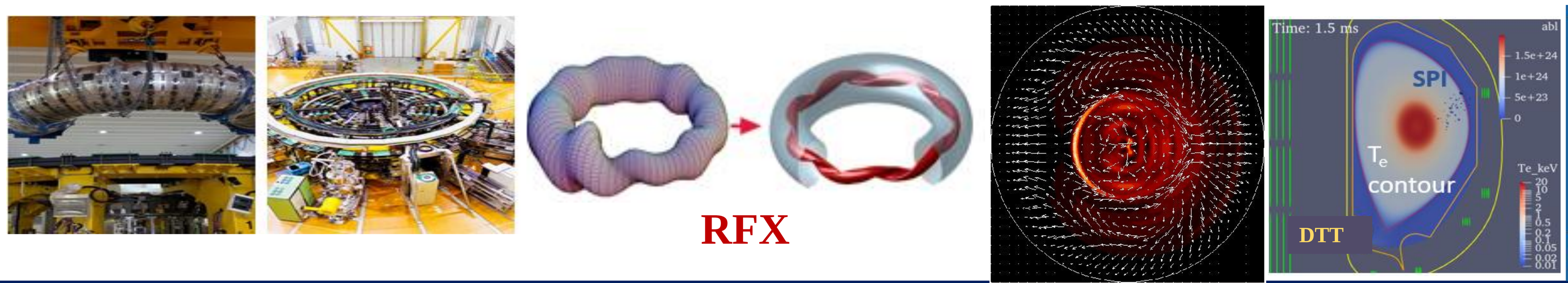

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3D nonlinear MHD studies at Consorzio RFX: Achievements and challenges in macroscopic modelling of fusion plasmas

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ABSTRACT

Macroscopic helical self-organization occur in pinch configurations:
Eminently in Reversed Field Pinches, and in Tokamak scenarios too, for example when dynamo/flux-pumping effects play a role.
Main achievements in 3D nonlinear MHD have been obtained within **visco-resistive full-MHD** (**SpeCyl and PIXIE3D codes**) [2,3]
i) Transition to Quasi Helical regimes in RFP (QSH)[6,7];
ii) Boundary Conditions extension toward realistic RFX-mod2 front-end (RFP and Tokamak) [10,11];
iii) Formation of Internal Transport Barriers in RFP (eITB), (Lagrangian Coherent Structures)[4,8];
iv) Large scale modes (dynamo/flux pumping effect), their control and characterization of plasma flow:
Magnetic Reconnection: RFPs and tokamaks, interplay with Alfvén waves (possible RFP ion heating mechanism) [9];
Then,
significant steps forward have been achieved within reduced-MHD **JOREK code** applications, important in view of DTT:
v) Assessment of **Shattered Pellet Injection to mitigate disruptions**, and comparison vs the MGI approach (extending JET applications [5,12]);
vi) Initial assessment about **ELM physics and correlation with 3D fields**. [13]

These lines of research are naturally interconnected with nonlinear MHD activities under EUROfusion (TSVV, WPTE) programmes.

References:
[1] 2025 NF Bonfiglio et al MHD, disruptions and control physics DOI 10.1088/1741-4326/adc7a0
[2] 1996 NF Cappello&Biskamp Reconnection processes and scaling laws in RFP MHD DOI 10.1088/0029-5515/36/5/I05
[3] 2010 PoP Bonfiglio et al Nonlinear 3D verification of the SPECYL and PIXIE3D MHD codes for fusion DOI 10.1063/1.3462908
[4] 2019 PPCF Pegoraro and Coherent magnetic structures in self-organized plasmas
[5] 2021 NF Hoelzl et al The JOREK non-linear extended MHD code and applications to large-scale instabilities and their control in magnetically confined fusion plasmas DOI 10.1088/1741-4326/abf99f
[6] 2004 PPCF Cappello Bifurcation in the MHD behaviour of a self-organizing system: the reversed field pinch DOI 10.1088/0741-3335/46/12B/027
[7] 2013 PRL Bonfiglio et al Experimental-like Helical Self-Organization in Reversed-Field Pinch Modeling DOI 10.1103/PhysRevLett.111.085002
[8] 2020 NF Veranda et al Helically self-organized regimes and magnetic chaos healing
[9] 2024 NF Kryzhanovskyy et al Global Alfvénic modes in ohmic tokamak following magnetic reconnection events
[10] 2024 PPCF Spinicci et al Impact of a free normal velocity boundary on external MHD modes
[11] 2026 ...
[12] 2026 Nucl Fus Bonfiglio et al "Validation of 3D MHD simulations of Ne/D2 mixed shattered pellet injection in JET" 2026 Nucl. Fusion 66 026014
[13] 2025-28 PhD project Calcagno "Modeling of ELM physics and correlation with 3D fields in view of DTT" (Consorzio RFX Supervisors: Bonfiglio and Pigatto)

Sections color code

- Introduction Experimental Motivation
- Toy model for helical self-organizationn
- SpeCyl numerical model 3D nonlinear visco-resistive MHD
- SpeCyl results for RFP
- SpeCyl results for Tokamak
- PIXIE3D & JOREK

Some open issues, Ongoing works:

Visco-Resistive 3D nonlinear MHD provides a fruitful global description of relaxation-reconnection features consistent with several aspects typical of both RFP and Tokamak configurations. Several aspects await for refined and extended modelling:

Upgrade toward realistic Boundary Conditions
Verification SpeCyl – PIXIE3D (Chacon-LosAlamos)
proof of principle studies on free-boundary modes
Spinicci, Bonfiglio et al, AIP Advances (2023), J. Plasma Phys. (2024)

Further develop analogies RFP – Tokamak
Alfven waves excitation at sawtoothing (ohmic)
Kryzhanovskyy,Bonfiglio et al, Nuclear Fusion 2022, Kryzhanovskyy, Bonfiglio et al, Nuclear Fusion 2024

Address momentum transport impact and estimate experimental effective Hartmann $H = (\nu\eta)^{-1/2}$
Momentum transport in plasmas is a longstanding open issue
Heuristic approach proposed in:
- *Terranova, Bolzonella, Cappello et al PPCF 2000*
Scaling of magnetic fluctuations in the RFX reversed field pinch
- *Vivenzi, Spizzo, Veranda et al, Theory Fusion Plasmas 2022 JPCS*
- *Vivenzi,Veranda, Cappello Bonfiglio PoP 2023*

What is the mechanism of "anomalous" ion heating in RFPs (observed at sawtoothing)?
Non resonant Alfvèn wave particle interaction
Veranda, Sattin et al in preparation

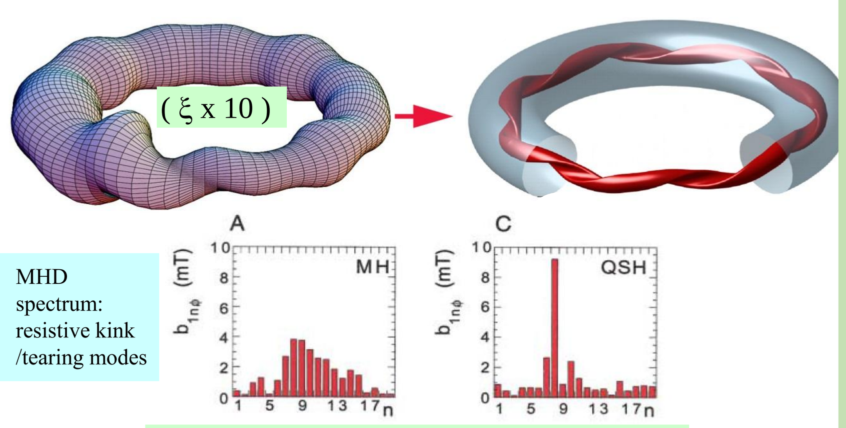
Assess magnetic topology characterization (and related transport) - Lagrangian Coherent Structures (LCS) validation on experimental eITB
follow up of Veranda et al, NF 2017

Extended modeling to be addressed with the 3D codes: PIXIE3D and, possibly, JOREK

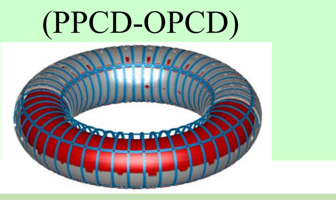
THIS CONFERENCE
L Carraro **Spettroscopia come finestra sul plasma: diagnosi e trasporto delle impurezze** 5 febbraio 10.40

INTRODUCTION

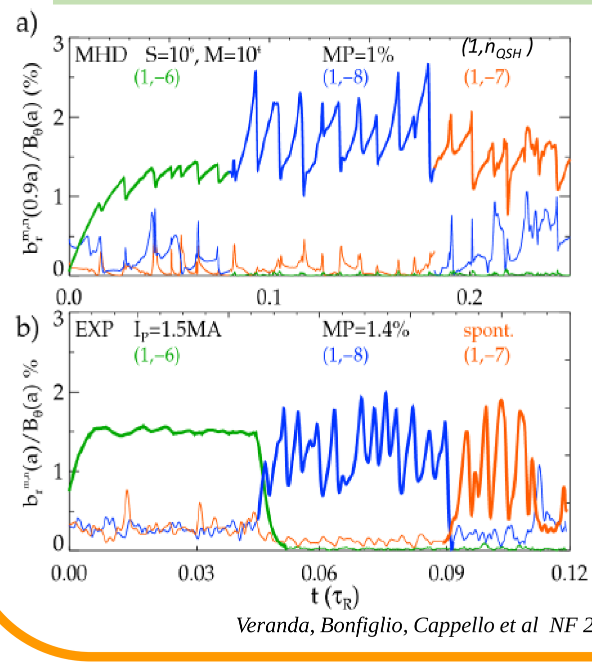
RFP experiments: at high current ↔ ordered KINKED plasma advanced operation with **Boundary Control**



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



SpeCyl: visco-resistive 3D nonlinear MHD code describes helical regimes

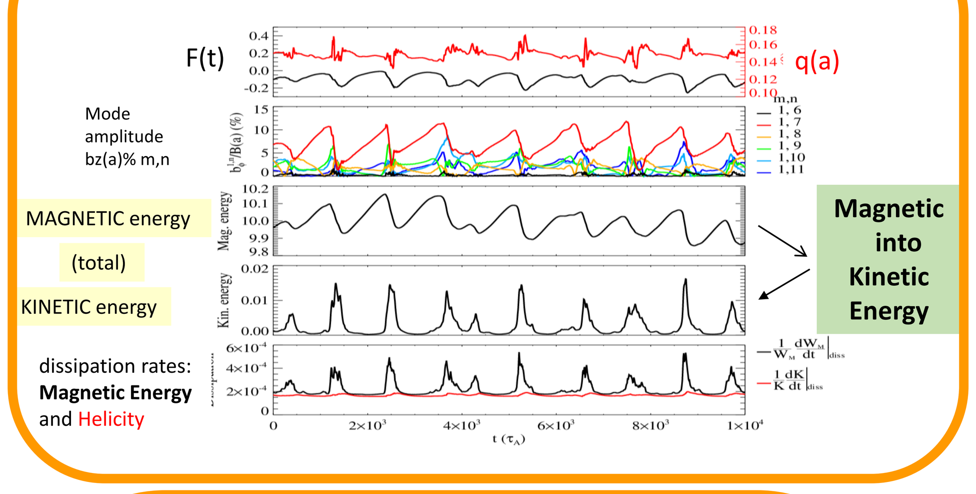


3D MHD nonlinear simulation MP assisted (SpeCyl)

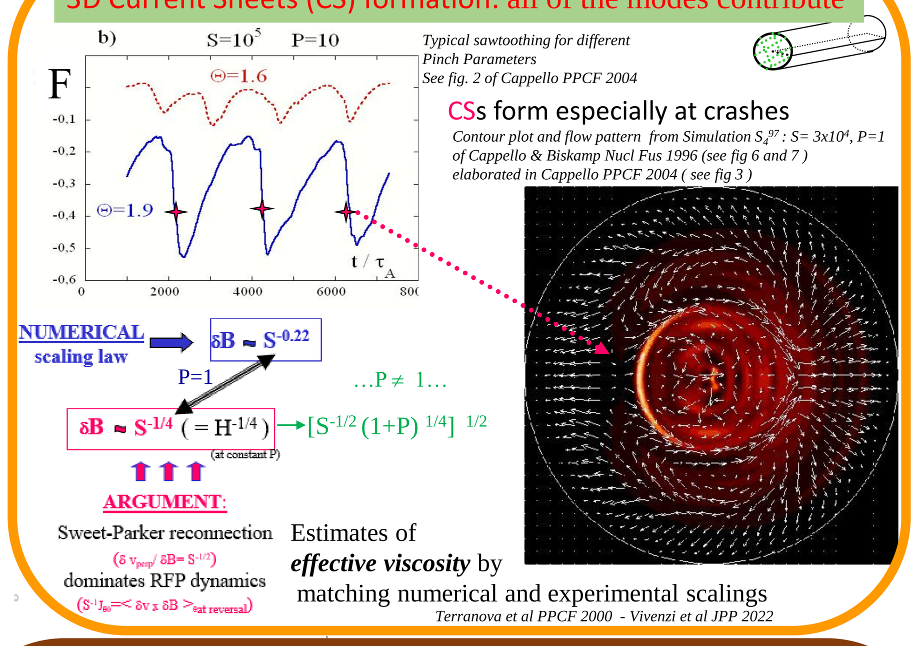
Successful RFX-mod experiments: alternative *ns* stimulated by seed MP

Veranda, Bonfiglio, Cappello et al NF 2017

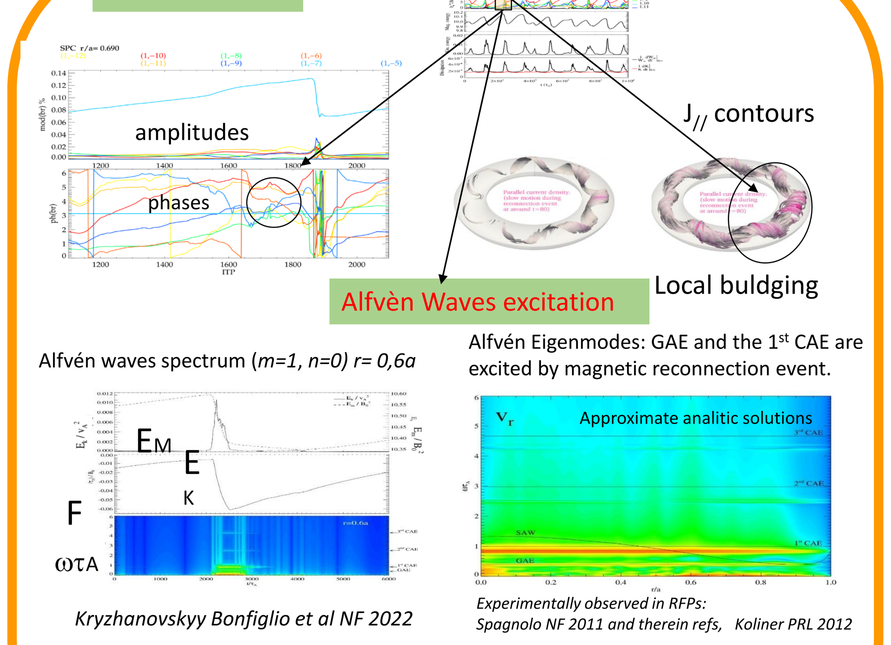
RFP SAWTOOTHING: nearly periodic relaxation – reconnection events



3D Current Sheets (CS) formation: all of the modes contribute



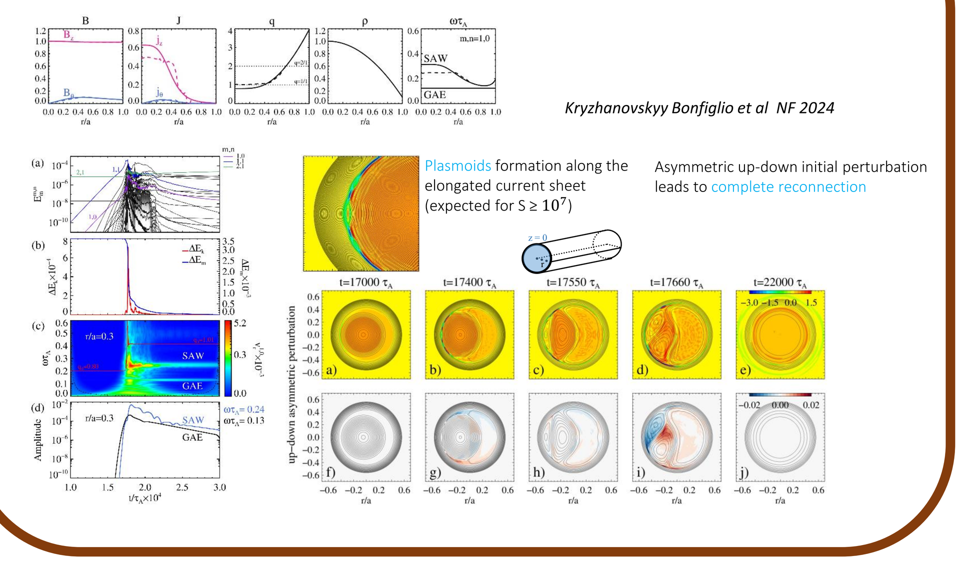
PHASE LOCKING



Stochastic ion heating mechanism under consideration
Heating mechanism frequently encountered in astrophysics.

Escande, D.F.; Gondret, V.; Sattin, F. Relevant heating of the quiet solar corona by Alfvén waves: adiabaticity breakdown https://www.nature.com/articles/s41598-019-50820-x

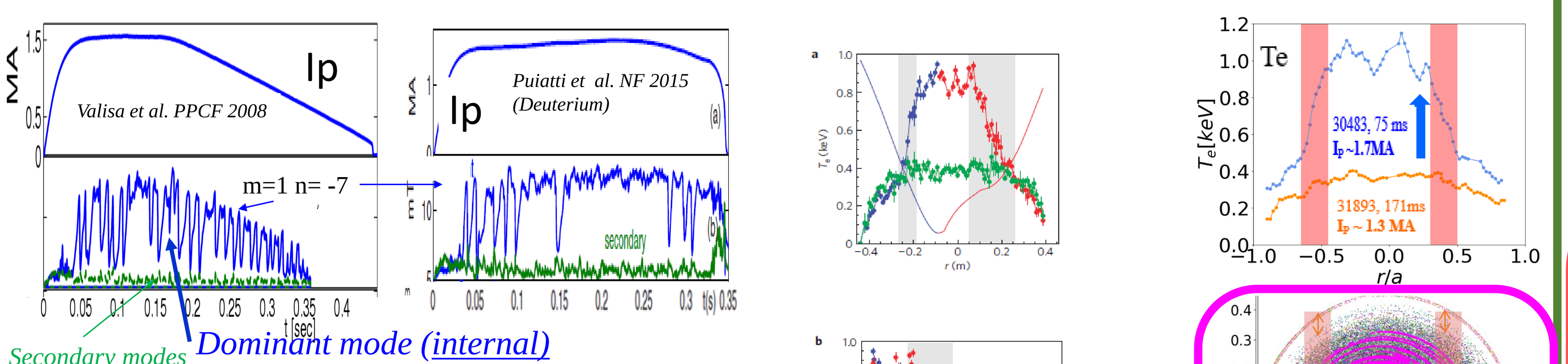
Reconnection-relaxation event in circular tokamak Plasmoids formation and Alfvèn Waves excitation — TOKAMAK



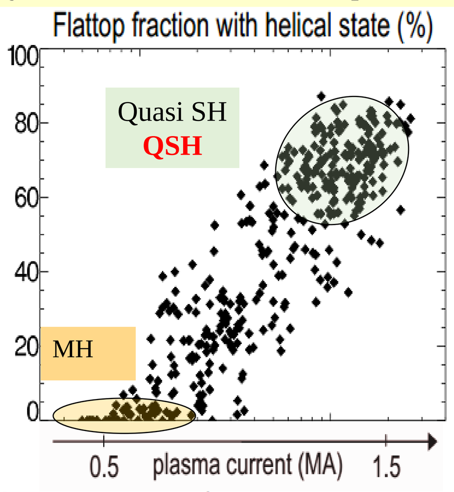
RFX-mod RFP OVERVIEW

Intermittent Quasi Helical Regimes develop at high Ip, when feedback coils scheme system aims at Br(a) = 0

T_e, n_e get a helical shape - eITB formation

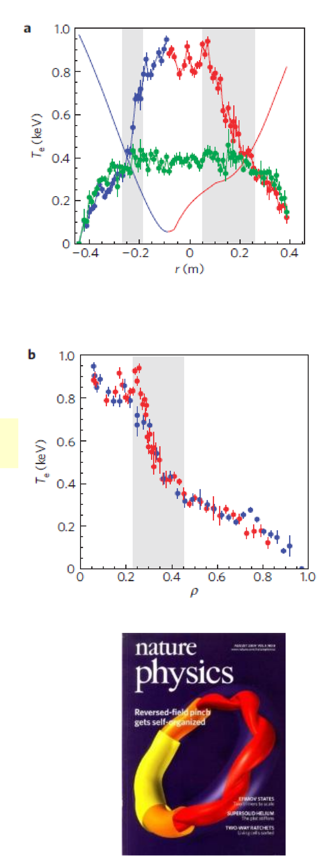


HELICAL persistency increases with current - up to 85% of flat top

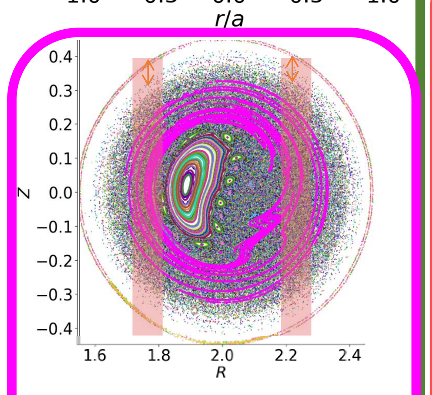


Piovesan et al NuclFus 2009

Similarly in MST experiment:
- Chapman et al IAEA EX/P6-01 (2012)
- Sarff et al NF (2013)



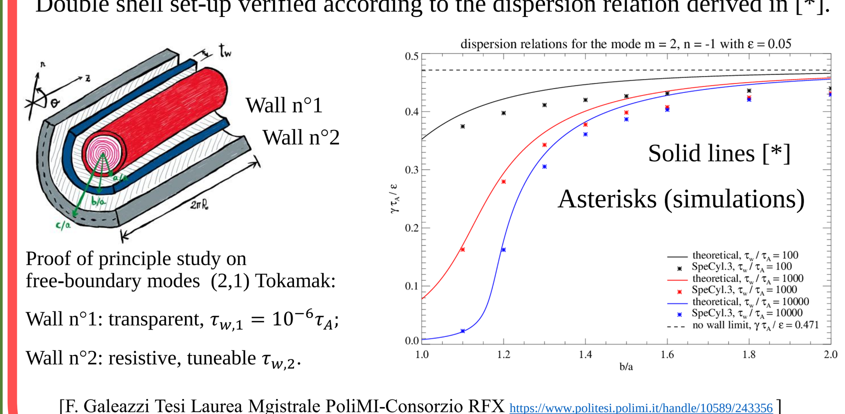
Lorenzini et al NatPhys 2009



LCSs are structures representing a robust hidden skeleton able to organize the dynamics of turbulent/stochastic dynamical systems [4,8]

SpeCyl - BC upgrade toward realistic RFX-mod front-end

Double shell set-up verified according to the dispersion relation derived in [*].



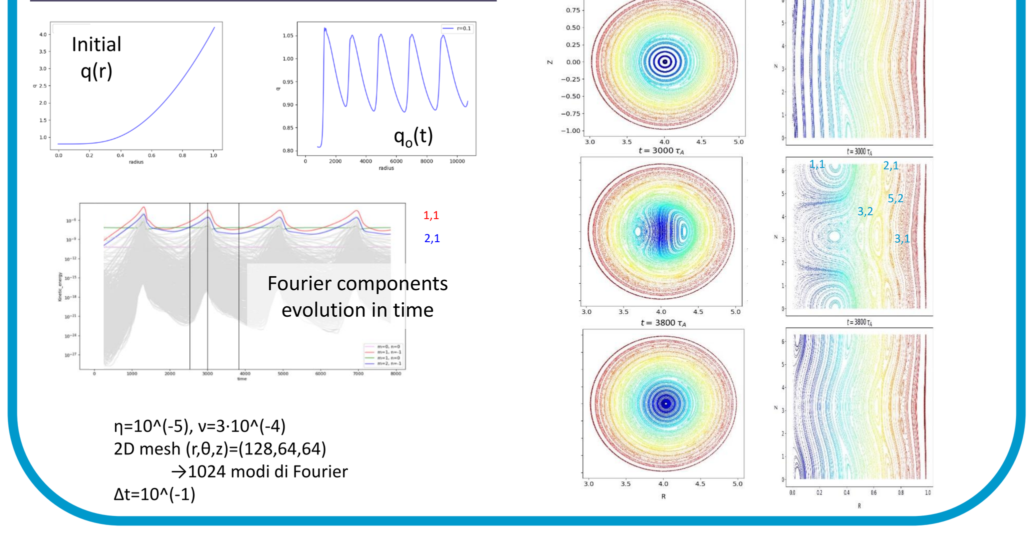
Proof of principle study on free-boundary modes (2,1) Tokamak:
Wall n°1: transparent, $\tau_{w,1} = 10^{-6}\tau_A$;
Wall n°2: resistive, tuneable $\tau_{w,2}$.

[F. Galeazzi Tesi Laurea Magistrale PoliMI-Consorzio RFX https://www.politesi.polimi.it/handle/10589/243356]

[*] Y. Liu, Albanese, Portone, Rubinacci, Villone. *An analytical demonstration of coupling schemes between magnetohydrodynamic codes and eddy current codes*. PoP (2008)

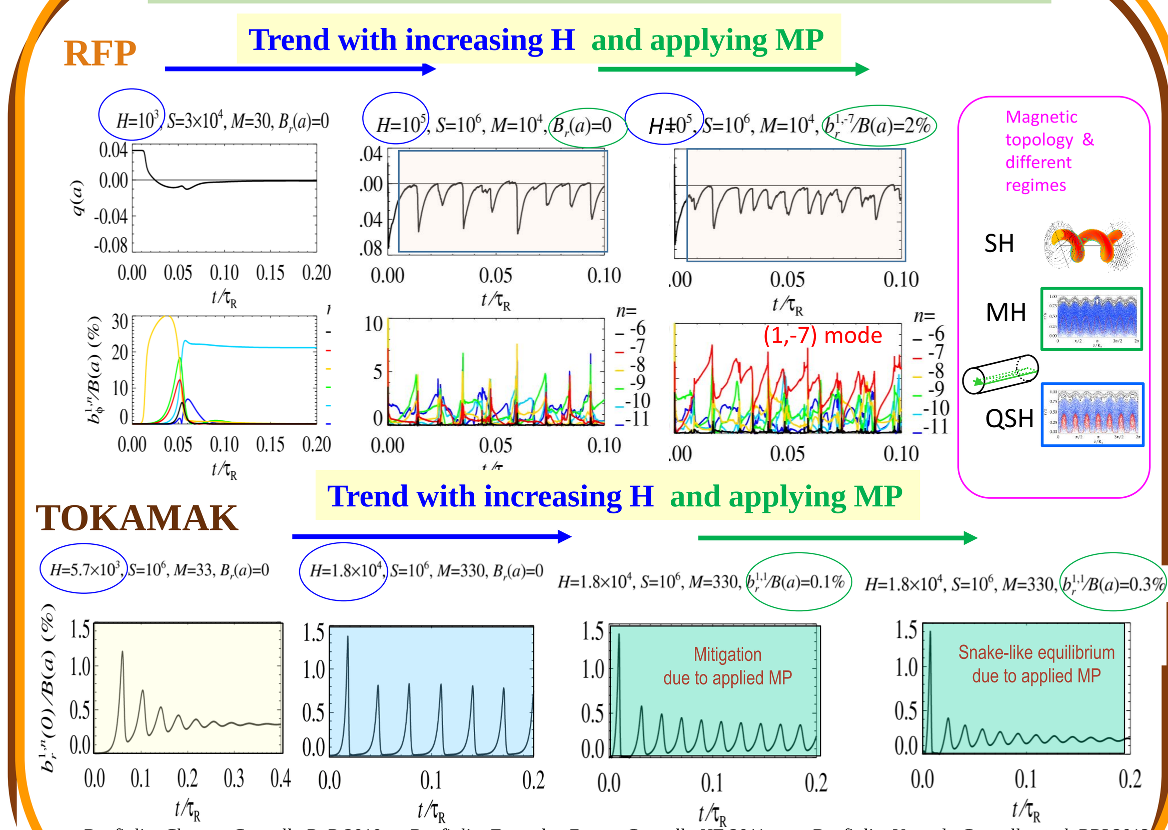
PIXIE3D toroidal geometry R/a =4

Tokamak Sawtooth visco-resistive approx.



η=10^(-5), ν=3·10^(-4)
2D mesh (r,θ,z)=(128,64,64)
→1024 modi di Fourier
Δt=10^(-1)

sawtooth cycle (both RFP & Tokamak) … and its MP- pacing

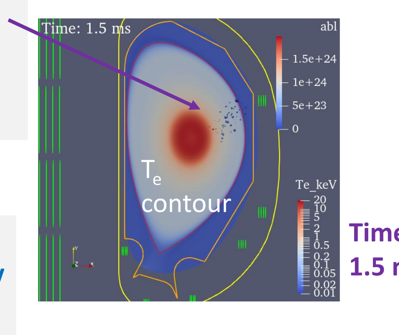


Bonfiglio, Chacon, Cappello PoP 2010 Bonfiglio, Escande , Zanca, Cappello NF 2011 Bonfiglio, Veranda Cappello et al PRL2013
Bonfiglio, Veranda , Cappello et akl PRL 2013 https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.111.085002
Bonfiglio Veranda Cappello et al et al PPCF 2015 https://iopscience.iop.org/article/10.1088/0741-3335/57/4/044001/meta

JOREK DTT - SPI

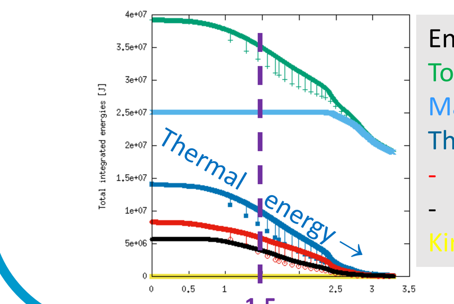
Work performed under the DTT activity area:
"Disruption Mitigation and Simulation" PHY-MHD-DMS

SPI fragments cool down the plasma along their path



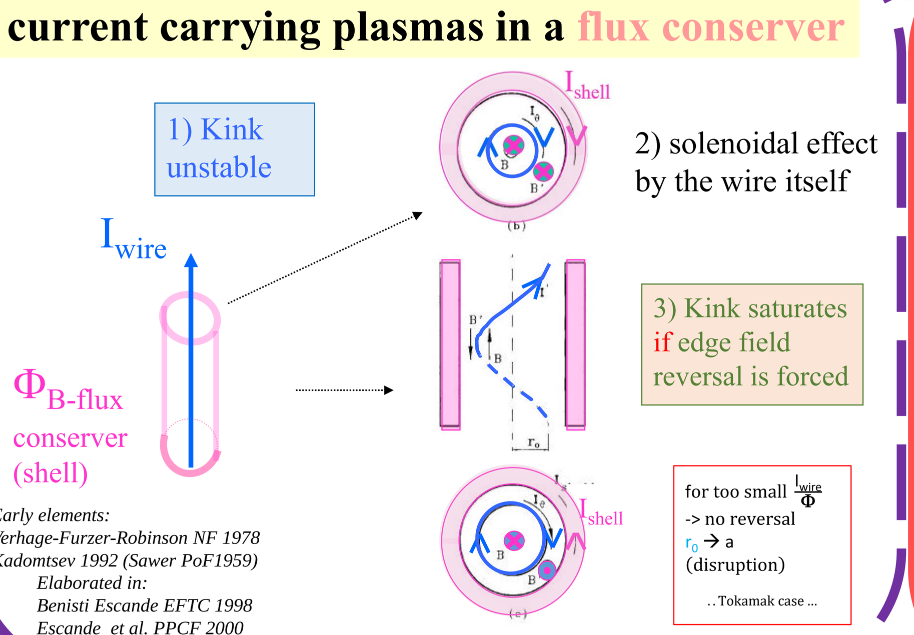
Time: 1.5 ms

… until most of **thermal energy** is radiated in a few ms



Energies:
Total
Magnetic
Thermal (total)
- Electron
- Ion
Kinetic

Toy model: the natural kinking of the current carrying plasmas in a flux conserver

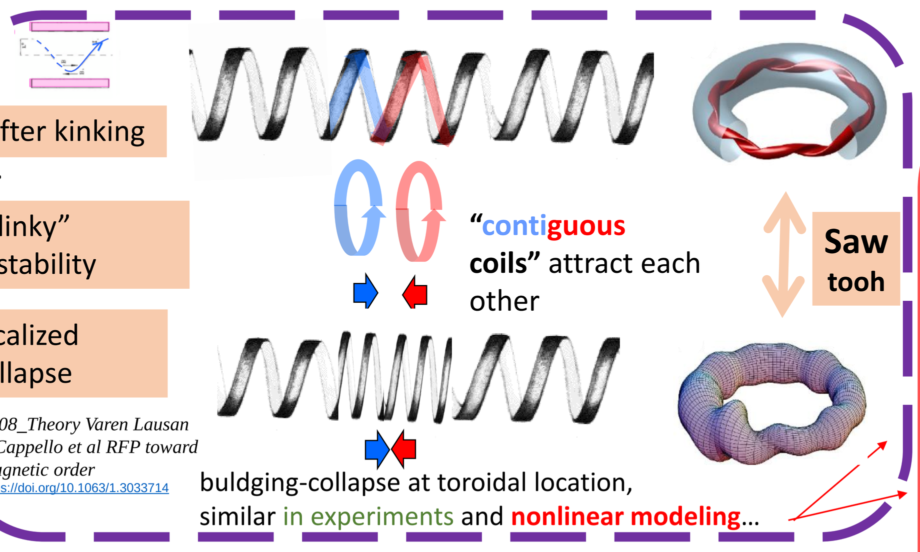


Early elements:
Verhage-Furzer-Robinson NF 1978
Kadomtsev 1992 (Sawer PoF1959)
Elaborated in:
Benisti Escande EFTC 1998
Escande et al. PPCF 2000
2008_Theory Varen Lausan _ Cappello et al RFP toward magnetic order

After kinking …

"slinky" instability

localized collapse



2008_Theory Varen Lausan _ Cappello et al RFP toward magnetic order
https://doi.org/10.1063/1.3033714

buldging-collapse at toroidal location, similar in experiments and nonlinear modeling…

Some additional references from ECMRP 2025 ->

Mini-Divulgazione
3 minuti youtube

3D nonlinear MHD

SpeCyl code visco-resistive approx.

Cappello & Biskamp Nucl. Fus. 1996

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

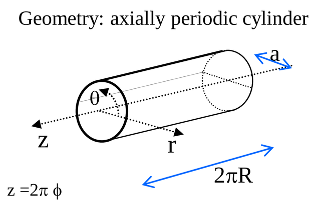
$$\frac{d\boldsymbol{v}}{dt} = \boldsymbol{J}\wedge\boldsymbol{B} + \nu\,\nabla^2\boldsymbol{v}$$

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

$\eta = \tau_A/\tau_R$
Lundquist: $S = 1/\eta$
Viscous Lundquist $M = 1/\nu$
$\nu = \tau_A/\tau_\nu$

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

Geometry: axially periodic cylinder



aspect ratio R/a= 4 (RFX)

"typical" boundary conditions:
- B'z =0 (**constant magnetic flux Φ**)
- Constant Ez
  - m,n: Ideal boundary
  - **MP on Br** $_{m,n}$ (~ 1%, 2%, 4 %.)
  - Thin shell +vacuum +idealwall
- velocity field: no slip.

initial conditions decide Φ, Iz

Model equations transformed: **The Hartmann number**

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

(S , M) → (η , ν) → (**H** , P)

Prandtl_mag $P = \nu/\eta = S/M$
Hartmann $H = (\nu\eta)^{-1/2}$

H regulates both current density and momentum diffusion

H measures the relative weight of:
- electromagnetic Lorentz forces
- visco-resistive friction
Governs the balance between
- nonlinear mode coupling and
- damping / smoothing
yielding the actual spectral broadening of MHD activity, excited by linear instability or external means (RMP)

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

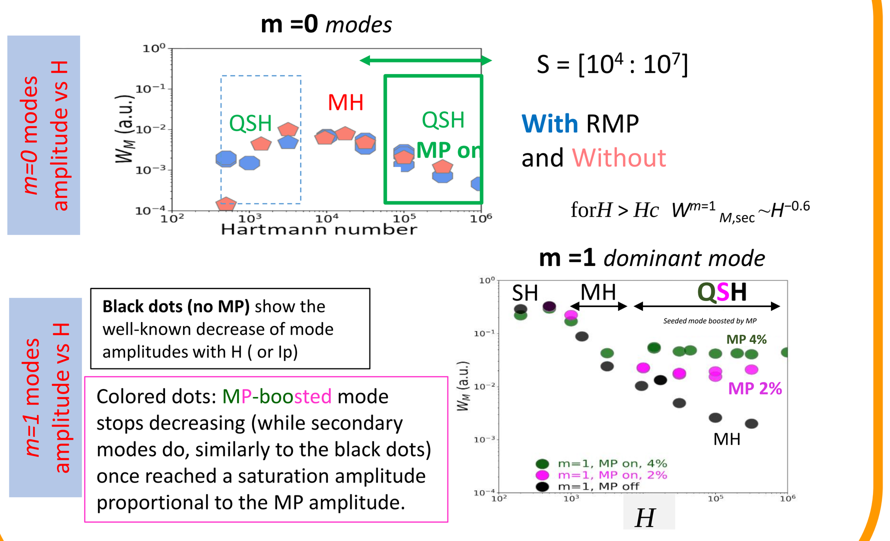
$$\frac{1}{P}\frac{d\bar{v}}{d\bar{t}} = \bar{J}\wedge\bar{B} + \nabla^2(H^{-1}\,\bar{v})$$

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

***H* rules the amplitude of the nonlinearly driven m=0 modes**

Cappello PPCF 2004
Cappello & Escande PRL 2000 (nonlinear)
Montgomery et al. PPCF 92-93 (linear)

The MP threshold needed to excite a QSH regime decreases with H, i.e. with increasing plasma current, as observed in experiments.



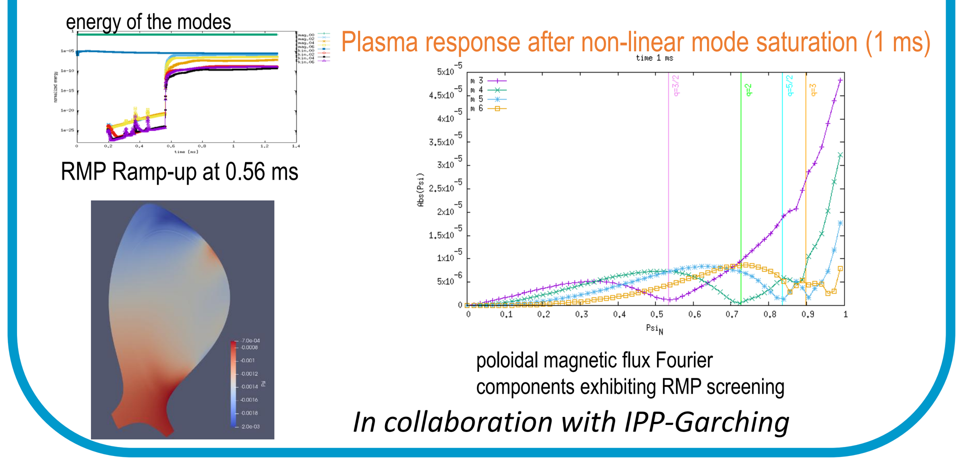
Black dots (no MP) show the well-known decrease of mode amplitudes with H (or Ip)

Colored dots: MP-boosted mode stops decreasing (while secondary modes do, similarly to the black dots) once reached a saturation amplitude proportional to the MP amplitude.

Veranda, Bonfiglio Cappello et al NF 2020 *Cappello et al IAEA 2020 FEC TH/P7-12 (2021)*
https://conferences.iaea.org/event/214/papers/17659/files/8536-Manuscript_IAEA_FT_v22.pdf

JOREK Preliminary study in preparation of DTT – RMP ELM mitigation

ASDEX Upgrade equilibrium [Willensdorfer and Mitterauer, Nature 2024]



poloidal magnetic flux Fourier components exhibiting RMP screening

In collaboration with IPP-Garching