversion (possible ion heating?)
- Current sheets formation – magnetic reconnection,
- Mode phase locking, (toroidal collapse of the helix)
- Excitation of Alfven waves

- Magnetic into Kinetic energy conversion

RFP “sawtoothing” cycle

F(t)

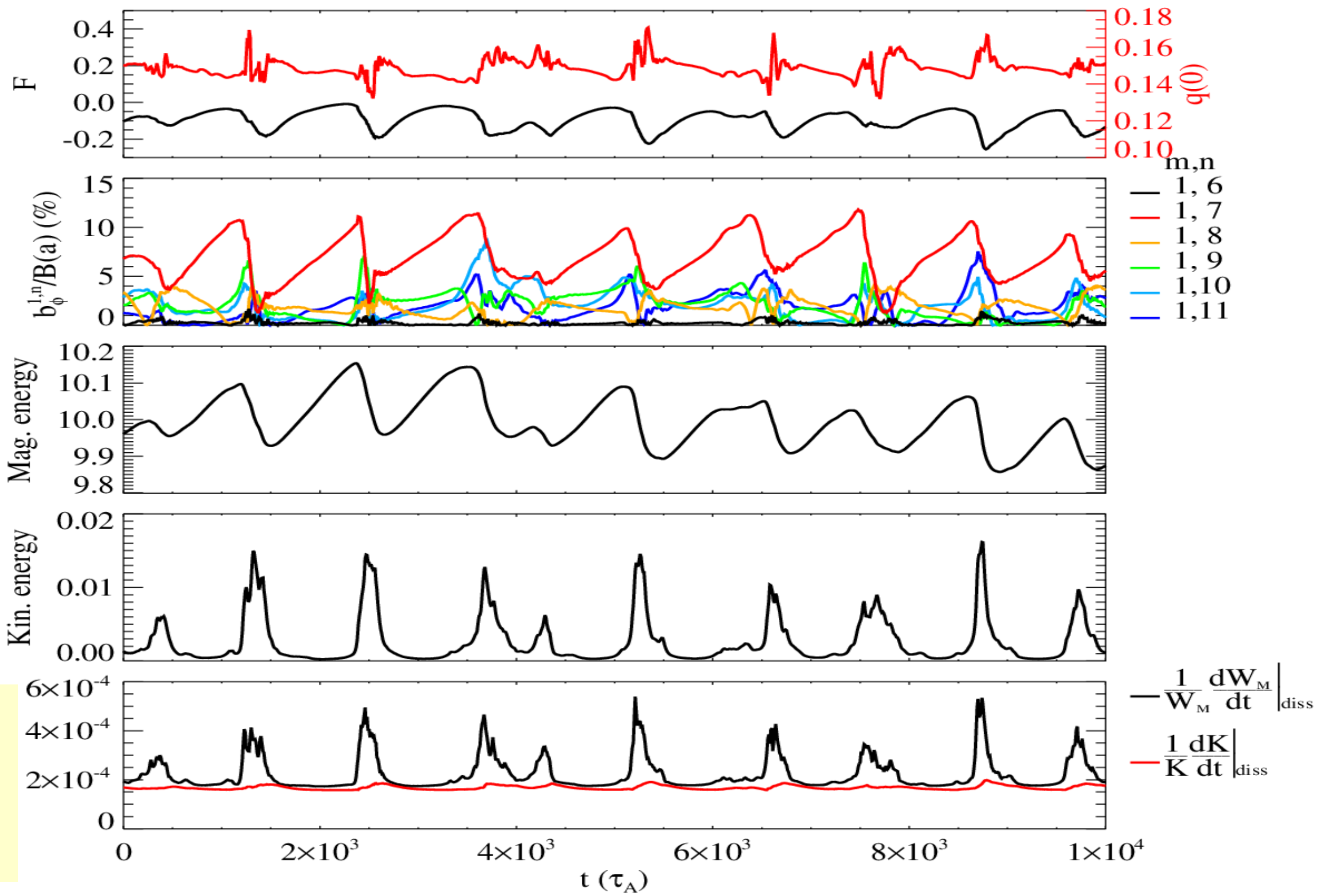
Mode amplitude
bz(a)% m,n

Total
MAGNETIC
energy

Total
KINETIC
energy

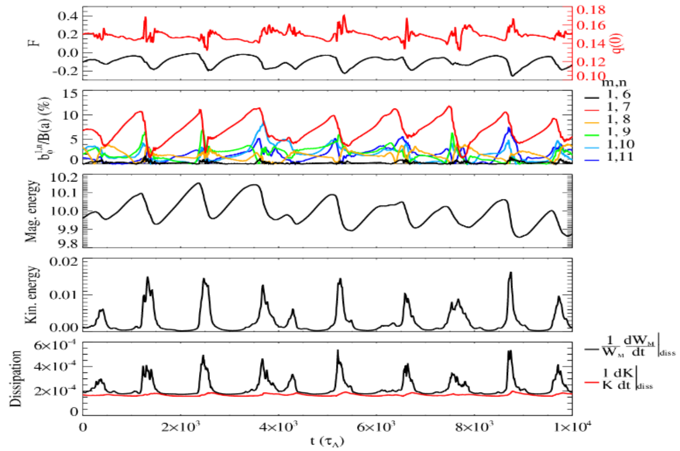
Magnetic
- **Energy** and
- Helicity

dissipation rates

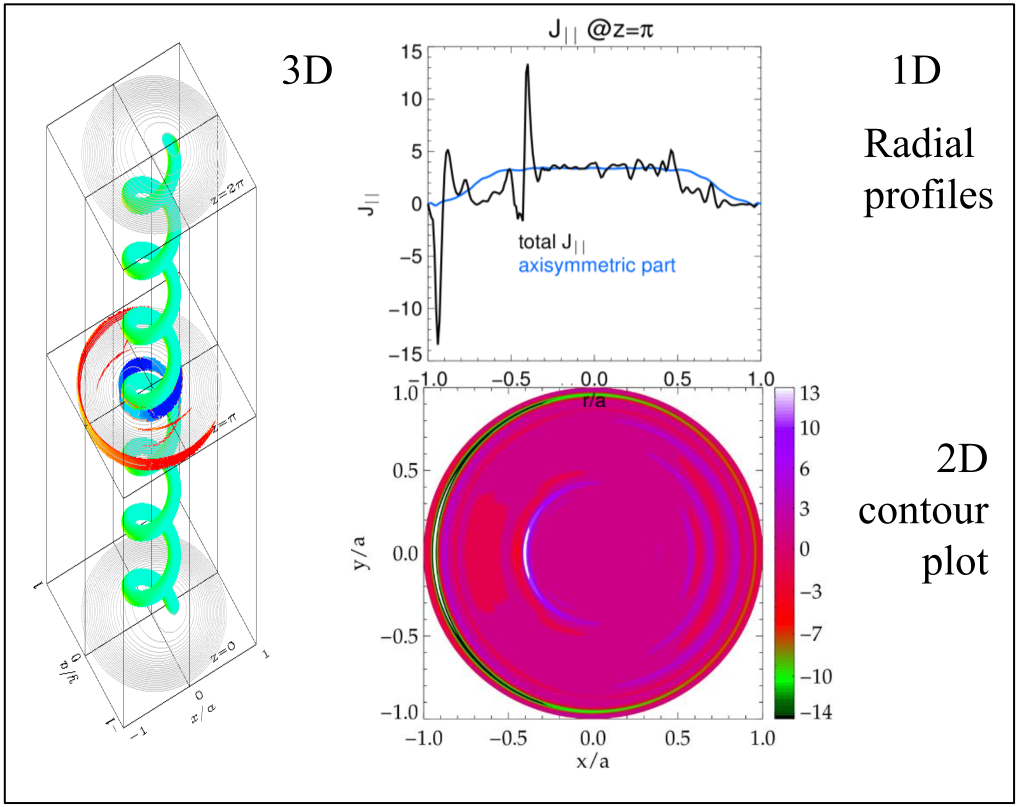


current sheets formation mode phase locking and excitation of Alfven waves

RFP S=10^5, P=10

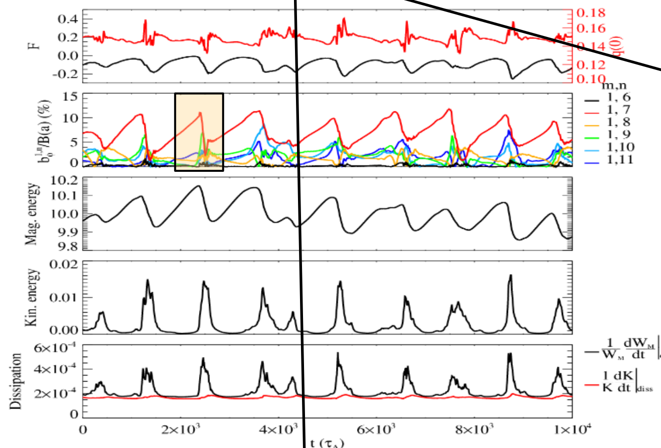


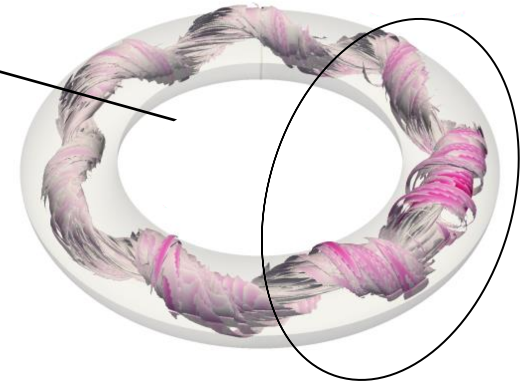
$J \cdot B$



current sheets formation **mode phase locking** and excitation of Alfven waves

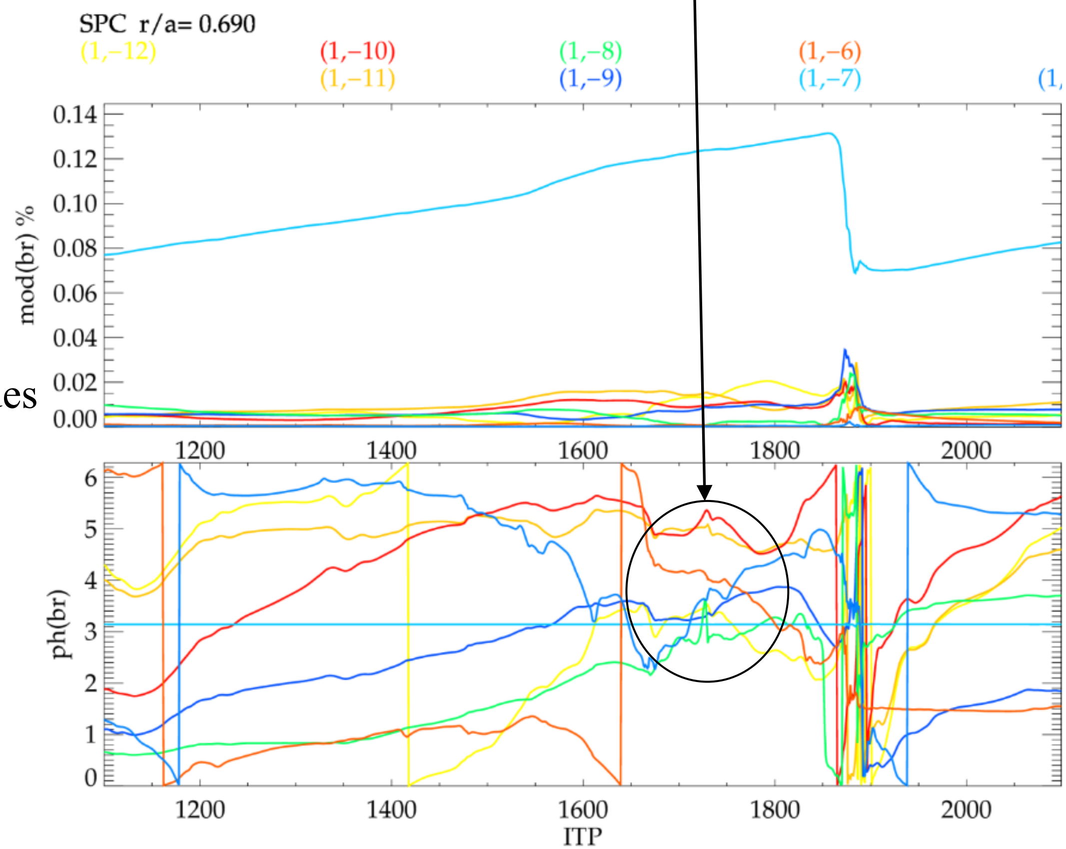
RFP $S=10^5$, $P=10$





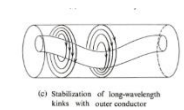
amplitudes

phases

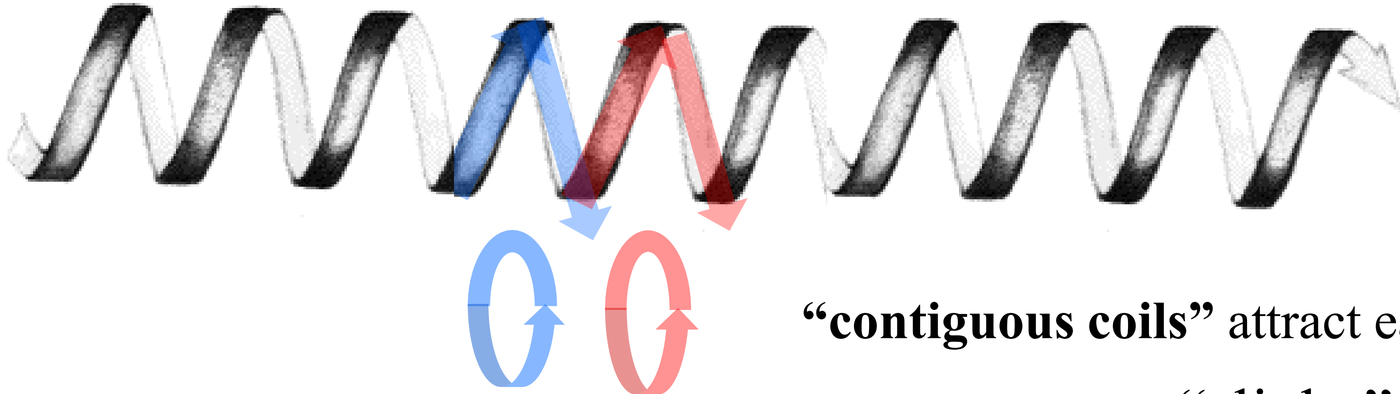


J// contours

RFP Toy model: useful to describe the “slinky -phase locking- effect ”



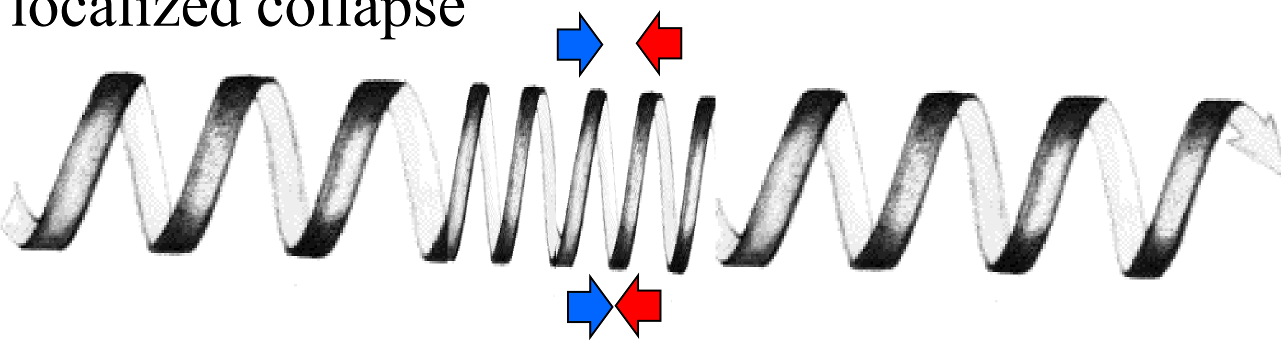
After kinking …



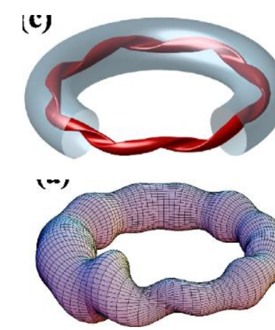
“contiguous coils” attract each other …

…“slinky” instability

… localized collapse



plasma buldging-collapse
at a toroidal location,
similarly in experiments
and nonlinear modeling…

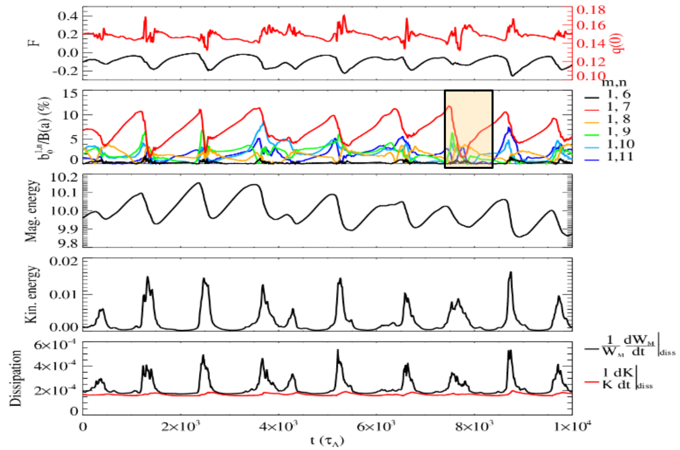


Cappello et al., Theory of Fusion Plamas - Varenna 2008

current sheets formation mode phase locking and **excitation of Alfven waves**

RFP $S=10^5$, $P=10$

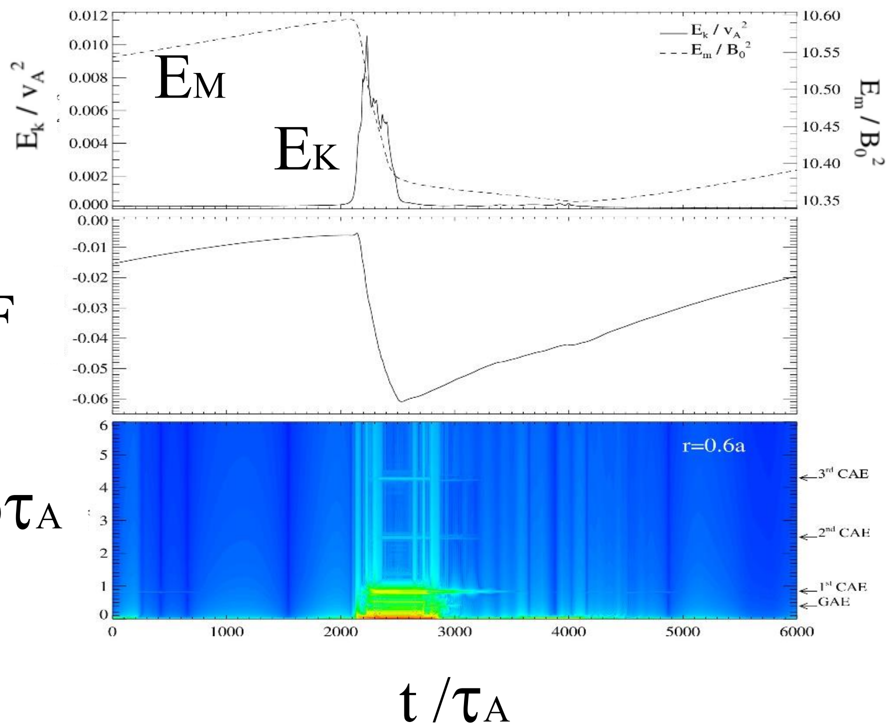
RFX-mod like density profile assigned

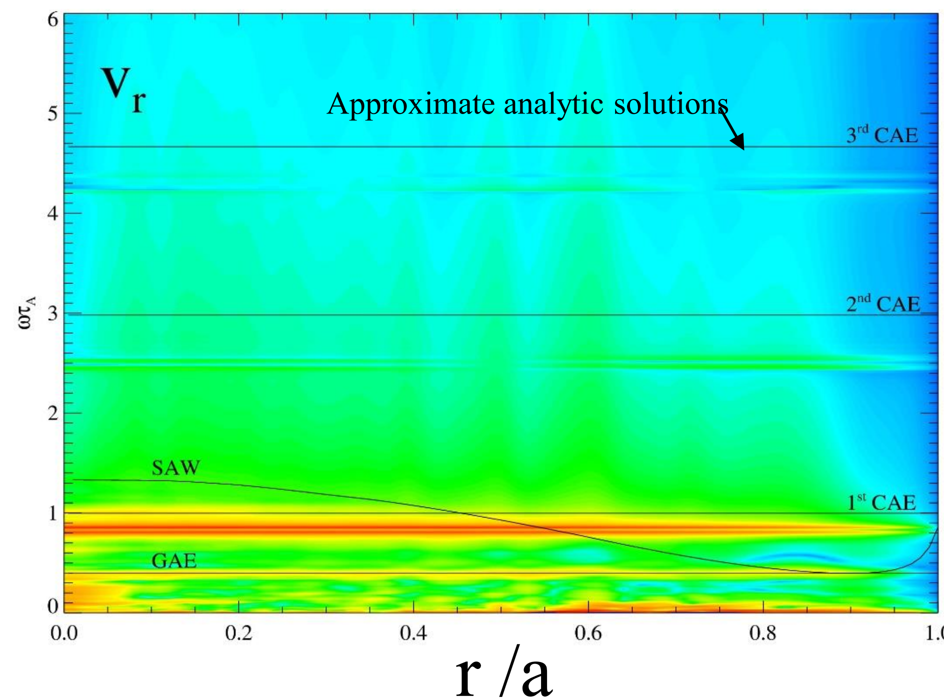


Kryzhanovskyy et al NF 2022

Alfvén Eigenmodes (in particular the GAE and the 1st CAE) are excited by magnetic reconnection event.

Alfvén waves spectrum
(m=1, n=0) r= 0,6a





Experimentally observed in RFPs:
Spagnolo NF 2011 and therein refs, Koliner PRL 2012

Next slides: transport and barrier formation in RFP (only mention)

Transport in RFP is believed to be ruled by **magnetic topology properties**:

Typical tool for topology inspection:

Poincarè surface of section approximated by **magnetic field lines punctur plot:**

Trace magnetic Field Line and mark intersection in chosen surface.

Chaotic magnetic field emerge in several conditions in RFP, Tokamak and Stellarator.

Magnetic Field line integration, numerical tools available at Consorzio RFX:

NEMATO [1]
benchmarked vs ORBIT code [2]

[1] Finn, Chacòn **PoP** 2005
[2] Ciaccio, Veranda, Bonfiglio, Cappello, Spizzo, White **PoP** (2013)

Magnetic field lines and magnetic surfaces

The two extreme dynamical regimes:

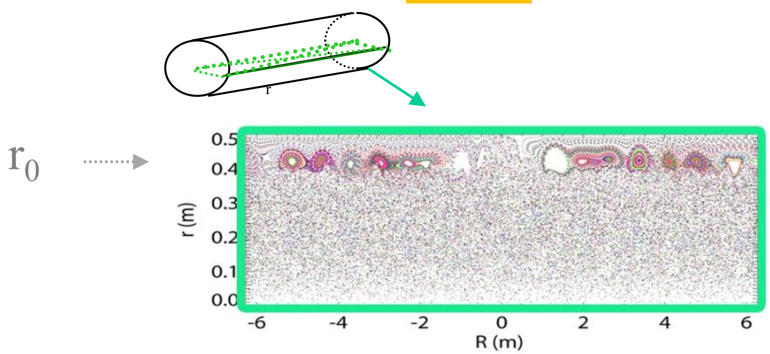
MH and SH (exist only in cylinder)

Magnetic field lines punctur plot:

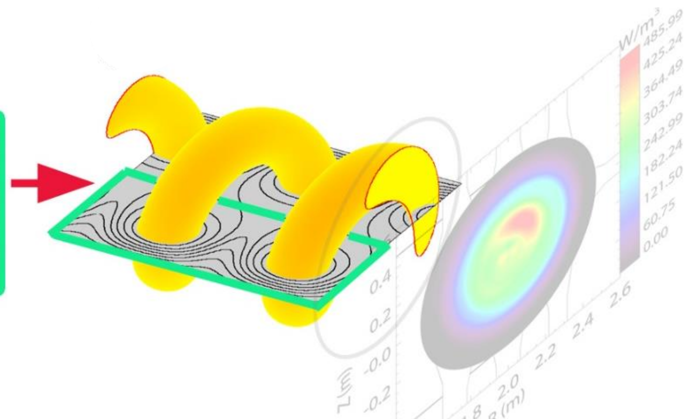
- Magnetic chaos spreads in the core of the domain
- A chain of magnetic islands exist at reversal radius:
  magnetic lines lie on that surfaces, do not move from them.

Magnetic flux surfaces perfectly conserved
In helical symmetry you can find a helical flux function,
the isosurfaces are magnetic flux surfaces:
Magnetic field lines lie on flux surfaces.

MH



SH



Chaos healing effect thanks to helical structure

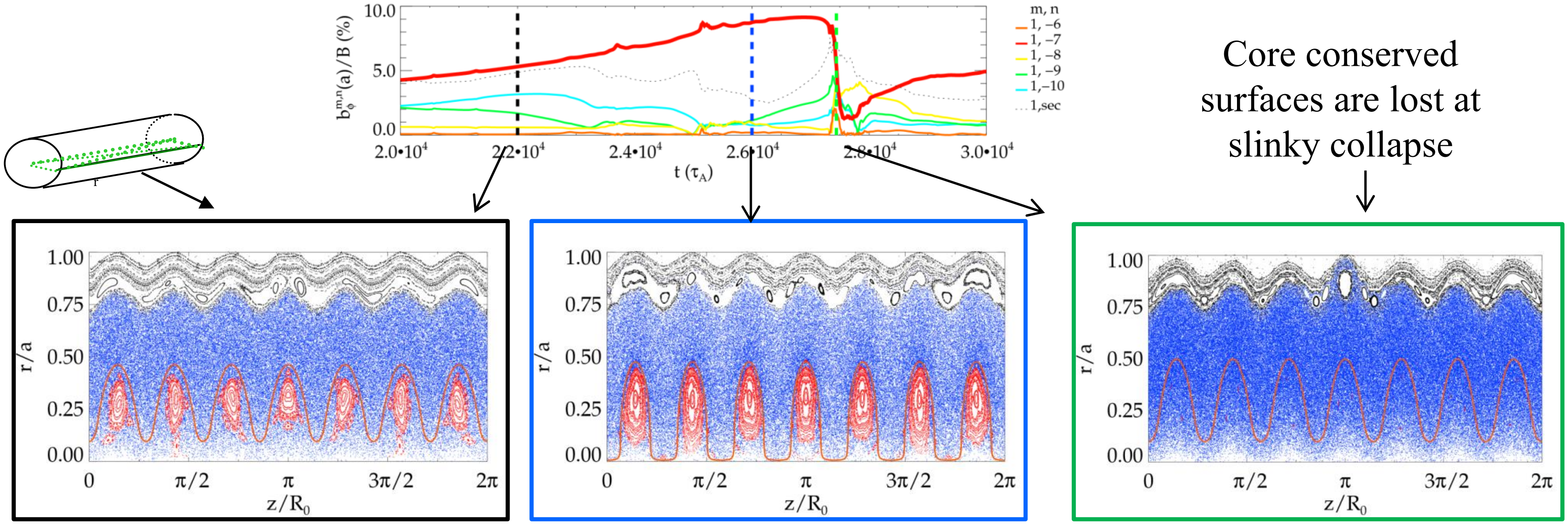
By inspection of magnetic topology during a typical QSH sawtoothing cycle in simulations we find an intermediate situation in between MH and SH: partial chaos healing

Chaos healing effect thanks to helical structure

[Dominant mode separatrix expulsion Escande et al PRL (2000)]

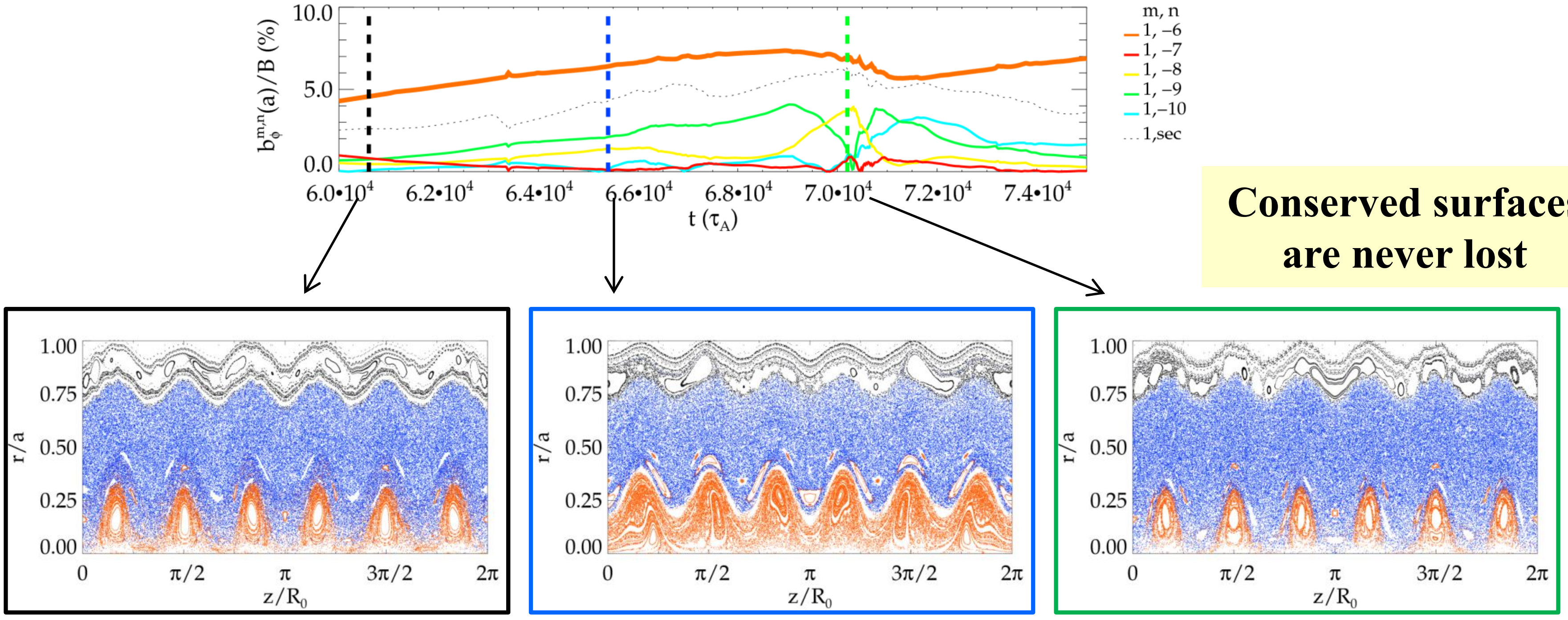
The width of conserved helical core evolves

Core conserved surfaces are lost at slinky collapse



Inspired by indications obtained in topology studies of numerical simulations we studied a Non-Resonant helical regimes

More efficient chaos healing by stimulating n=6 (Non Resonant)



Conserved surfaces are never lost

Poincare plots: secondary modes divided by 5 to match experimental amplitudes (as scaled to S= 10^7)

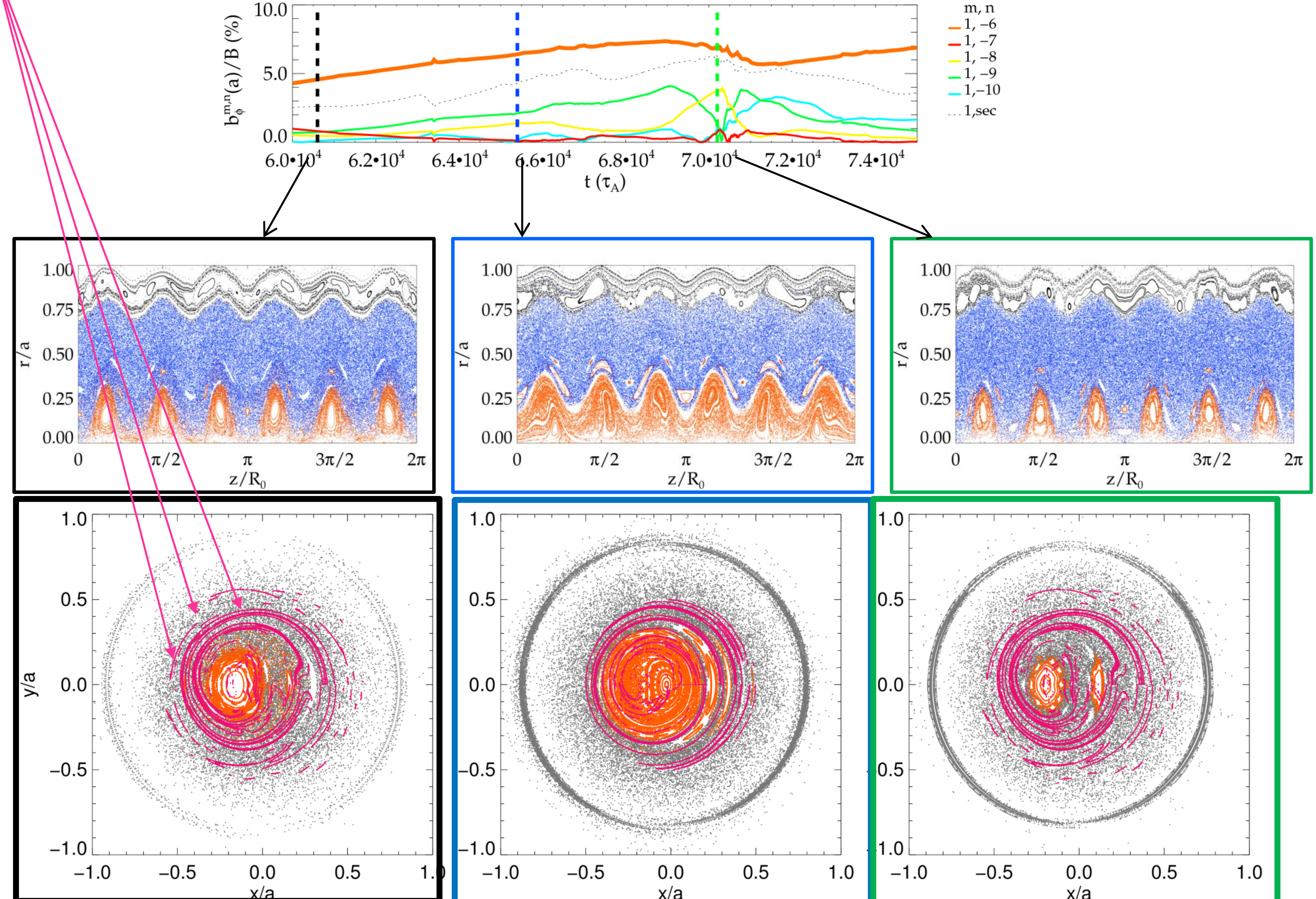
Lagrangian Coherent Structures, LCS, detected in simulation cases:

Barriers to the wandering magnetic field lines *embedded in chaotic domains*

- Di Giannatale, Bonfiglio, Cappello, Chacòn, Veranda NF (2021)
- Veranda, Bonfiglio, Cappello, Di Giannatale, Escande NF (2020)
- Pegoraro *, PPCF (2019)
- Di Giannatale, et al POP a,b (2019)
- Rubino °, Borgogno°, Veranda, Bonfiglio, Cappello, Grasso°, PPCF (2015)

Collaboration with
- ° ISC (Institute for Complex Systems) - CNR Torino Italy – Politecnico Torino
- * University of Pisa - Italy

Lagrangian Coherent Structures nearby conserved surfaces

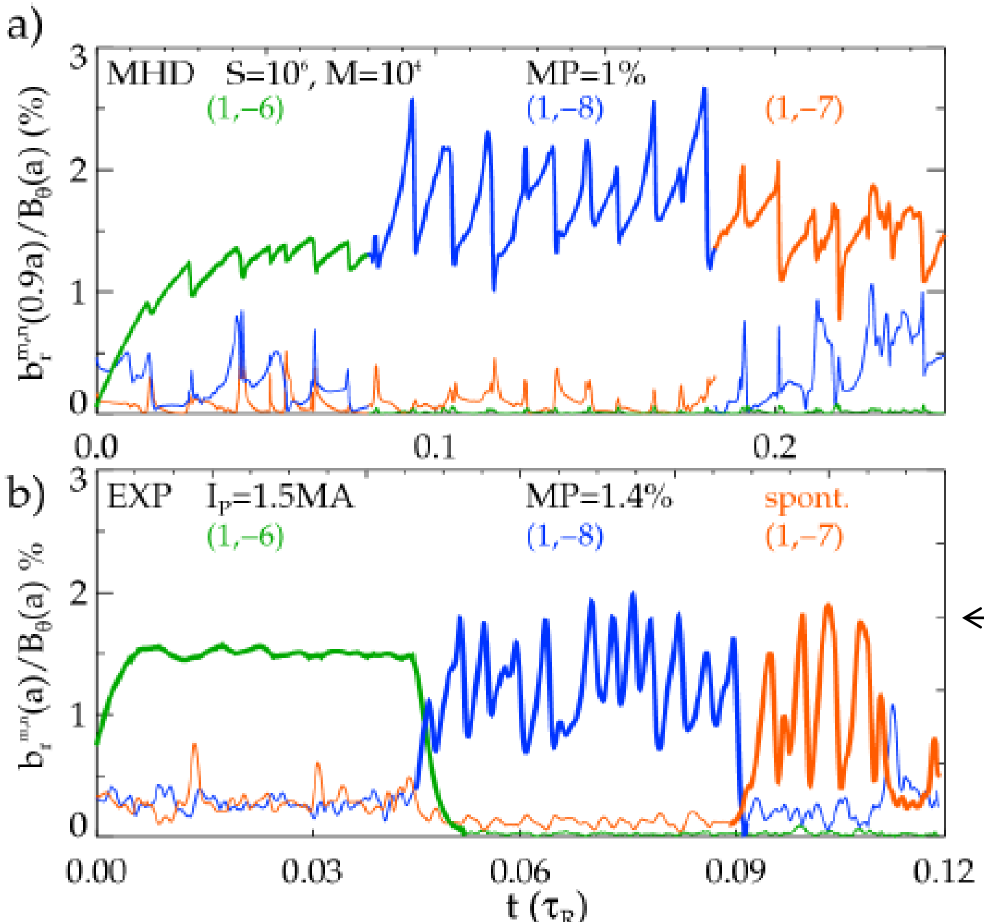


The possibility to convey the experimental discharge toward a "new" helical solution, in particular, low n non-resonant helix, has been tested in RFX-mod by applying suitable MP.

Dynamics successfully confirmed in RFX-mod experiment

<u>Small edge Magnetic Perturbations</u> (MP) **can drive new helical regimes**, with different pitch:

Validation example



Experimental discharge
#30932 RFX-mod

simulation

Successful RFX-mod experiments:
***alternative ns* stimulated by seed MP**

Veranda, Bonfiglio, Cappello et al NF 2017

Some open issues, Ongoing work:

Implementation of more realistic Boundary Conditions

Verification SpeCyl – PIXIE3D (Chacòn-LosAlamos)

Spinicci (PhD), Bonfiglio et al, EPS 2022

Addressing estimate of experimental *effective Hartmann*

Heuristic approach (momentum transport in plasmas is a long standing open issue)

Vivenzi (PhD) Veranda et al, EPS 2022 ; Vivenzi Veranda et al, Theory Fusion Plasmas 2022 submitted JPCS

Assessing magnetic LCS validation on experimental eITB

follow up of Veranda et al, NF 2017

Further develop analogies RFP – Tokamak - …

- Alfven waves excitation at sawtoothing (ohmic)

Kryzhanovskyy (PostDoc), Bonfiglio et al, Nuclear Fusion 2022 https://doi.org/10.1088/1741-4326/ac6ad3

Kryzhanovskyy (PostDoc), Bonfiglio et al, paper under revision

- What is the role of visco-resistive "quality" in determining MHD mode coupling in Tokamak ?

Possible impact on density limit processes (both RFP and Tokamak) under discussion

What is the mechanism of "anomalous" ion heating in RFPs (observed at sawtoothing) ?

non resonant Alfvèn wave particle interaction

susanna.cappello@igi.cnr.it

spare slides

Theory and Simulation Group at Consorzio RFX:

Susanna Cappello
[3D nonlinear MHD (head of the group)] *nome.cognome@igi.cnr.it*
Fabio Sattin
[particle statistics and wave-particle]
Daniele Bonfiglio
[3D nonlinear MHD]
Italo Predebon
[gyrokinetics, MHD]
Marco Veranda
[3D nonlinear MHD, magnetic topology]
Emanuele Spada
[high voltage holding (MITICA-NBTF) / theoretical studies]

+ 2 Post Doc (Kryzhanovskyy, Spinicci)
+ 1 PhD student (Calcagno)
+ international collaborators

Main NUMERICAL TOOLS involved on the modeling side

- **3D nonlinear MHD** – viscoresitive approximation:

  SpeCyl [a] - PIXIE3D [b] (benchmarked codes) [c]

- **Magnetic Field line integration**:

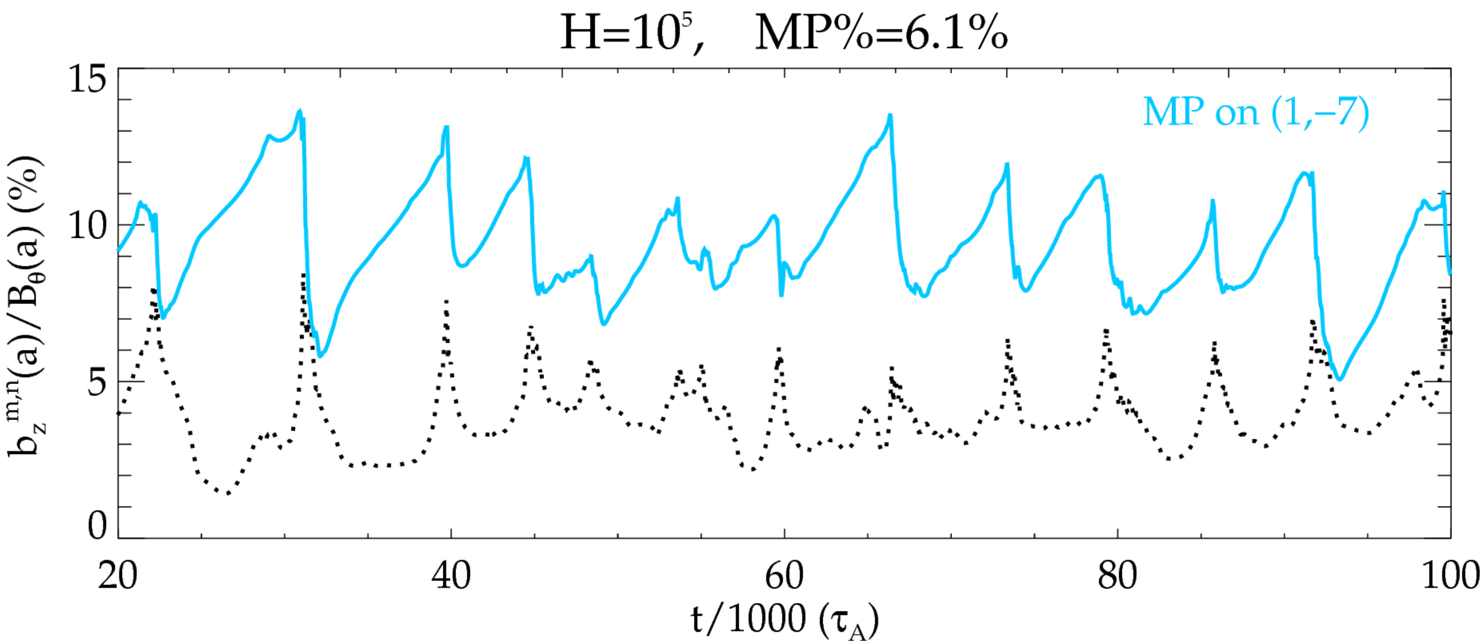
  NEMATO [d] (benchmarked vs ORBIT code [e])

- **Lagrangian Coherent Structures** detection [f, g]

[a] Cappello, Biskamp **NF** 1996
[b] Chacòn **CPC** 2004, Chacòn **PoP** 2008
[c] Bonfiglio, Chacon, Cappello **PoP** 2010
[d] Finn, Chacòn **PoP** 2005
[e] Ciaccio, Veranda, Bonfiglio, Cappello, Spizzo, White **PoP** (2013)
Recent collaboration with Borgogno (CNRS-Nice), Rubino and Grasso (CNR – ISC Torino, PoliTO) :
[f] Rubino, Borgogno, Veranda, Bonfiglio, Cappello, Grasso **PPCF** (2015)
[f] Di Giannatale, et al **POP** a,b (2019)
[f] Pegoraro, **PPCF** (2019)

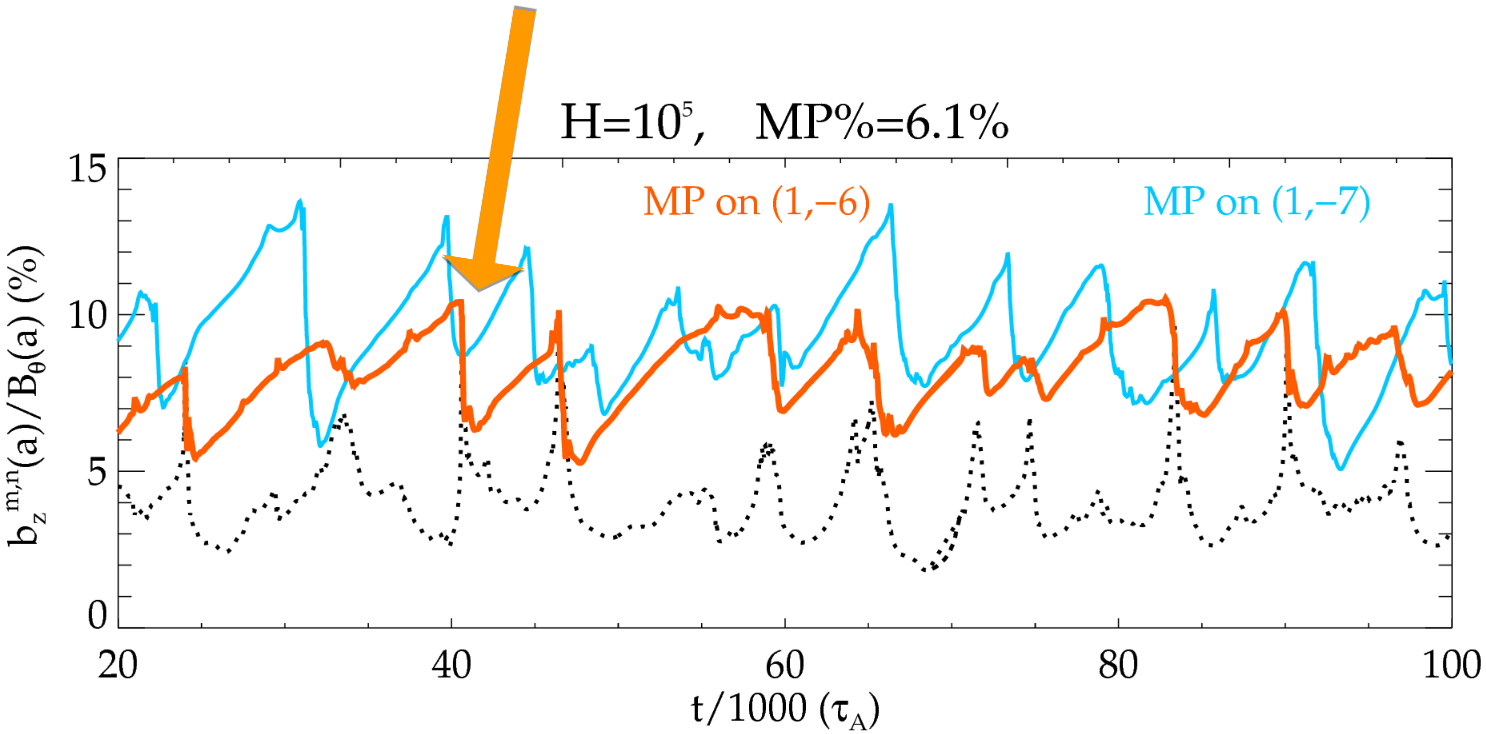
Possible to excite different *n*s

Dominant (1,-7) and sum of secondary modes



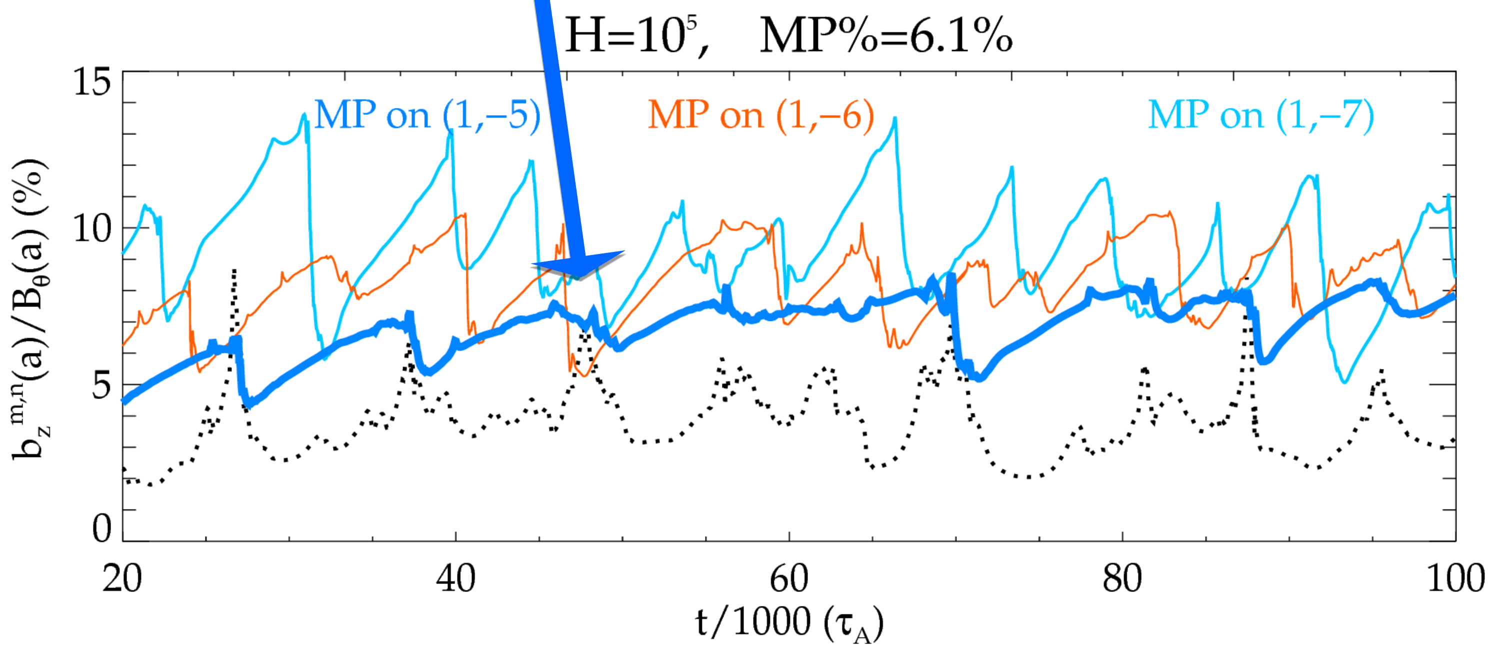
Response to different MPs : comparison

Dominant (1,-6) less reactive than -7



Response to different MPs : comparison

Dominant (1,-5) even less reactive

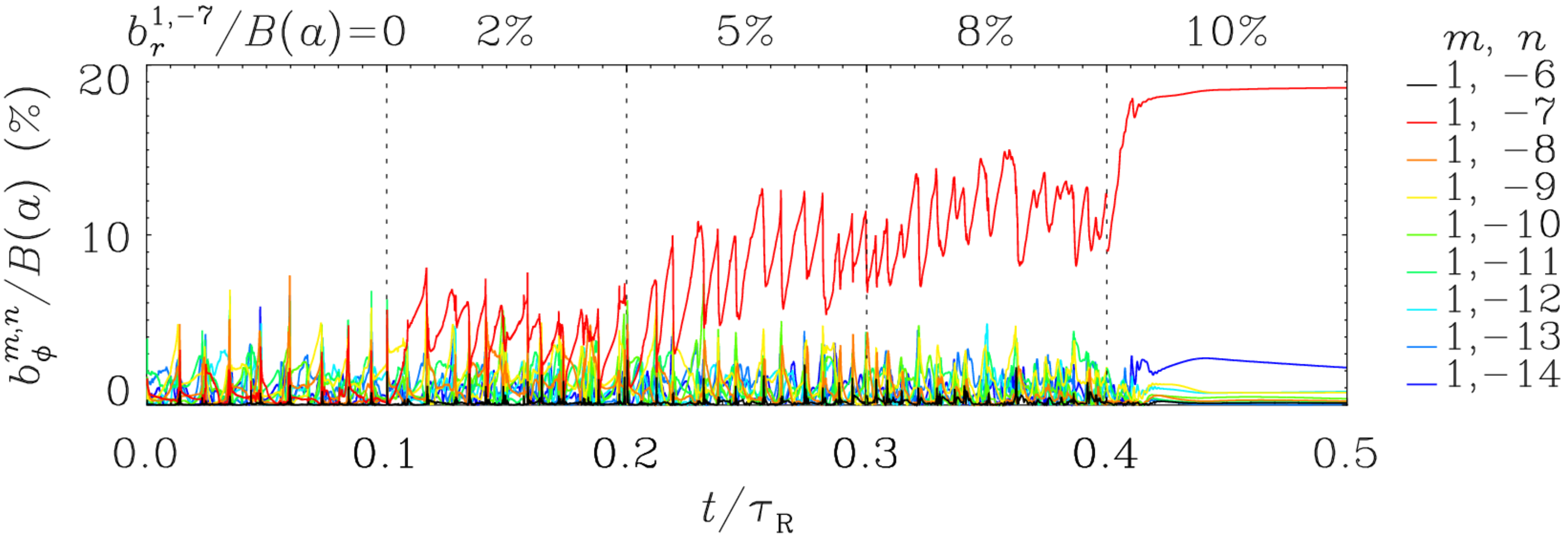


NOTE: the lower the n_{MP} -> the smaller the **Frequency&Amplitude** of cyclic oscillations

Larger MPs leads to steady helical saturation

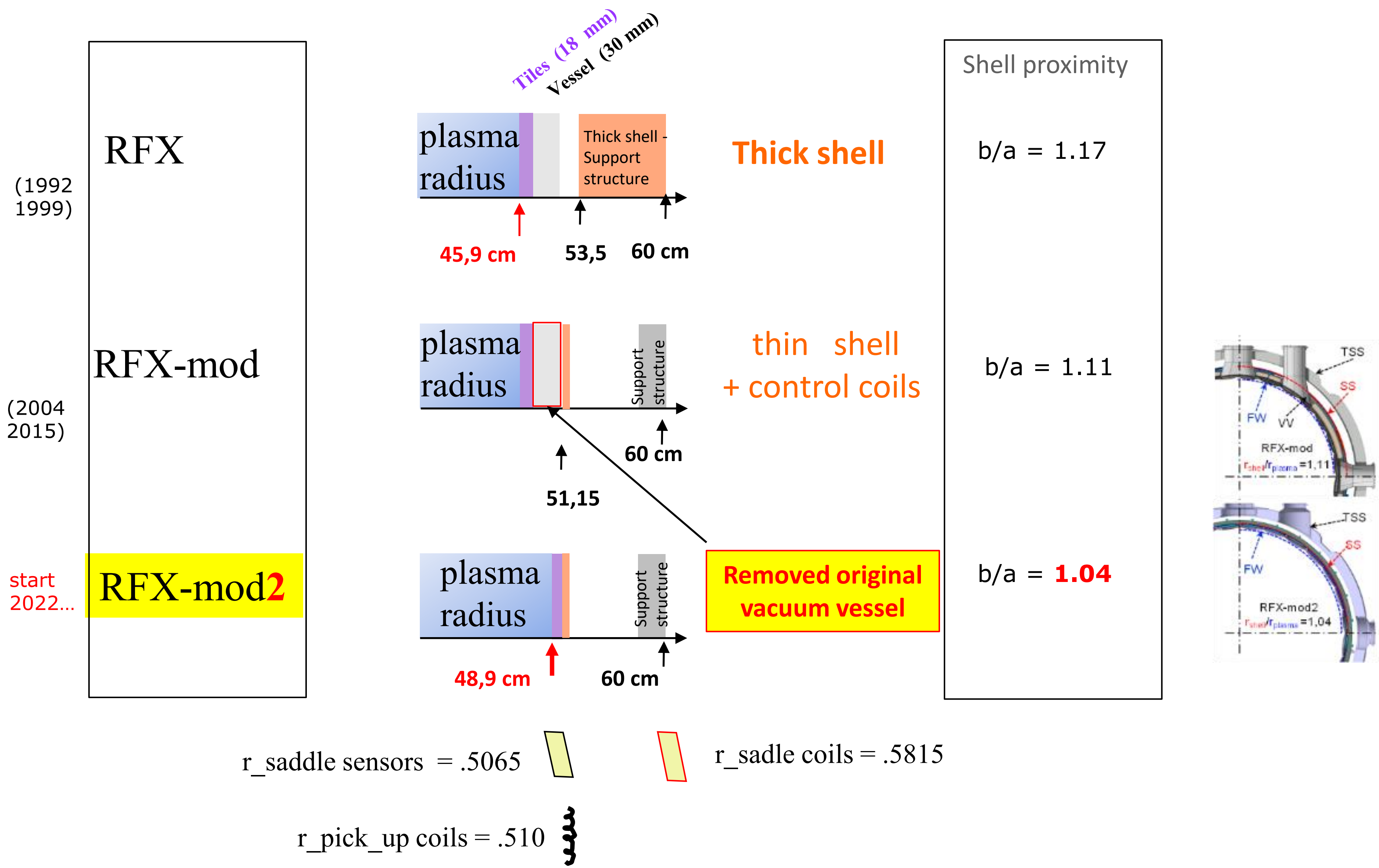
(Similar to the ones obtained at high dissipation)

Veranda PPCF 2013
Bonfiglio PPCF 2015



… to be explored in experiments

RFX device evolution: plasma radius and magnetic front-end



RECONNECTION PROCESSES AND SCALING LAWS IN REVERSED FIELD PINCH MAGNETOHYDRODYNAMICS

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Associazioni Euratom–ENEA–CNR–Univerita' di Padova,
Padova, Italy

D. BISKAMP
Max-Planck-Institut für Plasmaphysik,
Euratom Association, Garching, Germany

ABSTRACT. Reversed field pinch (RFP) sustainment is studied in the framework of three dimensional magnetohydrodynamic (MHD) numerical simulations. The scaling law for the magnetic fluctuation amplitude with Lundquist number S is $\delta B \approx S^{-0.22}$, which can be understood if the basic dynamic processes are governed by current sheet reconnection. Quasi-periodic oscillations are in fact found to be correlated with the presence of localized sheet currents, which for sufficiently large S make the major contribution to the average power dissipated by fluctuations. Special attention is paid to numerical convergence in the simulations. The results are compared with experimental observations.

The $m = 0$ modes are found to contribute directly to the dynamo action. Figure 9 shows the radial profile (time averaged over $3500\tau_A$) of the contributions to the poloidal electric field $E_\theta^D(r) = -(\overline{v \times b_\theta})$ of the

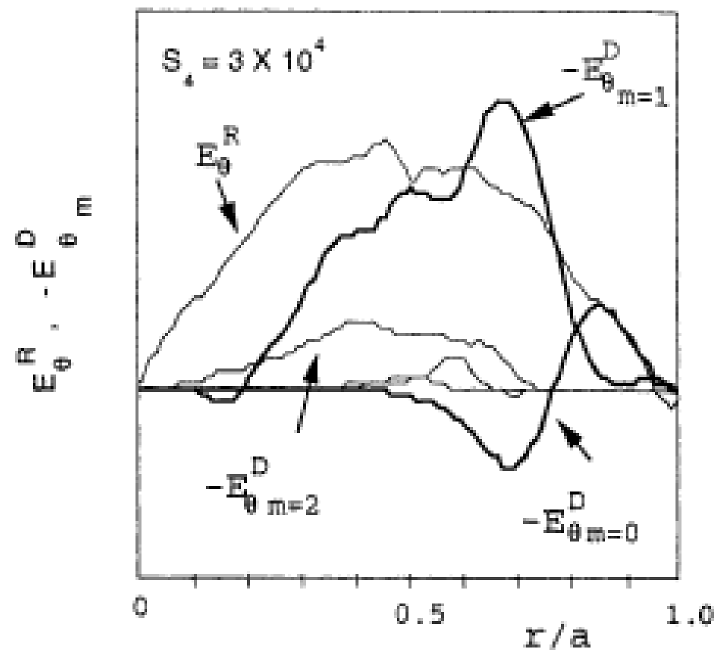


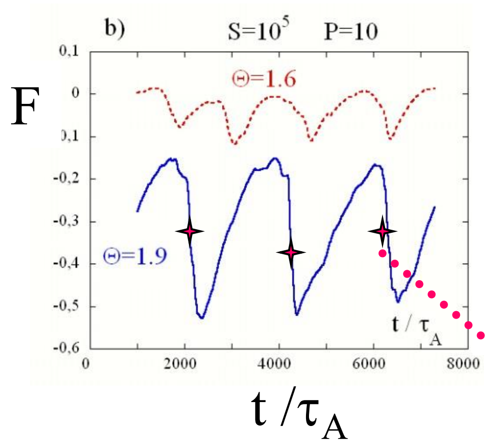
FIG. 9. Poloidal electric field along the radius: resistive and dynamo contributions: $E_\theta^R(r)$ *and* $-E_{\theta m}^D(r)$.

different m modes in the $S = 3 \times 10^4$ case, E_θ^D balancing the resistive term $E_\theta^R(r) = \eta J_\theta$ in Ohm's law. The $m = 1$ modes give the largest contribution to E_θ^D over the major part of the plasma radius, but the $m = 0$ contribution becomes comparable in amplitude in the outer half of the radius and, in particular, by changing sign in the vicinity of the reversal is the

MH regime:

Nearly-periodic relaxation events

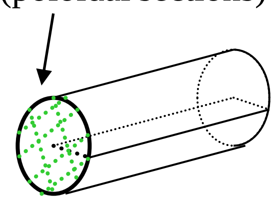
(similarly to low current experimental observations)

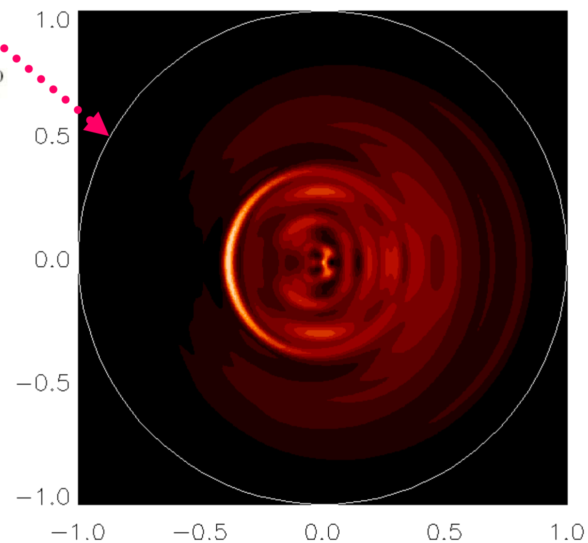


with formation of current sheets

$J \cdot B$

Current density contour plots (poloidal sections)





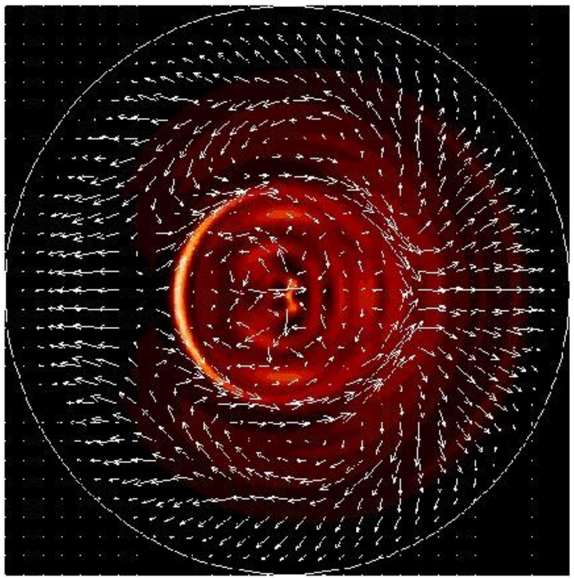
(3D: all of the modes contribute)

Bright colour => high current

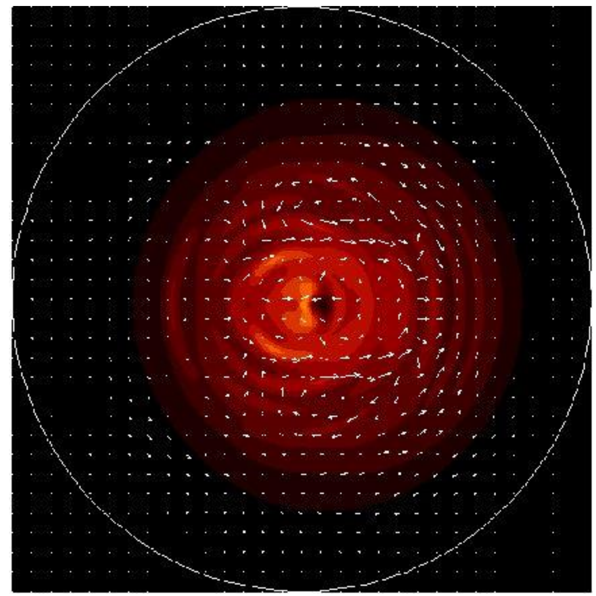
Cappello & Biskamp Nucl Fus 1996

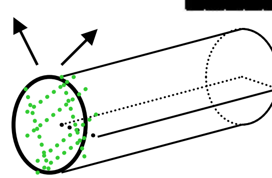
$J \cdot B$ contour plot and flow pattern

during RFP relaxation event



… in between relaxation events

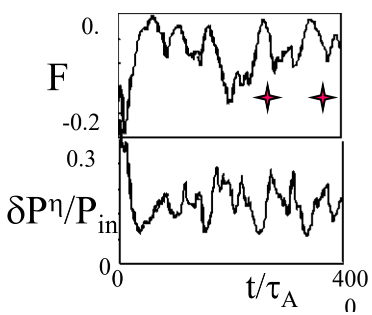


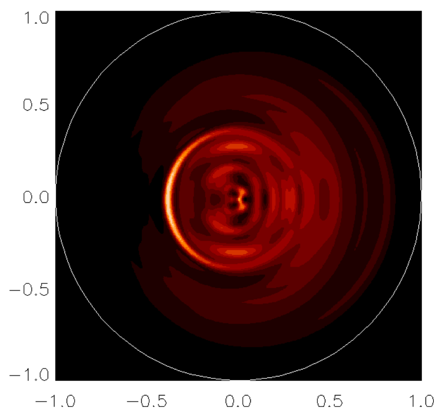


Bright colour => high current

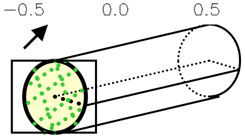
MH regime: MHD Reconnection and scaling laws

(P =1) S = 3 x 10^4





$J \cdot B$



Cappello & Biskamp Nucl Fus 1996

Quasi-periodic relaxation events

with formation of current sheets (3D)

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

$\delta B \approx S^{-1/4}$ (= $H^{-1/4}$)

(at constant P)

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 ≠ 1 ...

\+

RFX data

➔

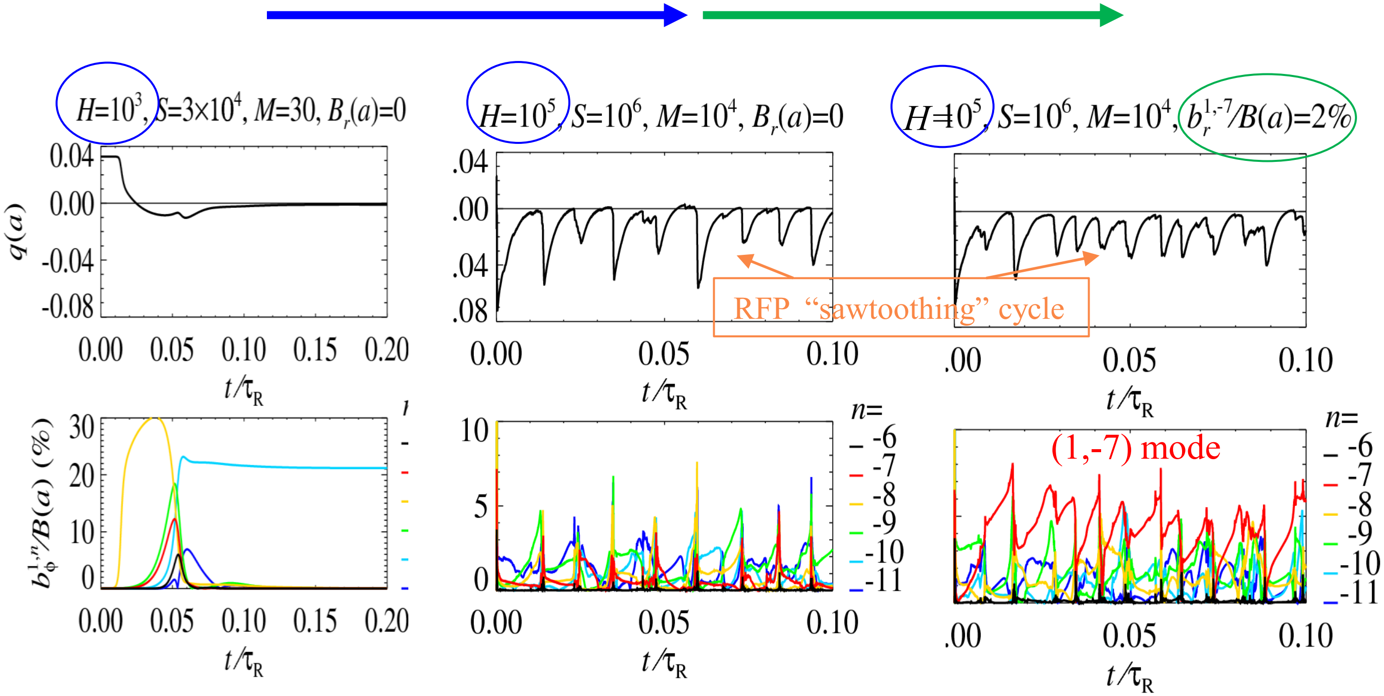
ITG turbulent viscosity may characterize the RFPs

Terranova et al. PPCF 2000

3D nonlinear MHD

Reversed Field Pinch in viscoresistive SpeCyl simulations: + MP $_{(1,-7)}$

Trend with increasing H and applying MP



Similar to RFX-mod discharges at "intermediate" values of plasma current

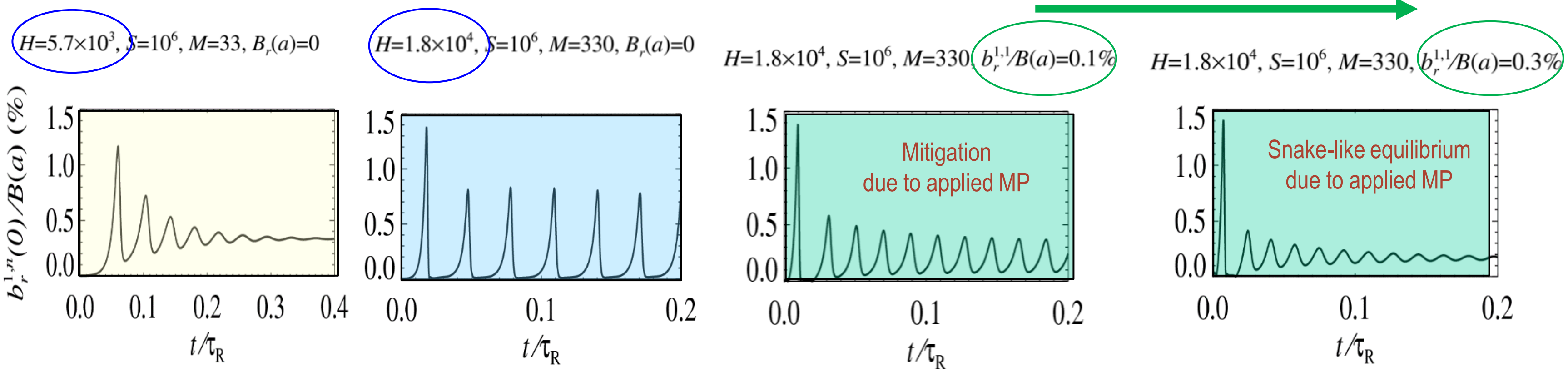
3D nonlinear MHD

Circular tokamak in viscoresistive SpeCyl simulations: + MP (1,1)

Snake like (high dissipation) → periodic sawtoothing (low dissipation)

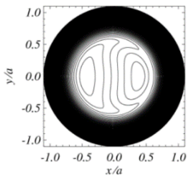
approaching snake (**same dissipation but MP applied**)

Trend with increasing H and applying MP

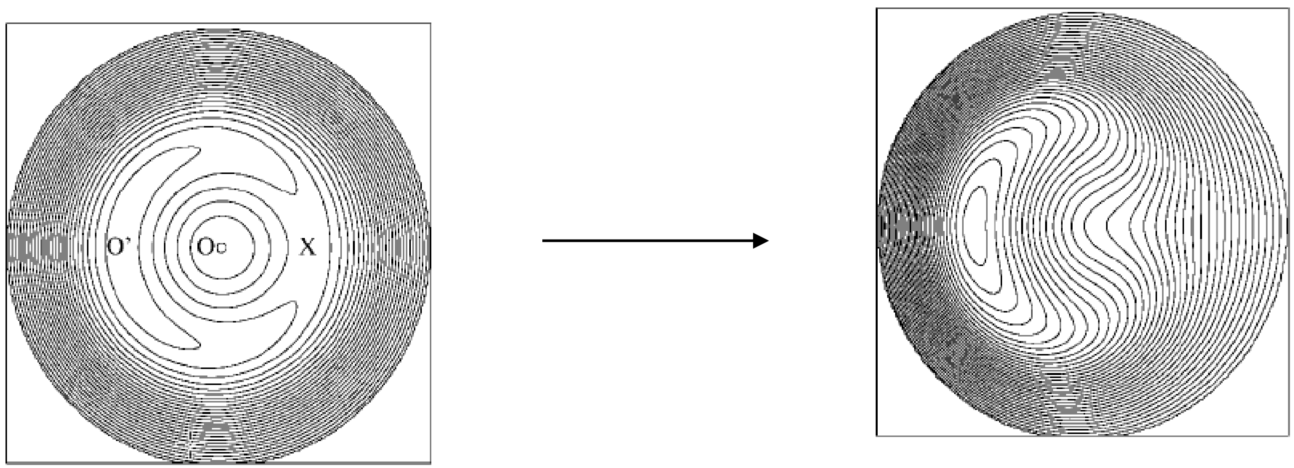


Dissipation & MP produce similar dynamical effects as in RFP

Bonfiglio, Chacon, Cappello PoP 2010
Bonfiglio, Escande , Zanca, Cappello NF 2011
Veranda, Bonfiglio Cappello et al EPS 2012
Bonfiglio, Veranda , Cappello et al PPCF 2015



When QSH dominant mode GROWS: separatrix expulsion occurs, and



(a) (b)

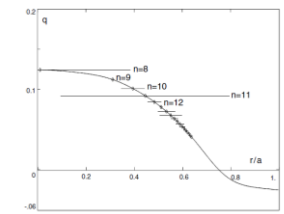
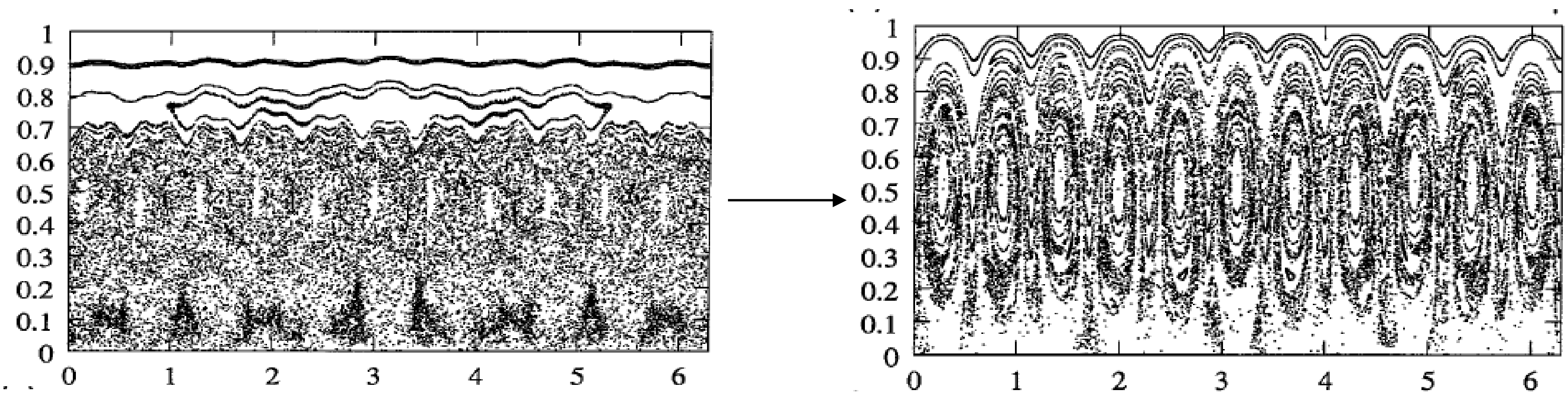


FIG. 2. q profile and magnetic islands width (shown by horizontal bars) of different $m = 1$ modes.

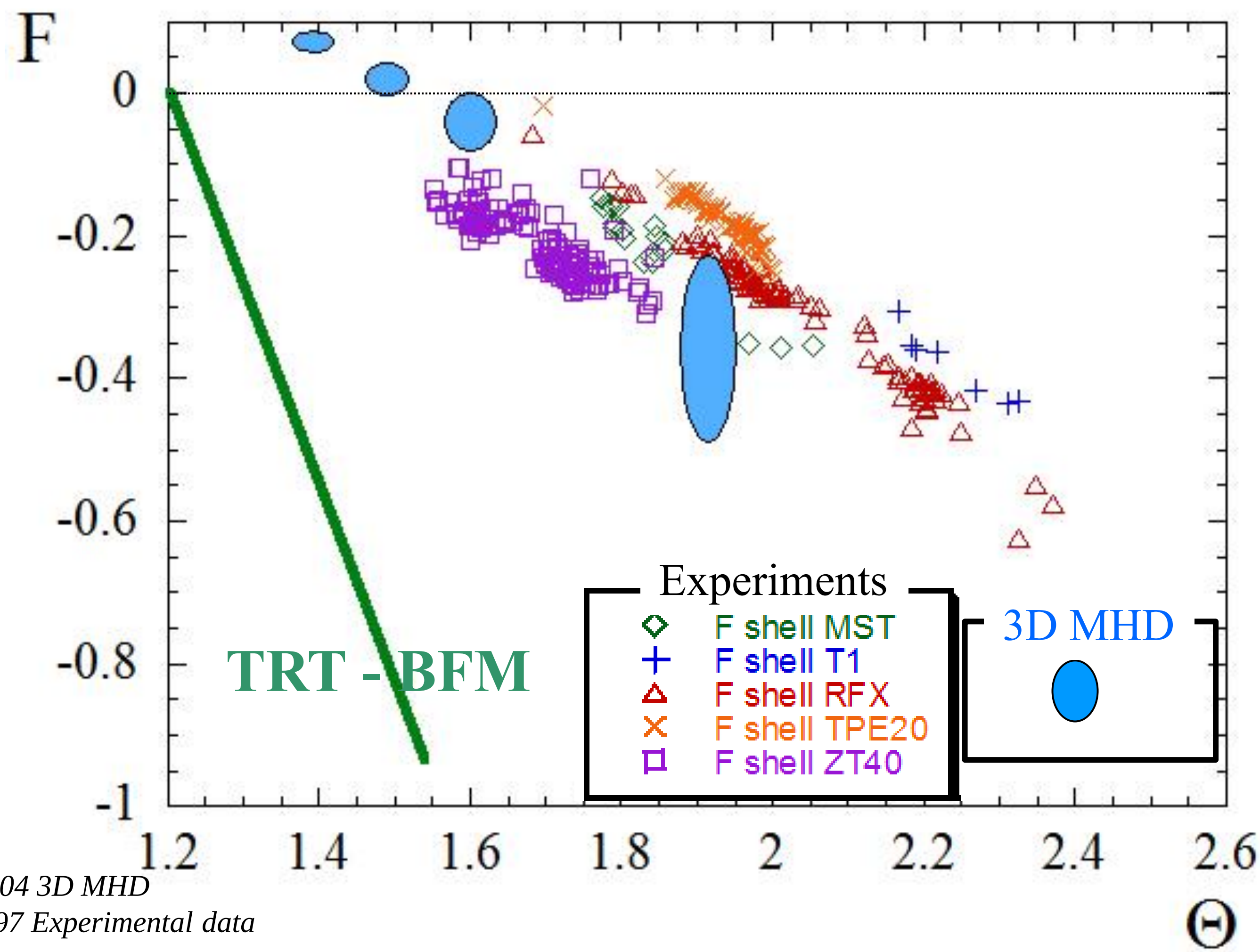
…clean helical topology emerges



Escande, Paccagnella, Cappello et al PRL 2000

Comparison “operational points”:

Numerical modelling – Experiments - Taylor’s Theory



S. Cappello PPCF 2004 3D MHD

T. Bolzonella EPS1997 Experimental data

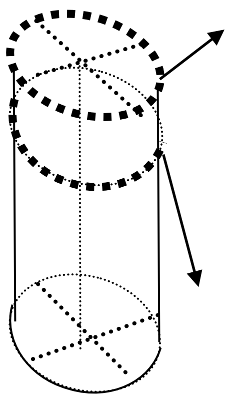
A finite radial magnetic field component at the boundary was suggested to favour attainment of helical ohmic equilibrium (Helical Grad-Shafranov problem)

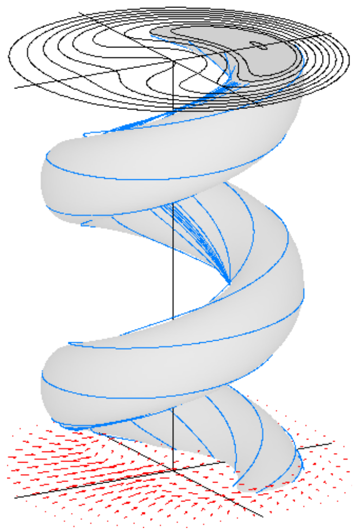
Bonfiglio, Escande, Zanca et al NF 2011

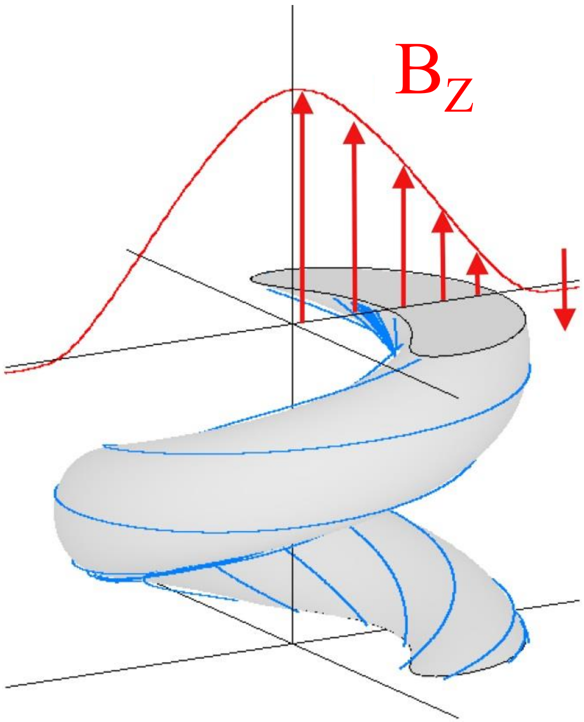
SH regime: “ the simplest **RFP** ”

Magnetic flux surfaces & field lines

... and corresponding reversed mean profile of B_Z





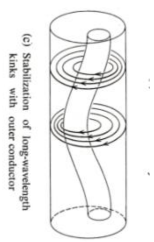


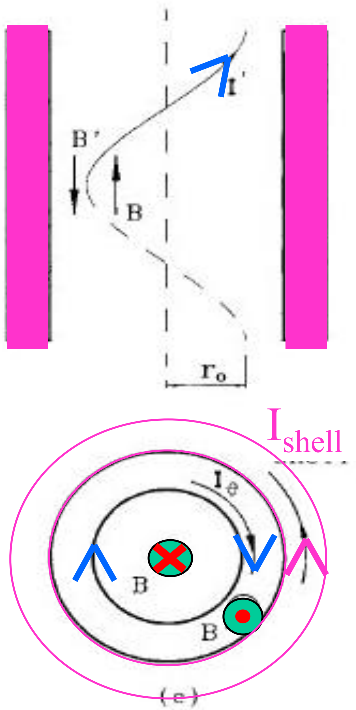
note the **velocity field** (red arrows), it is a helical pinch
it provides the Edynamo = coherent modulation <δv /\ δB>)

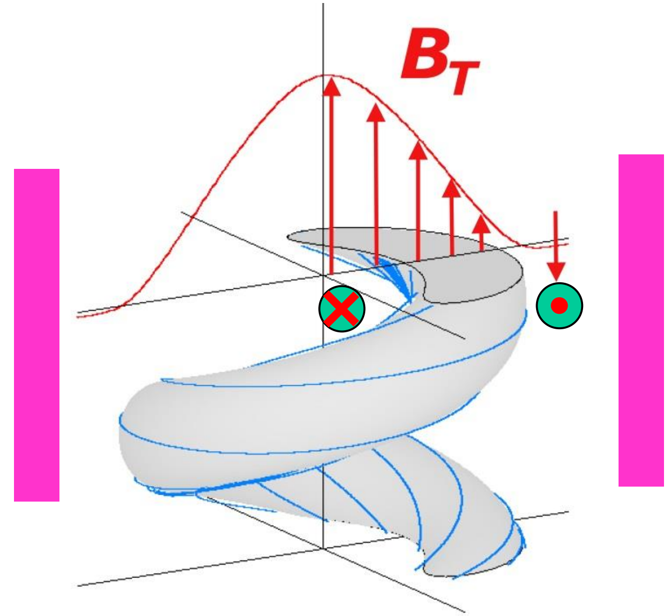
➔ drift velocity induced by the electrostatic potential …

Bonfiglio, et al PRL 2005

SH solutions resemble the toy model







kinked wire

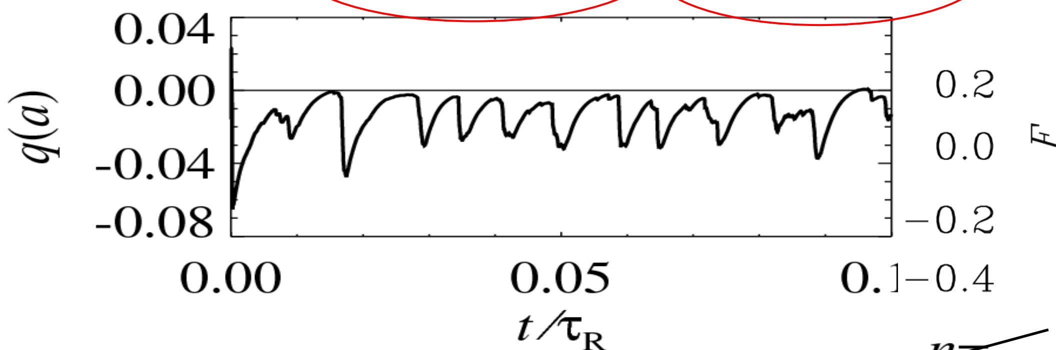
SH in viscoresistive modelling

Nearly-periodic relaxations QSH akin to experimental ones with MP (1,7)

(Ideal wall + MP)

$H=10^5$, $S=10^6$, $M=10^4$, $b_r^{1,-7}/B(a)=2\%$

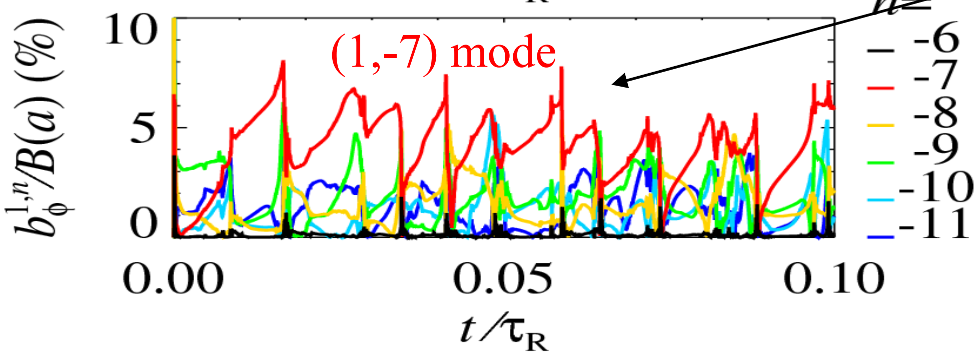
Typical RFP sawtoothing



RFP "sawtoothing" cycle

Mode amplitude

(1,-7) mode



Bonfiglio NF 2011
Veranda PPCF 2013
Bonfiglio PRL 2013

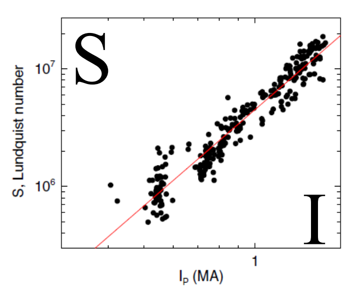
The amplitude of secondary modes decreases with Lundquist, S, and Hartmann H

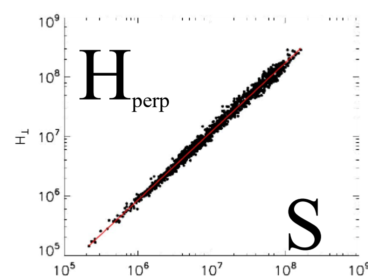
The threshold MP% to excite a dominant mode decreases with S (H) too,

... explains the experimental trend of the helical regime emerging clearly at high currents.

RFX-mod:
I ≥ 1MA
S ≥ 5 10^6

Piovesan, Zuin et al NF 2009





Vivenzi , Spizzo, Veranda, Bonfiglio, Cappello et al Theory Fusion Plamas Varenna 2022