3D magnetic reconnection, mode locking, and flow in reversed-field pinch and tokamak

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RFX-mod Team

we thank D.F. Escande for many discussions

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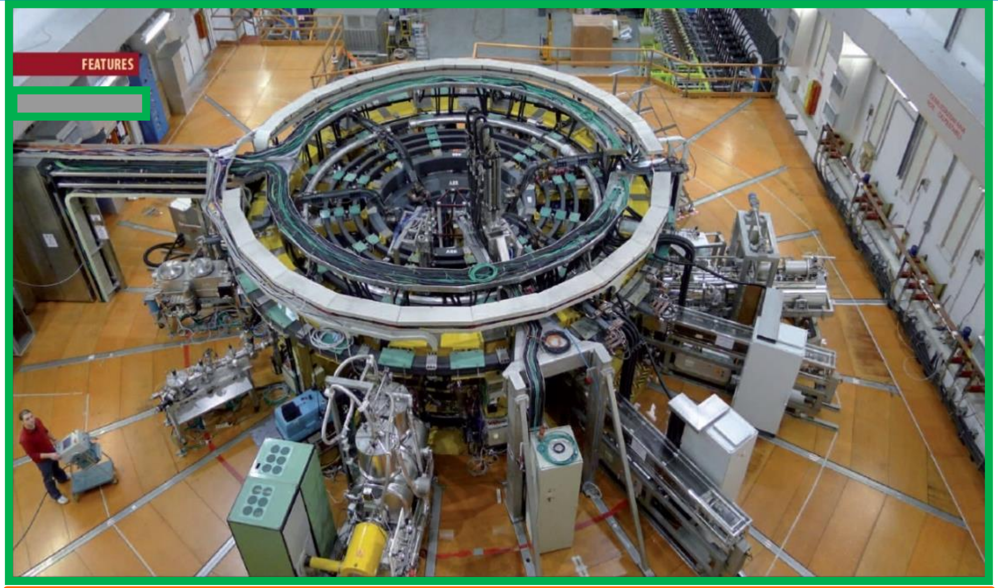
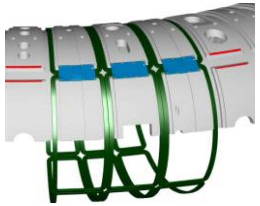
the RFX-mod2 device in Padova → an upgrade of RFX-mod (2004-2015)



in RFX-mod advanced active-feedback control system of MHD modes, allows



- I_P to increase up to 2MA with $B_\phi \sim 0.55$ as an RFP
- $I_P \sim 0.1$ MA with $B_\phi \sim 0.55$ as a tokamak
- temperature above 1keV;

leading to development of **quasi helical regimes, QSH**

in RFX-mod2 plasma closer to passive shell, with likely improvement of feedback coils action.

Expected a reduction of perturbations to the helical state [a, b, c, d]

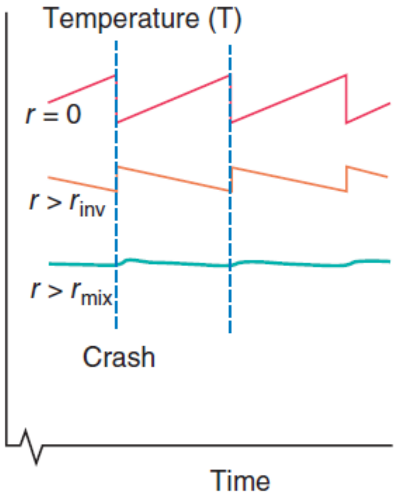
$$R_0 = 2\mathrm{m}$$
$$a = 0.45\mathrm{m}$$
$$B_\phi^{ext,max} = 0.7\mathrm{T}$$
$$n_e = [10^{19}\colon 10^{20}]\mathrm{m}^{-3}$$

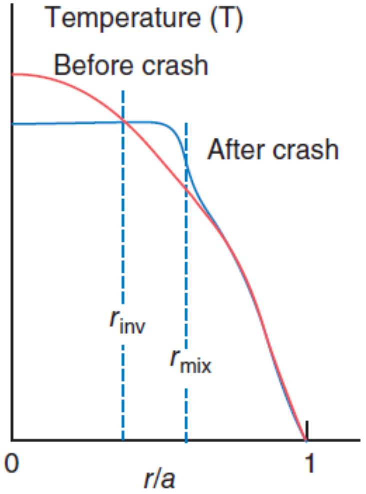
Other RFPs: MST (US) RELAX (JP) KTX (CN) EXTRAP T2R (EU)

[a] Sonato et al, **FED** (2003)
[b] Marrelli et al, **PPCF** (2007)
[c] Peruzzo et al, **FED** (2019)
[d] Marrelli et al, **NF** (2021)

associated with “sawtoothing” and with bursts in MHD activity:

sawtooth[1] refers to MHD initiated plasma reorganization events, sometimes called “discrete dynamo event” or “relaxation events”, which may lead to saturated helical structures involved in the so-called “flux pumping” [2,3] effect (the saturated mode generates an axisymmetric loop voltage causing a redistribution of central current and magnetic fluxes).



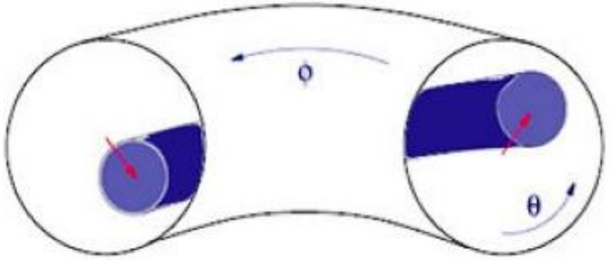


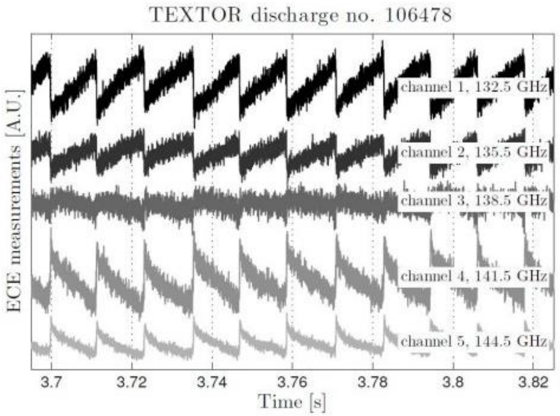
underlying mechanism: internal kink mode, driven by current gradients, influenced by resistivity, viscosity, finite ion Larmor radius, energetic particles. See Hender et al NF 47 (2007)

[1] Porcelli, Boucher, Rosenbluth **PPCF** 38 (1996)
[2] Piovesan, Bonfiglio et al, **NF** 57 (2017)
[3] Jardin, Krebs, Ferraro **PoP** 27 (2020)
[5] Chapman **PPCF** 53 (2011)
[4] Borgogno, Grasso, Porcelli et al **PoP** 12 (2005)

picture from Zohm Magnetohydrodynamic Stability of Tokamaks (2015) Wiley

m=1 n=1 internal kink mode



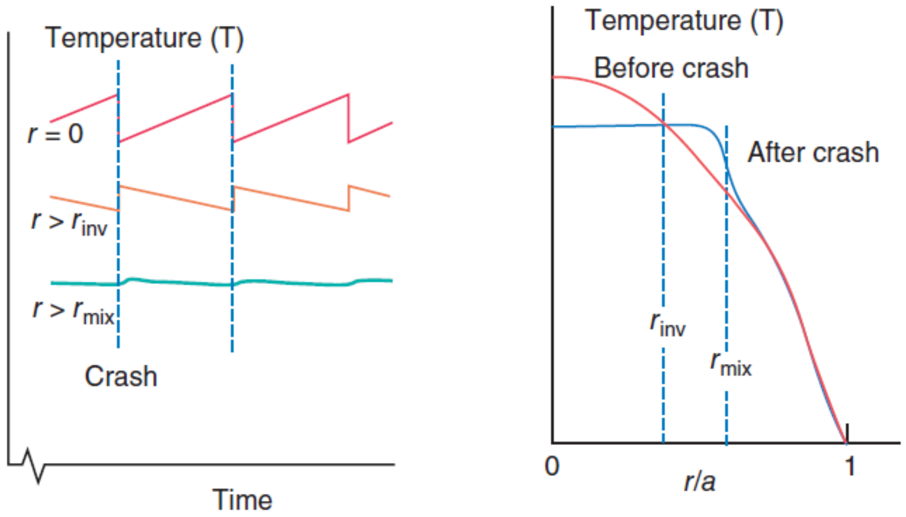


picture from Ian T. Chapman
Sawtooth Instability
https://link.springer.com/chapter/10.1007/978-3-662-44222-7_4

reconnections in current carrying plasmas (tokamaks, RFPs) are ubiquitous

associated with "sawtoothing" and with bursts in MHD activity:

Small sawteeth can benefit the plasma, large ones result in serious losses of plasma energy and confinement degradation. Modelled since a long time [1,2,3, 4], advancements in controlling it [5]



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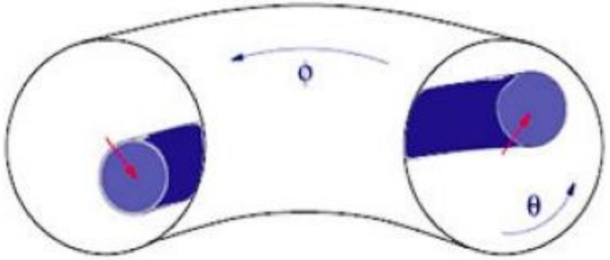

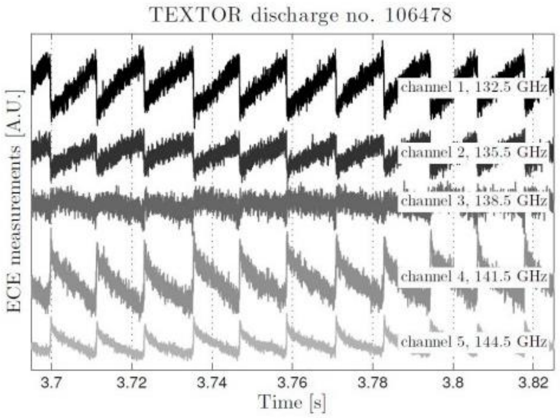

picture from Ian T. Chapman
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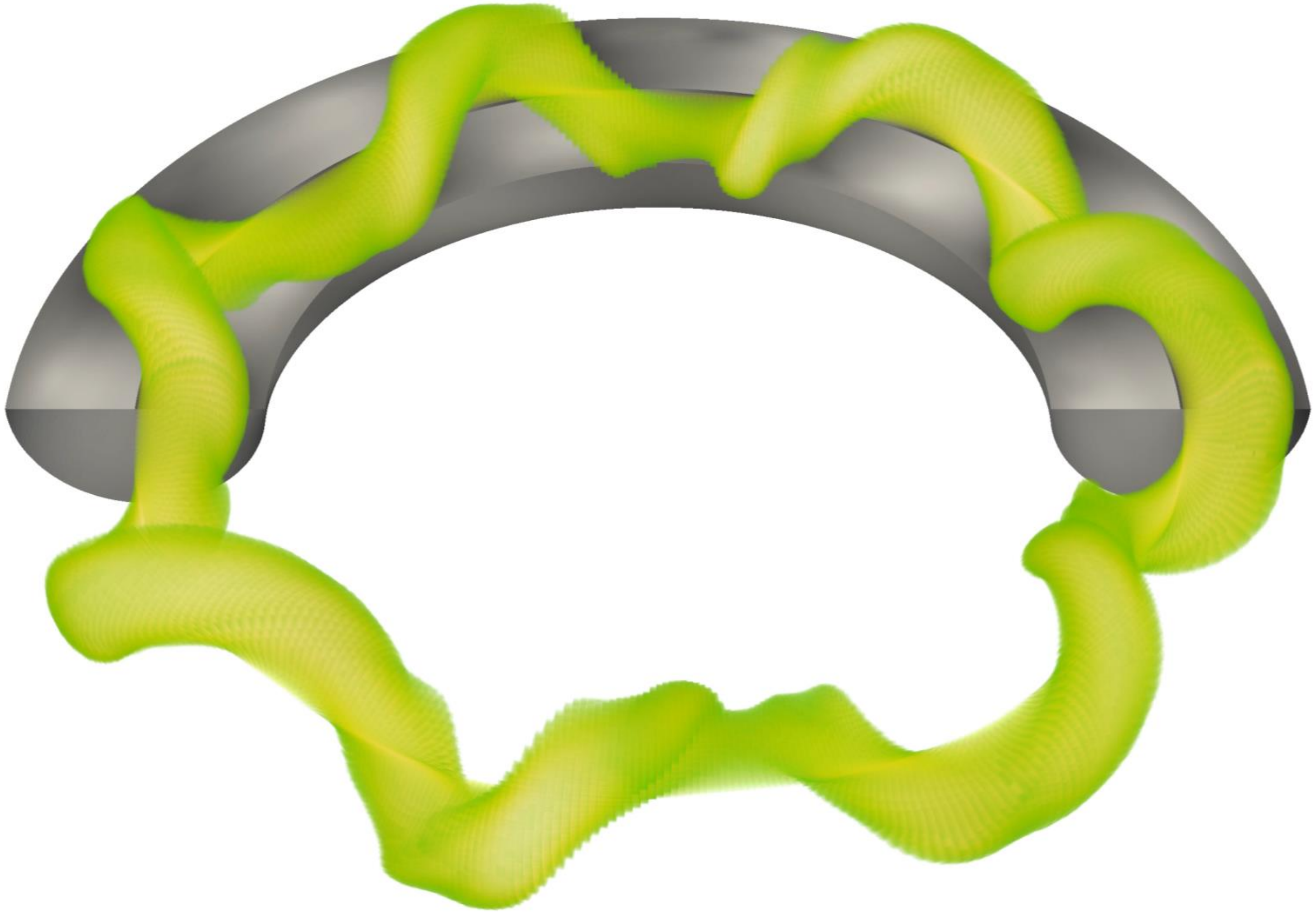
sawtoothing also in RFPs: the relatively higher plasma current causes one MHD instability to saturate and sustain a Quasi-Single Helicity state



contour plot B_r

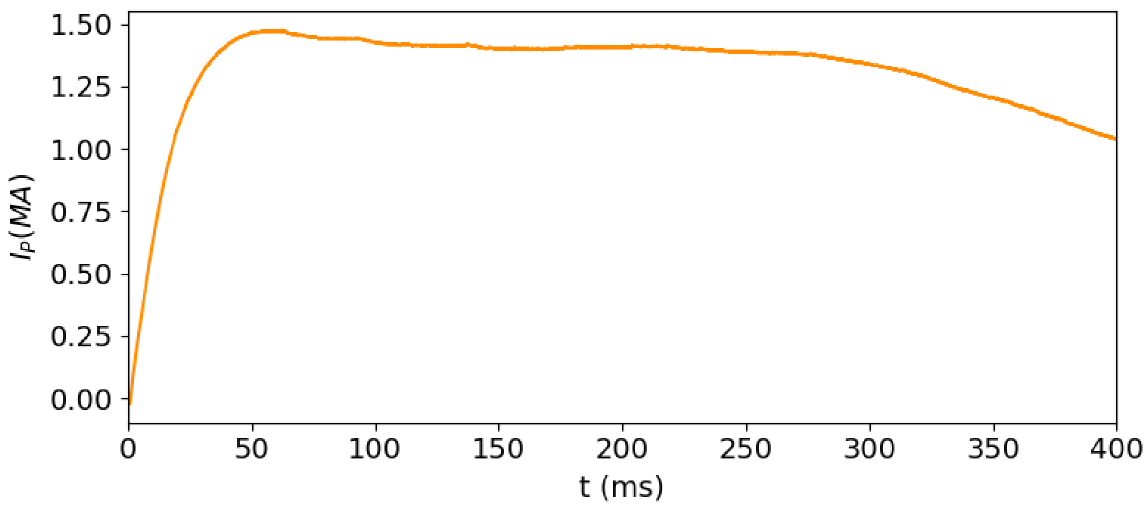
$m = 1, n = 7$
in Fourier space

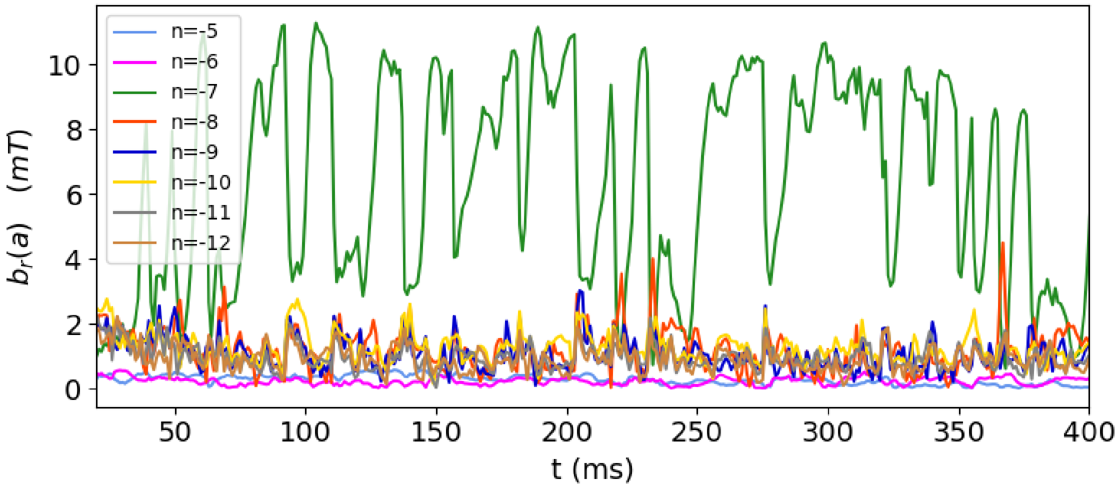
$$\frac{I_P}{\Phi_t}^{RFP} \sim 10 \frac{I_P}{\Phi_t}^{TOK}$$

RFP is more self-organized

best Quasi Helical States (QSH) in RFX-mod: a single MHD mode dominates the Fourier spectrum of physical quantities

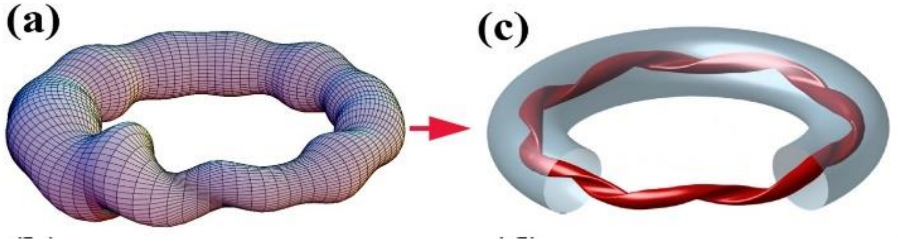
shot #37537





theoretical-numerical studies showed the possibility for the plasma to spontaneously develop a helical configuration, corresponding to a saturated kinked plasma column

increase of magnetic order



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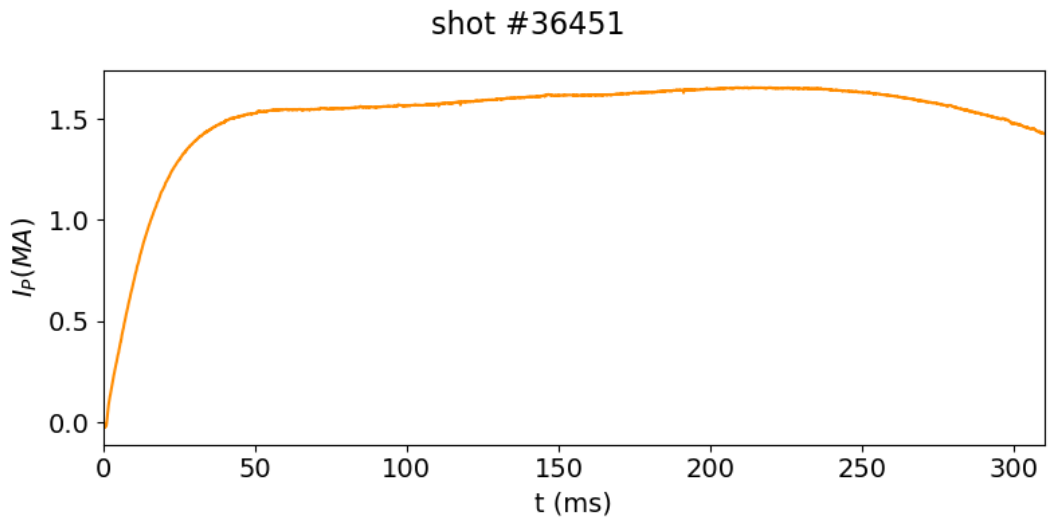

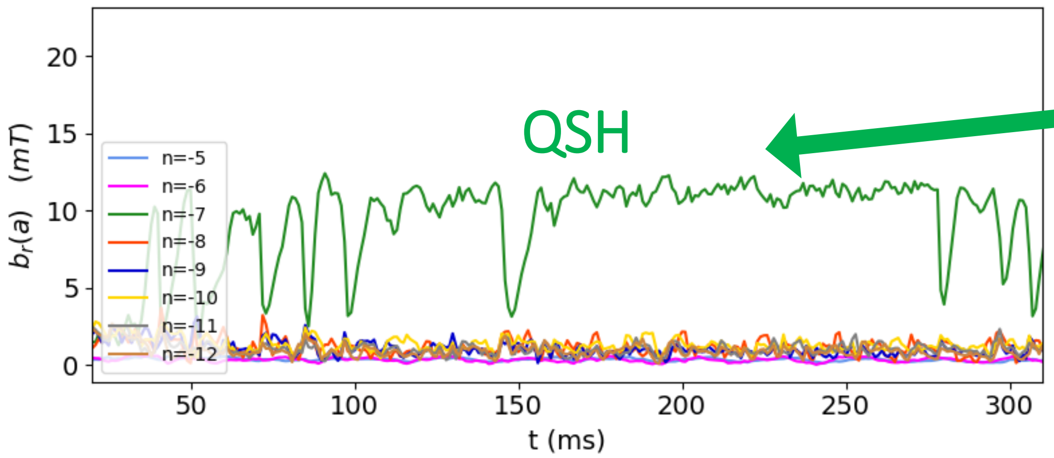

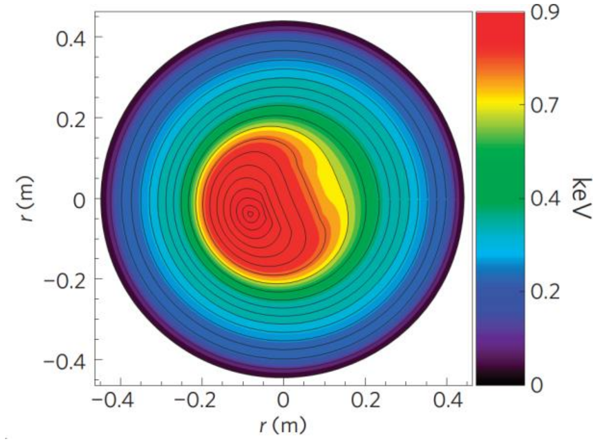

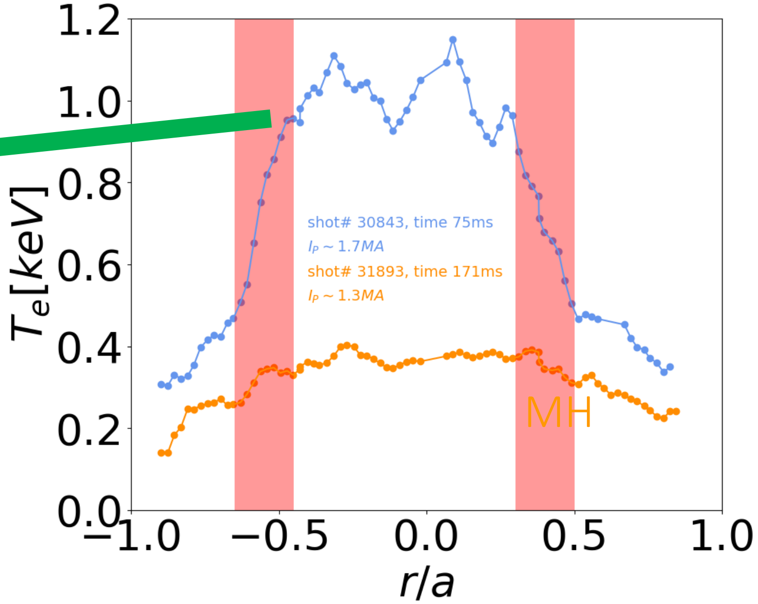

[1] Lorenzini et al **Nature Physics** (2009)
[2] Zuin, Vianello, Spolaore et al **PPCF** 51 (2009)
[3] Puiatti et al **PPCF** 51 (2009)
[4] Gobbin et al **PPCF** 55 (2013)
[5] Momo et al **NF** 60 (2020)
[6] Porcu Spizzo et al **PoP** 31 (2024)

OUTLINE

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- Modelling methods: 3D nonlinear visco-resistive MHD
- features of the reconnection
  - conversion of magnetic to kinetic energy
  - a localized locking of MHD modes
  - observed as asymmetries of various plasma quantities
  - resulting in “current sheets” and forces that tend to destroy the helical state
- consequences of the reconnection events are:
  - coalescence of helixes and the role of plasma flow
  - excitation of Alfvén waves, with the possibility of particles energization
  - effects on magnetic topology, stochasticity, Lagrangian Coherent Structures
- strategies to control, penalize, favor reconnection events
- FINAL REMARKS

Numerical tools can describe and predict experimental behaviour

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MAIN NUMERICAL TOOLS EMPLOYED:

- nonlinear 3D MHD visco-resistive approximation:
  SpeCyl [1] - PIXIE3D [2] (benchmarked codes) [3]
- magnetic field lines integration:
  NEMATO [4] (benchmarked vs ORBIT code [5])

$$\rho(\partial_t \boldsymbol{v} + \boldsymbol{v} \cdot \nabla \boldsymbol{v}) = \boldsymbol{J} \times \boldsymbol{B} + \frac{1}{M} \nabla^2 \boldsymbol{v}$$

$$\partial_t \boldsymbol{B} = \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B} - \frac{1}{S} \boldsymbol{J})$$

$$\nabla \times \boldsymbol{B} = \boldsymbol{J}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

all the numerical codes in our suite have been numerically verified [3,5,6]

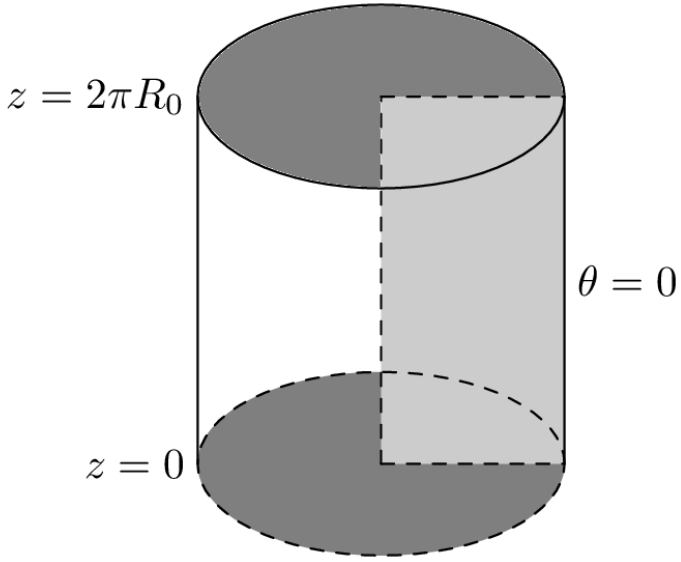
[1] Cappello, Biskamp **NF** (1996)
[2] Chacòn **CPC** (2004), Chacòn **PoP** (2008)
[3] Bonfiglio, Chacòn, Cappello **PoP** (2010)
[4] Finn, Chacòn **PoP** (2005)
[5] Ciaccio, Veranda, et al **PoP** (2013)
[6] Veranda et al **NF** (2017), **NF** (2019)

3D nonlinear visco-resistive MHD

- numerically solved by SpeCyl [a]
- main approximations:
  - cylindrical geometry
  - neglected pressure force and density evolution
  - resistivity and viscosity fixed in time

Boundary conditions for B field: ideal wall / Magnetic Perturbations (MP): helical boundary conditions at domain edge [b]

Boundary conditions for V field: no slip



$$\rho(\partial_t \boldsymbol{v} + \boldsymbol{v} \cdot \nabla \boldsymbol{v}) = \boldsymbol{J} \times \boldsymbol{B} + \frac{1}{M} \nabla^2 \boldsymbol{v}$$

$$\partial_t \boldsymbol{B} = \nabla \times \left(\boldsymbol{v} \times \boldsymbol{B} - \frac{1}{S} \boldsymbol{J}\right)$$

$$\nabla \times \boldsymbol{B} = \boldsymbol{J}$$

$$\nabla \cdot \boldsymbol{B} = 0$$

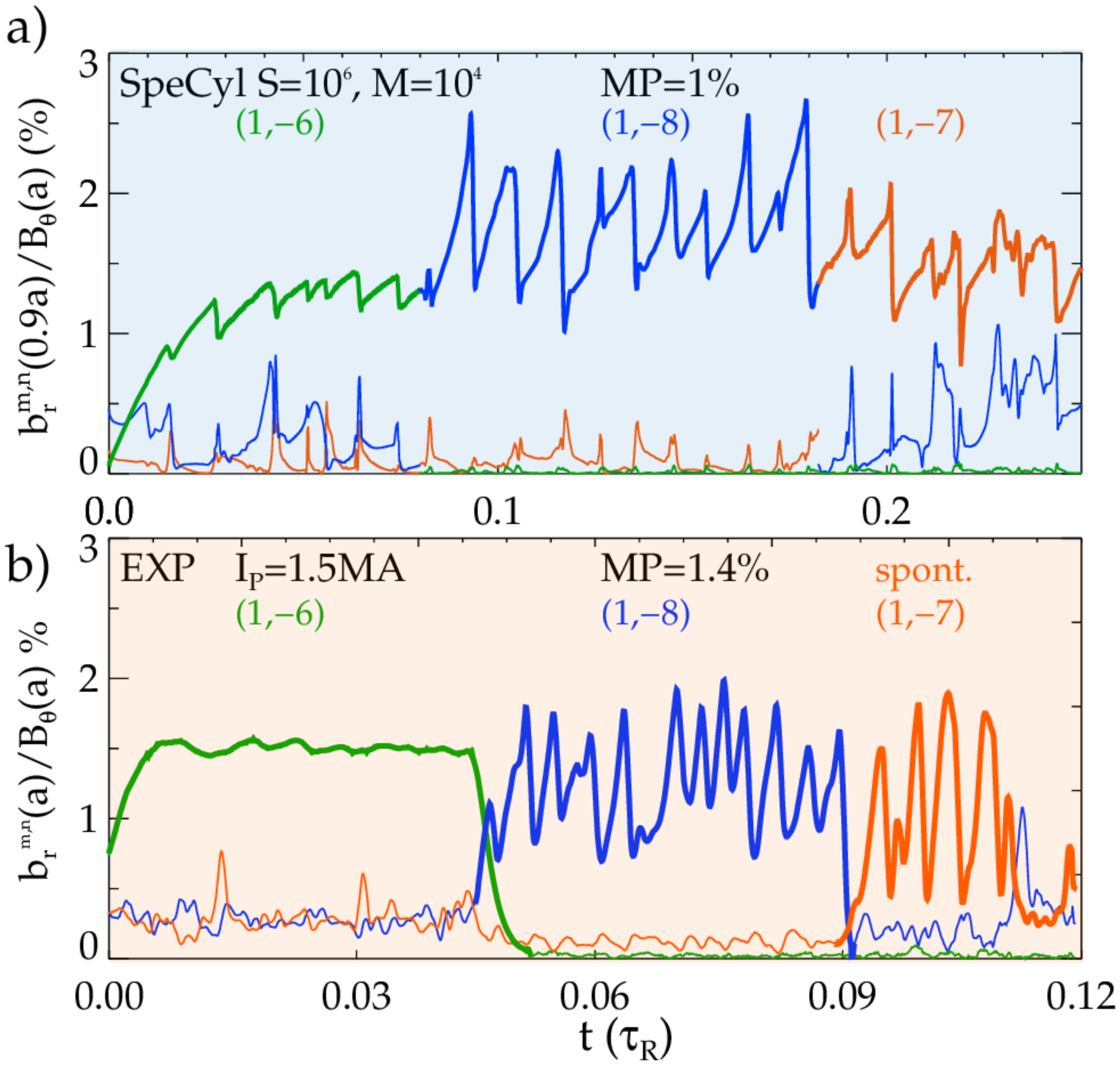
The Hartmann number

$$H = (SM)^{1/2}$$

rules the MHD dynamics of RFP [1, 2, 3, 4, 5]

[1] Cappello et al, **NF** (1996)
[2] Bonfiglio et al, **NF** (2011)
[3] Bonfiglio, Chacòn, Cappello **PoP** (2010)
[4] Ciaccio, Veranda, et al **PoP** (2013)
[5] Veranda et al **NF** (2019)

experiments confirm 3D MHD predictions



SpeCyl-code [1]

$S = 10^6$

$M = 10^4$

RFX-mod

$S \sim 2 \cdot 10^7$

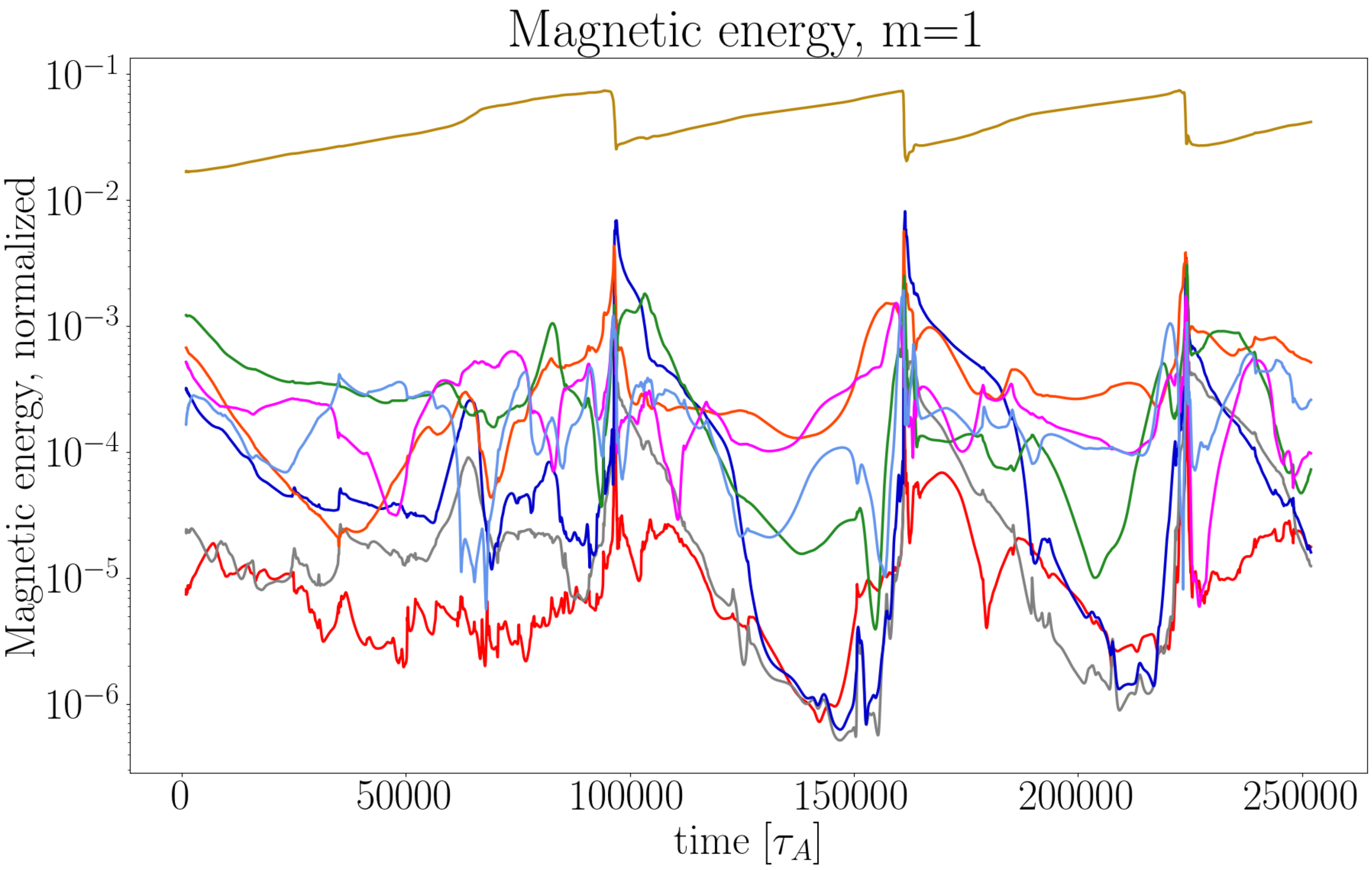
$M \sim 10^3 : 10^7$

shot #30932

$n_e = 3 \cdot 10^{19} m^{-3}$

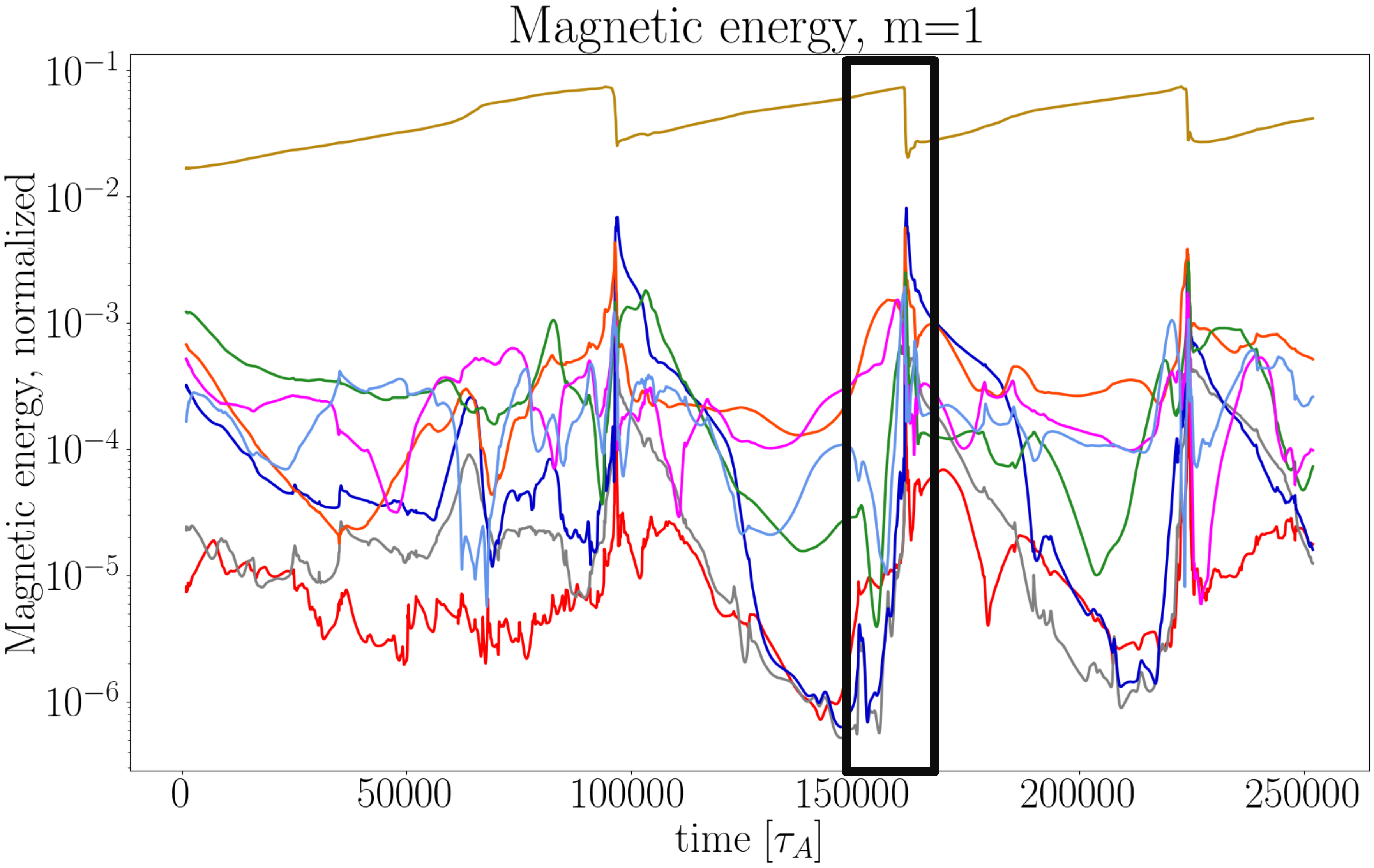
[1] Veranda, Bonfiglio, Cappello et al **NF** (2017)

RFP sawtoothing: similar to tokamak, mutatis mutandis



$$S = \frac{1}{\eta} = 10^7$$
$$M = \frac{1}{\nu} = 10^4$$
$$H = \sqrt{SM} = 3.1 \cdot 10^5$$
$$n_{MP} = -7,$$
$$MP = 4\%$$

RFP sawtoothing: similar to tokamak, mutatis mutandis



$\mathcal{M}$

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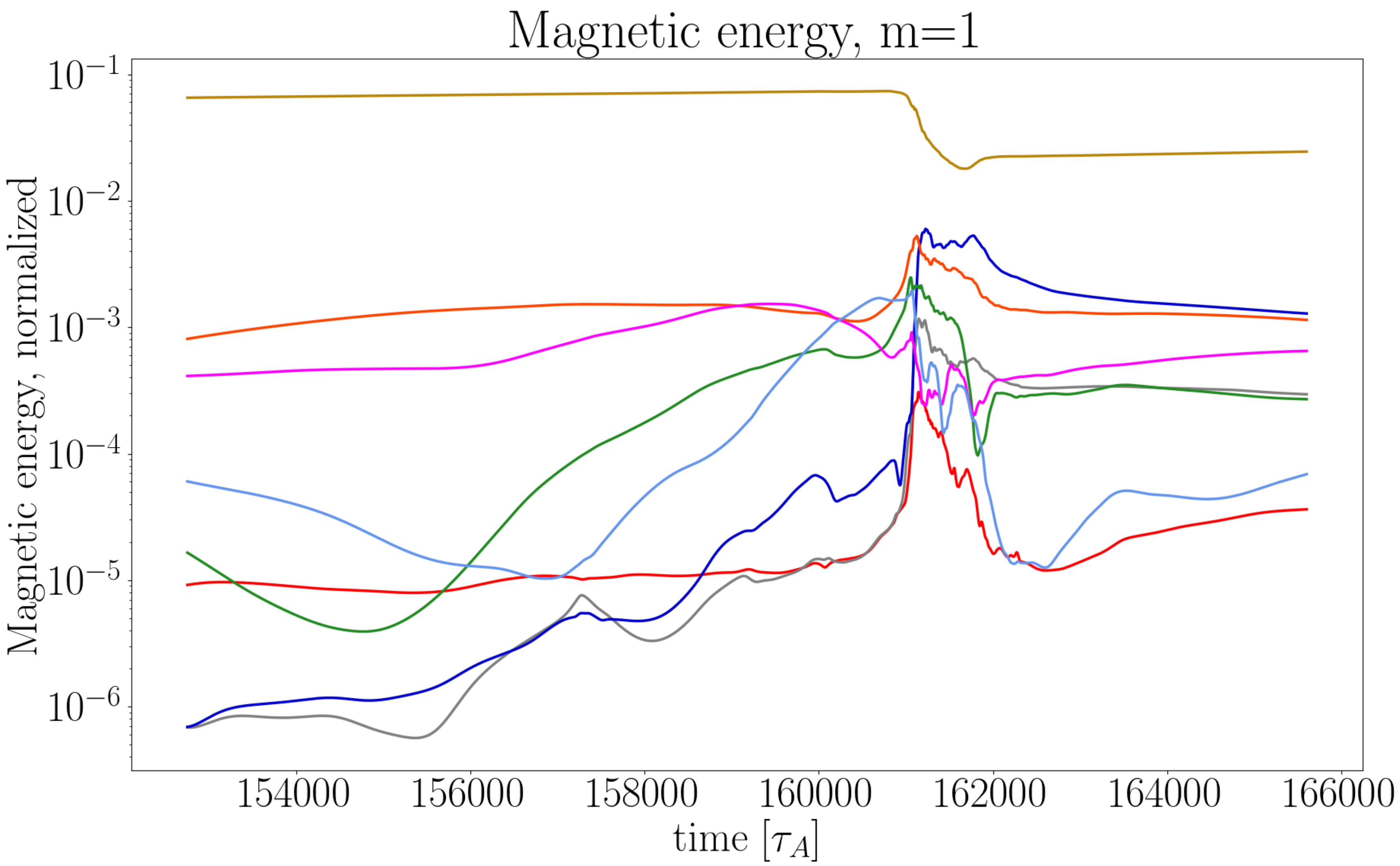
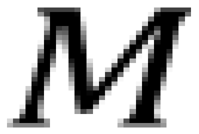
focus on a single reconnection event





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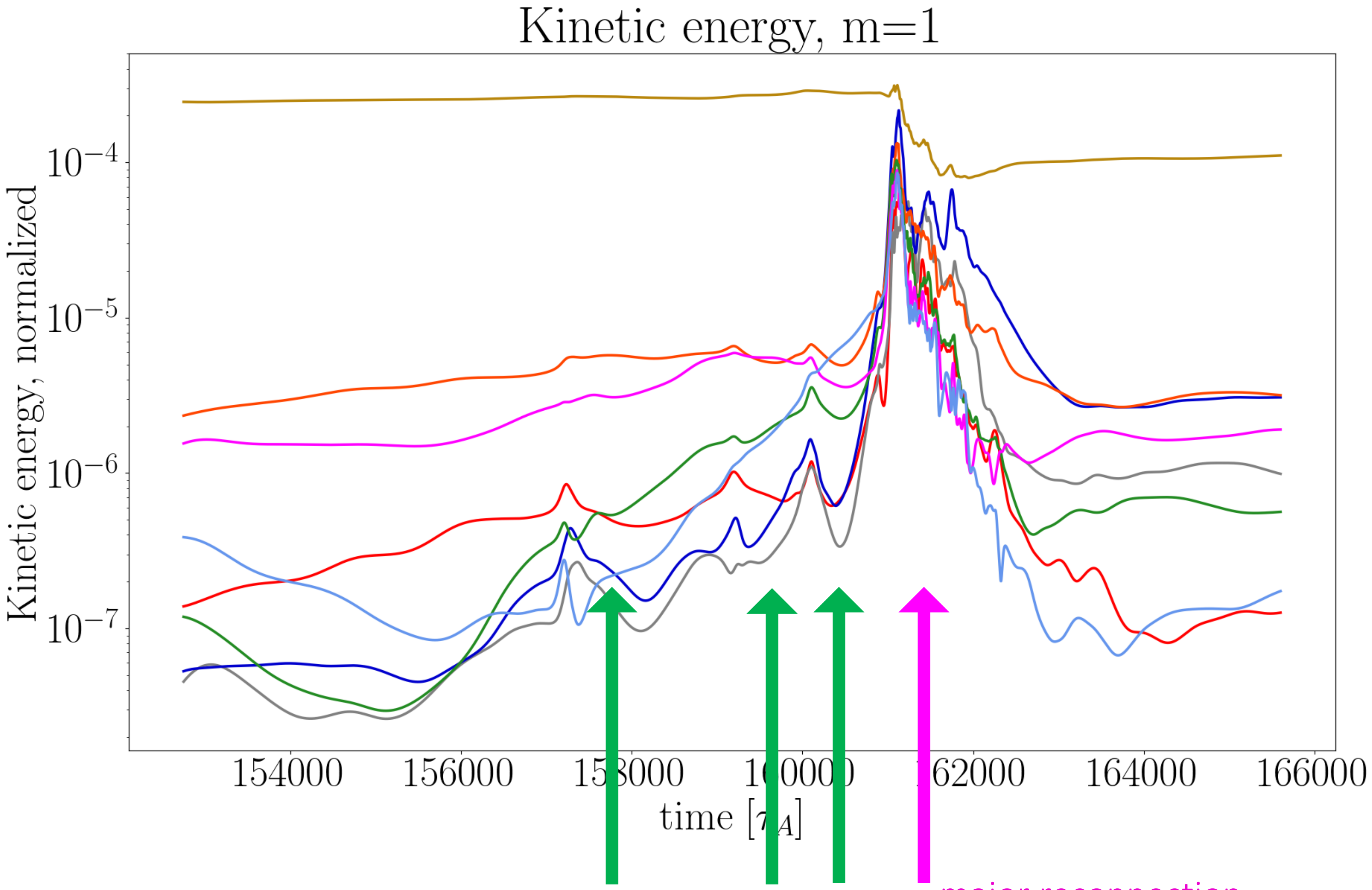

minor reconnections

major reconnection

M

$$S = \frac{1}{\eta} = 10^7$$
$$M = \frac{1}{\nu} = 10^4$$
$$H = \sqrt{SM} = 3.1 \cdot 10^5$$
$$n_{MP} = -7,$$
$$MP = 4\%$$

During the reconnection event magnetic energy is converted into kinetic energy

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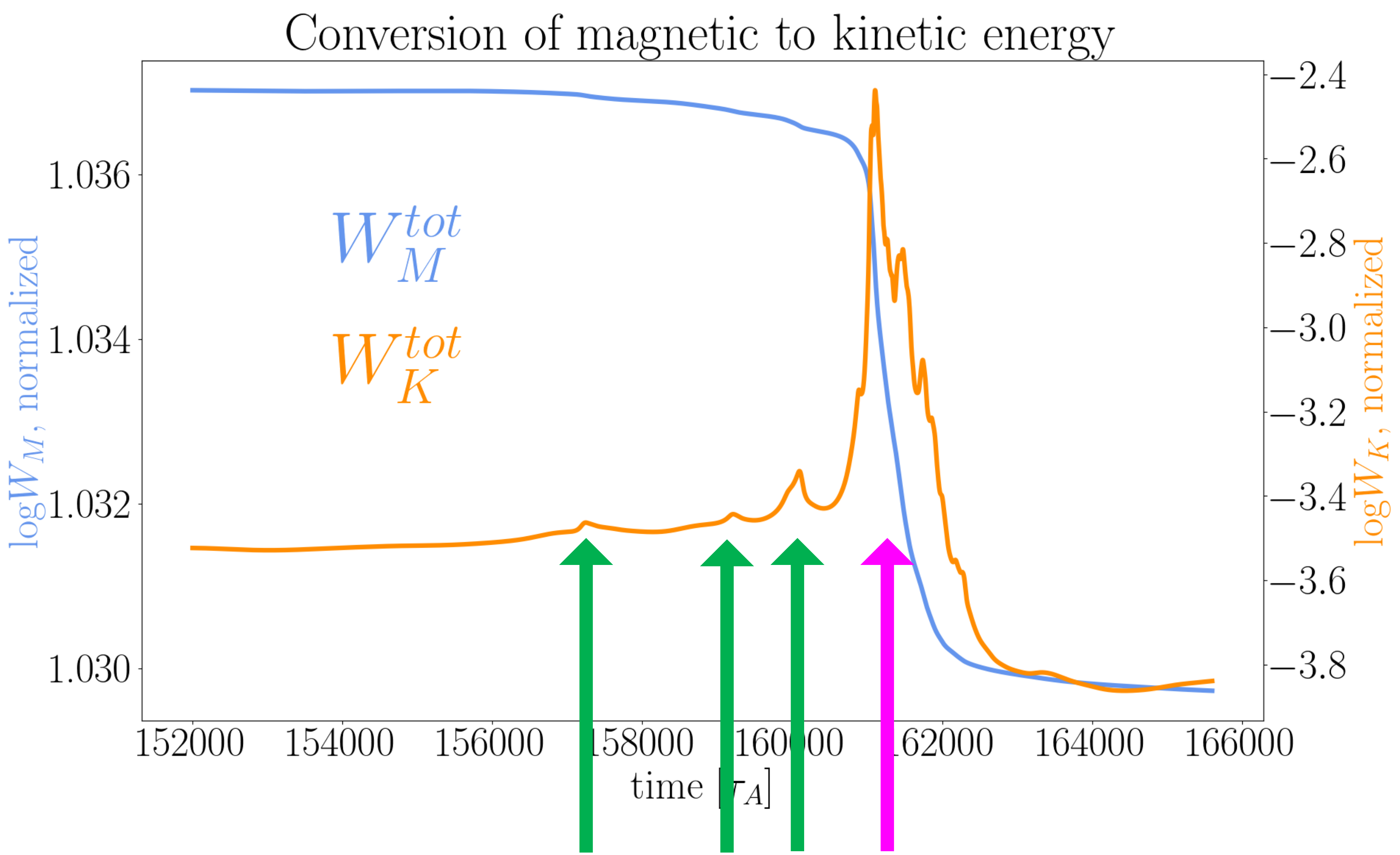
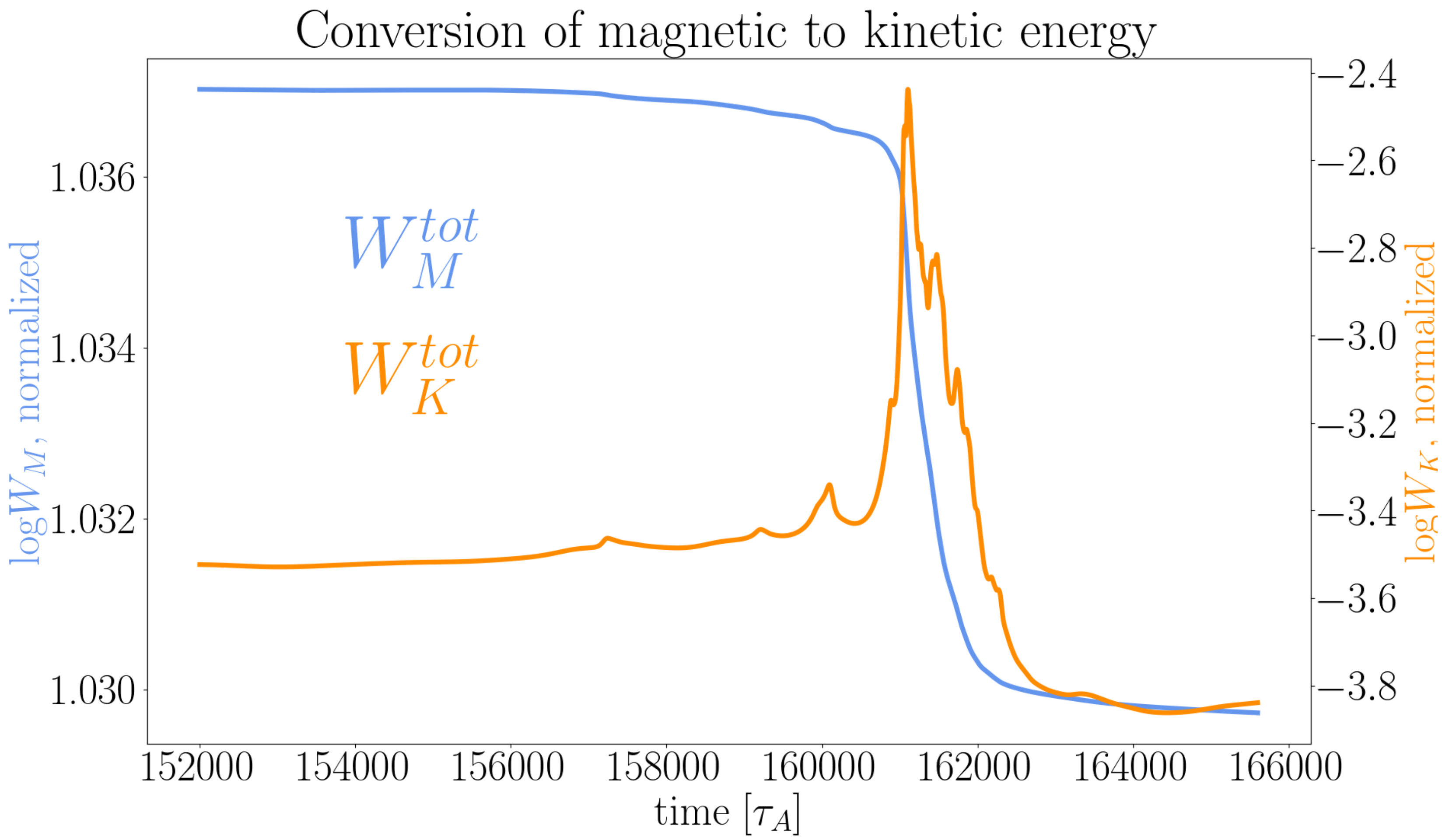


minor reconnections major reconnection

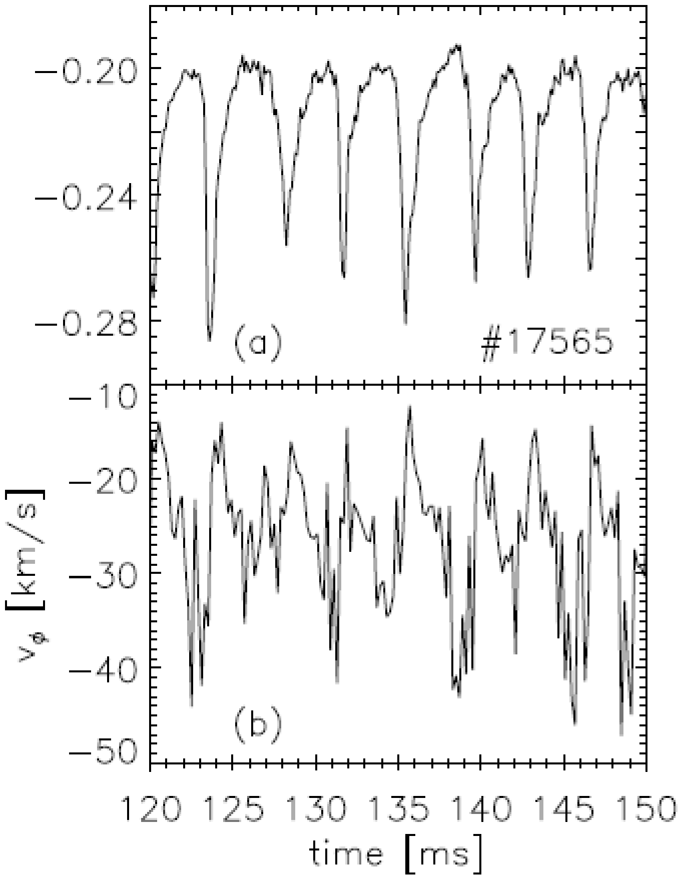
$$\frac{\Delta W_M}{W_M} \sim 1\%$$

the rest of the energy goes into visco-resistive dissipation
remind that in our simulations the plasma is driven by external means

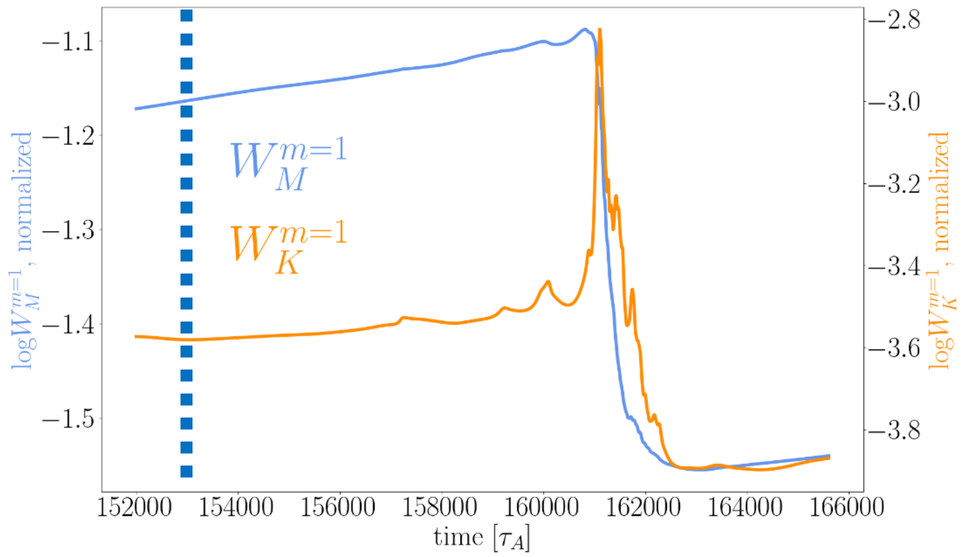


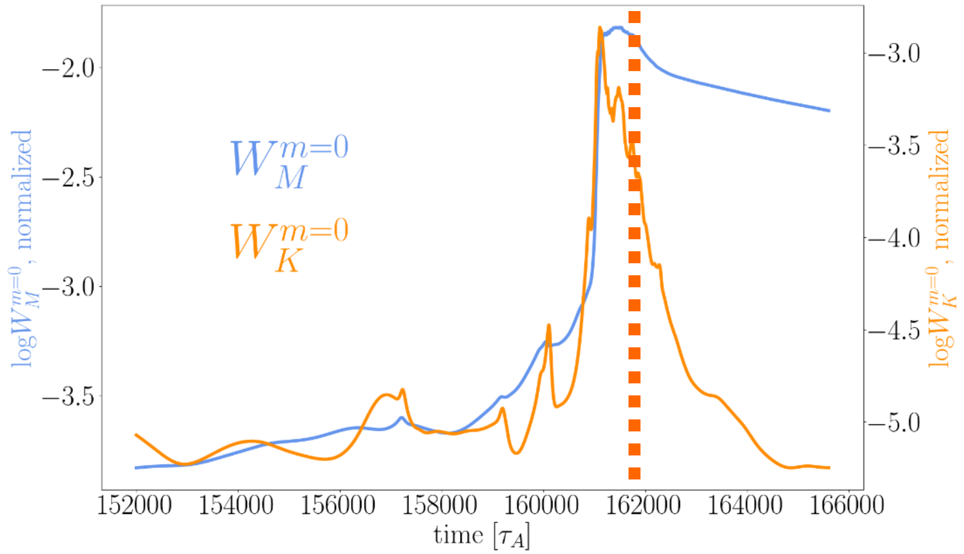
M.Agostini, R.Cavazzana, F.Sattin et al
EPS 2006, Roma

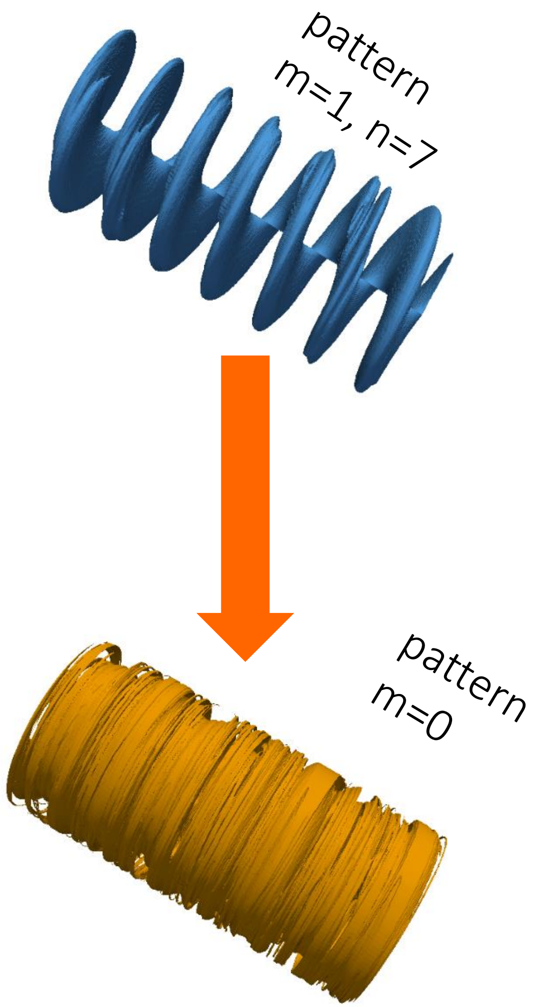
spike of toroidal velocity about 1ms before the decrease of F



m=1 magnetic energy is converted into m=0 magnetic and kinetic energy







$$\frac{\Delta W_M}{W_M} \sim 1\%$$

[1] Zuin, Vianello Spolaore et al **PPCF** 51 (2009)
[2] Momo, Isliker, Cavazzana et al **NF** 60 (2020)

features of the reconnection event: mode locking, routinely used in experimental analysis

“toroidal mode locking” σ_m quantifies the alignment of the phases of MHD modes

$$\sigma_m(t, r, \theta, z) \propto \sum_{j=n_{min}}^{n_{max}} \sum_{k=n_{min+1}}^{n_{max}} \left|\cos(\Phi_{m,j} - \Phi_{m,k})\right|$$

higher σ_m means that modes are “more locked”

in RFX-mod excessive mode locking results in a localized Plasma-Wall Interaction (PWI)

features of the relaxation event: mode locking, routinely measured in experiments

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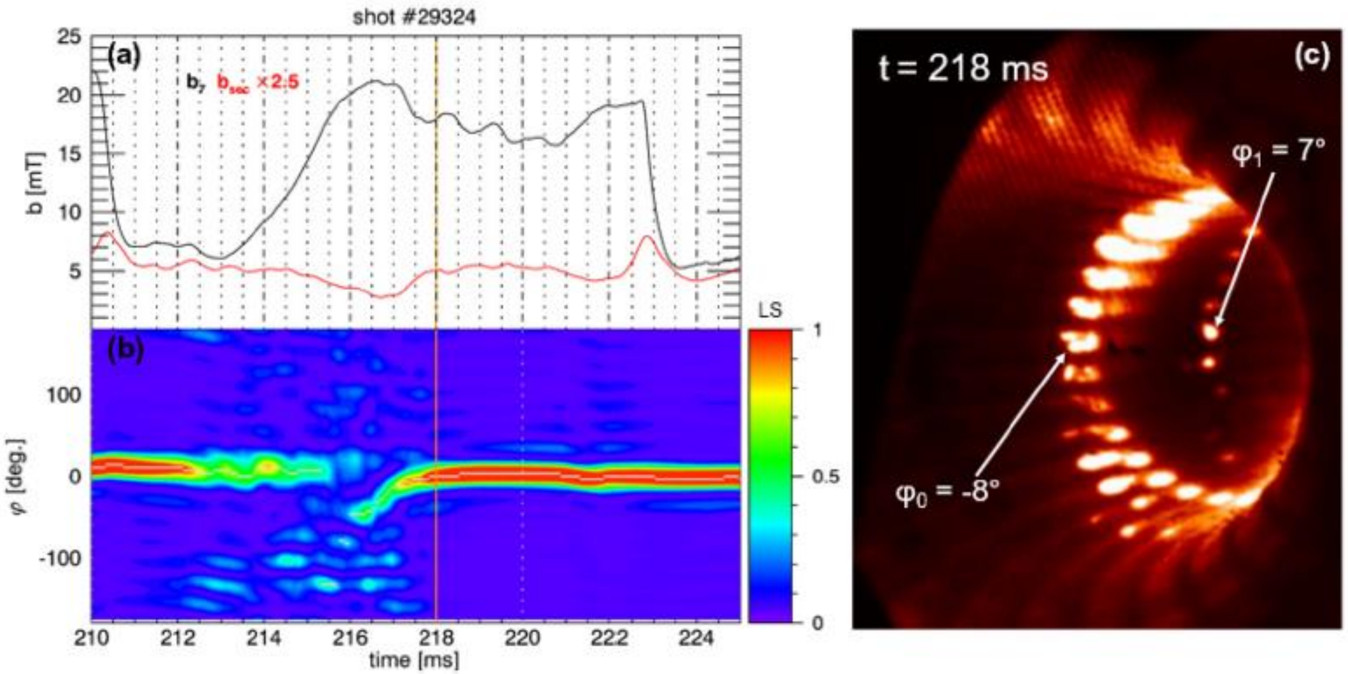


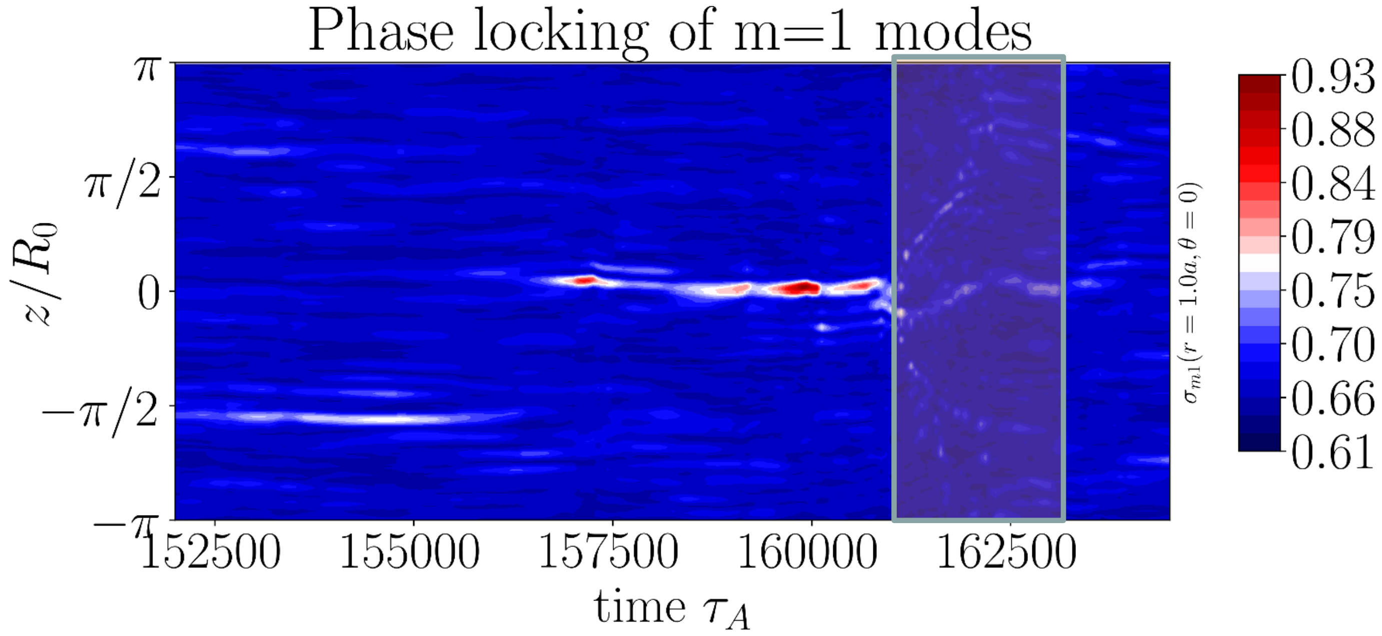
picture from Porcu, Spizzo, Veranda et al **PoP** 2023
coming from studies of Scarin et al **NF** 2019
and from Spizzo et al **NF** 2017

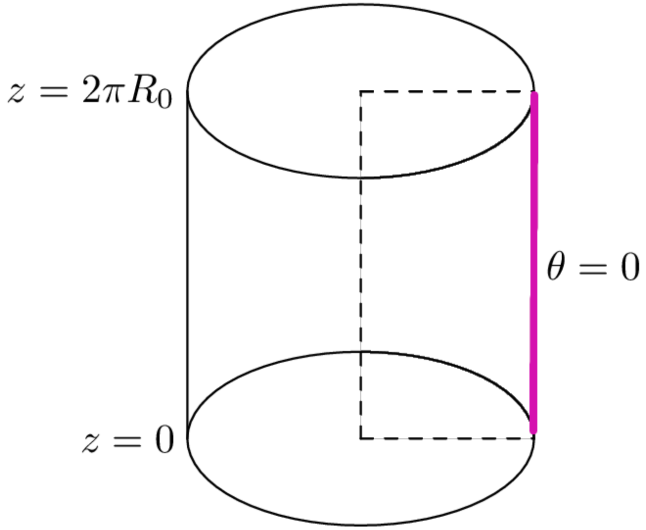
Locked mode phenomenology observed in all RFPs since the ‘80s, together with the wall-locking. Various technique to mitigate the bad effects have been tested, culminating in Clean Mode Control in RFX-mod

MINIMAL LITERATURE ABOUT MODE LOCKING IN RFPs

Tamano T et al **PRL** 59 (1987)
Fitzpatrick R. **NF** 33 (1993)
Valisa, Bolzonella, Carraro et al **JNM** 241-243 (1997)
Bartiromo, Bolzonella, Buffa et al **PRL** 83 (1999)
Zanca **PoP** 8 (2001)
Fitzpatrick and Zanca **PoP** 9 (2002)
Marrelli, Zanca, Valisa et al **PPCF** 49 (2007)
Marrelli, Cavazzana et al **NF** 59 (2019)
Marrelli, Martin et al **NF** 61(2021)

presence of locking before the big reconnection event





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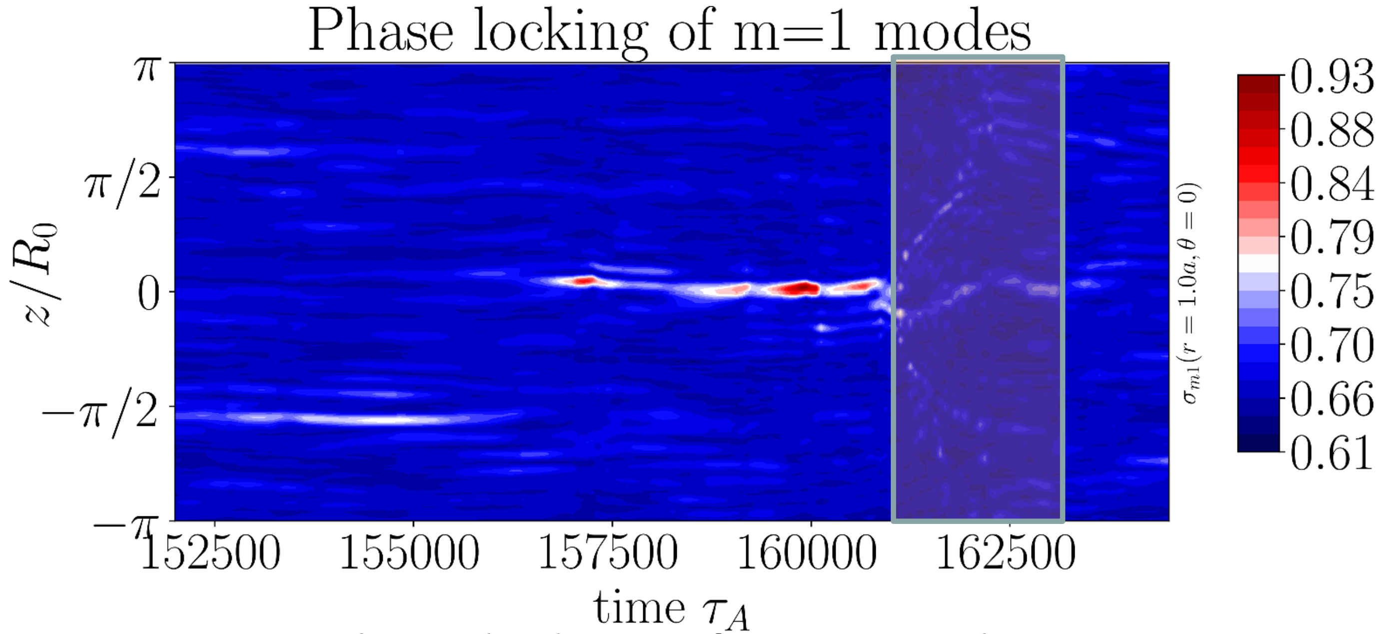
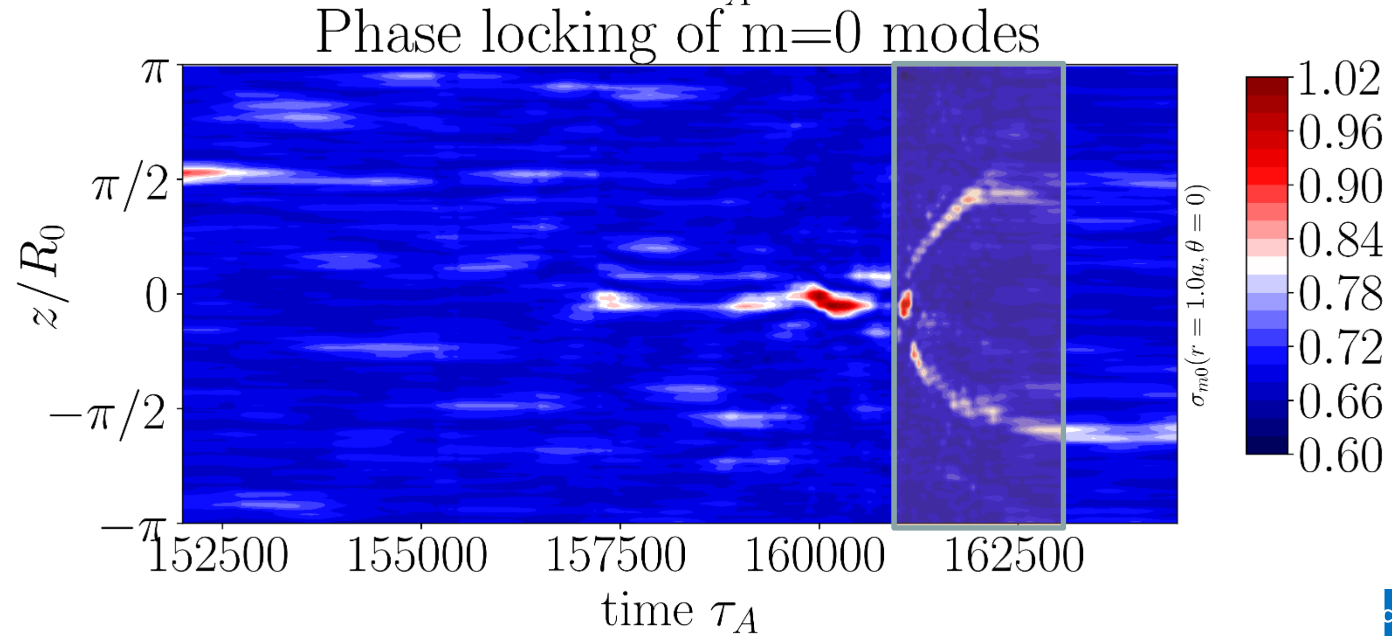




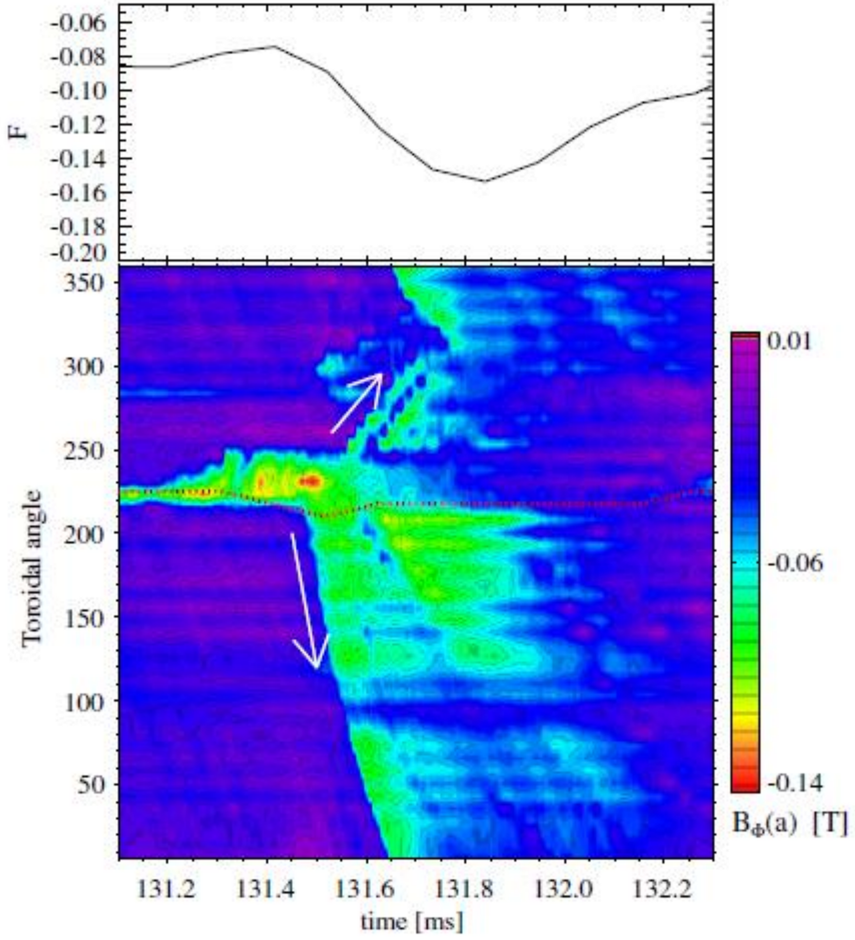
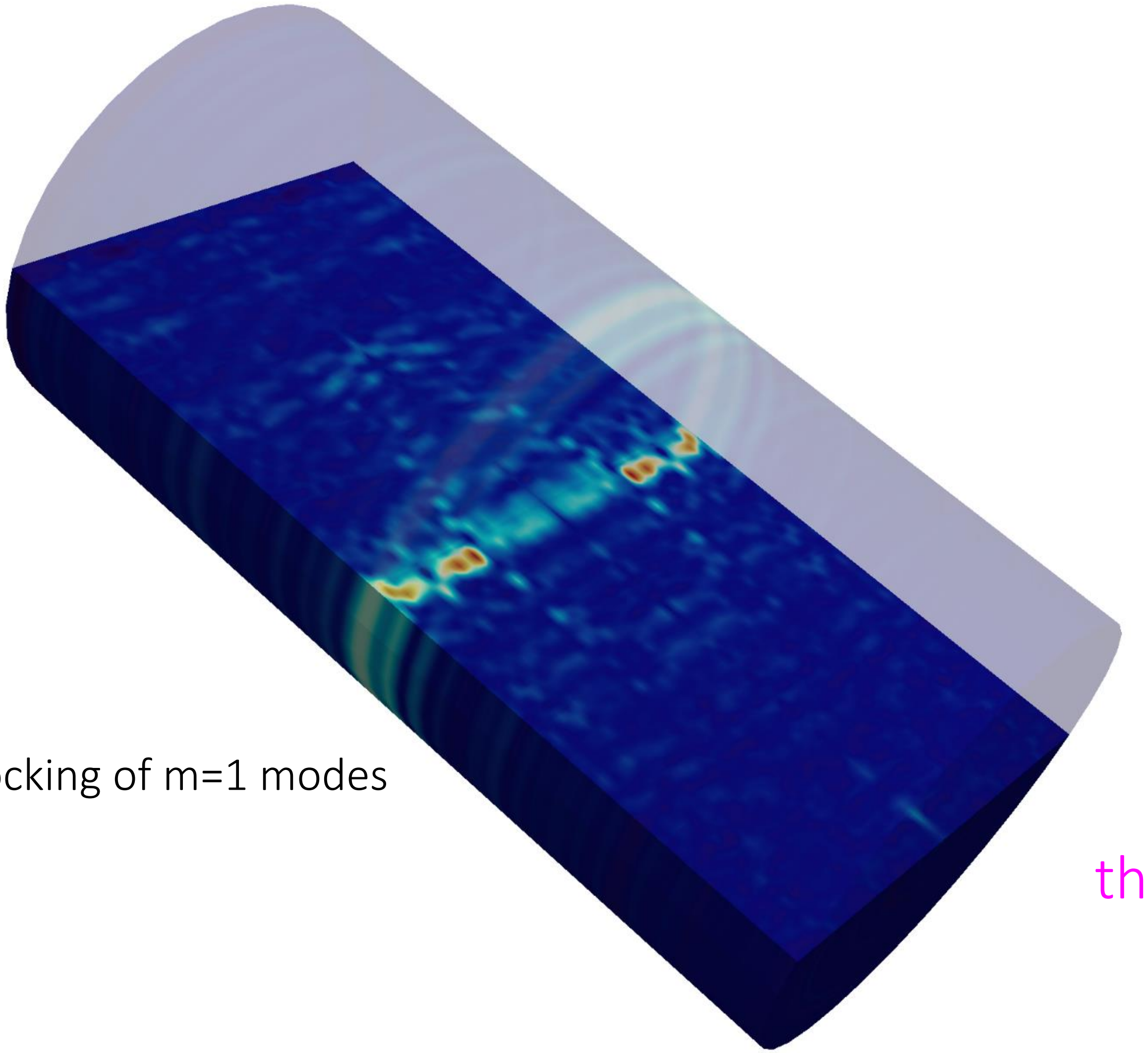


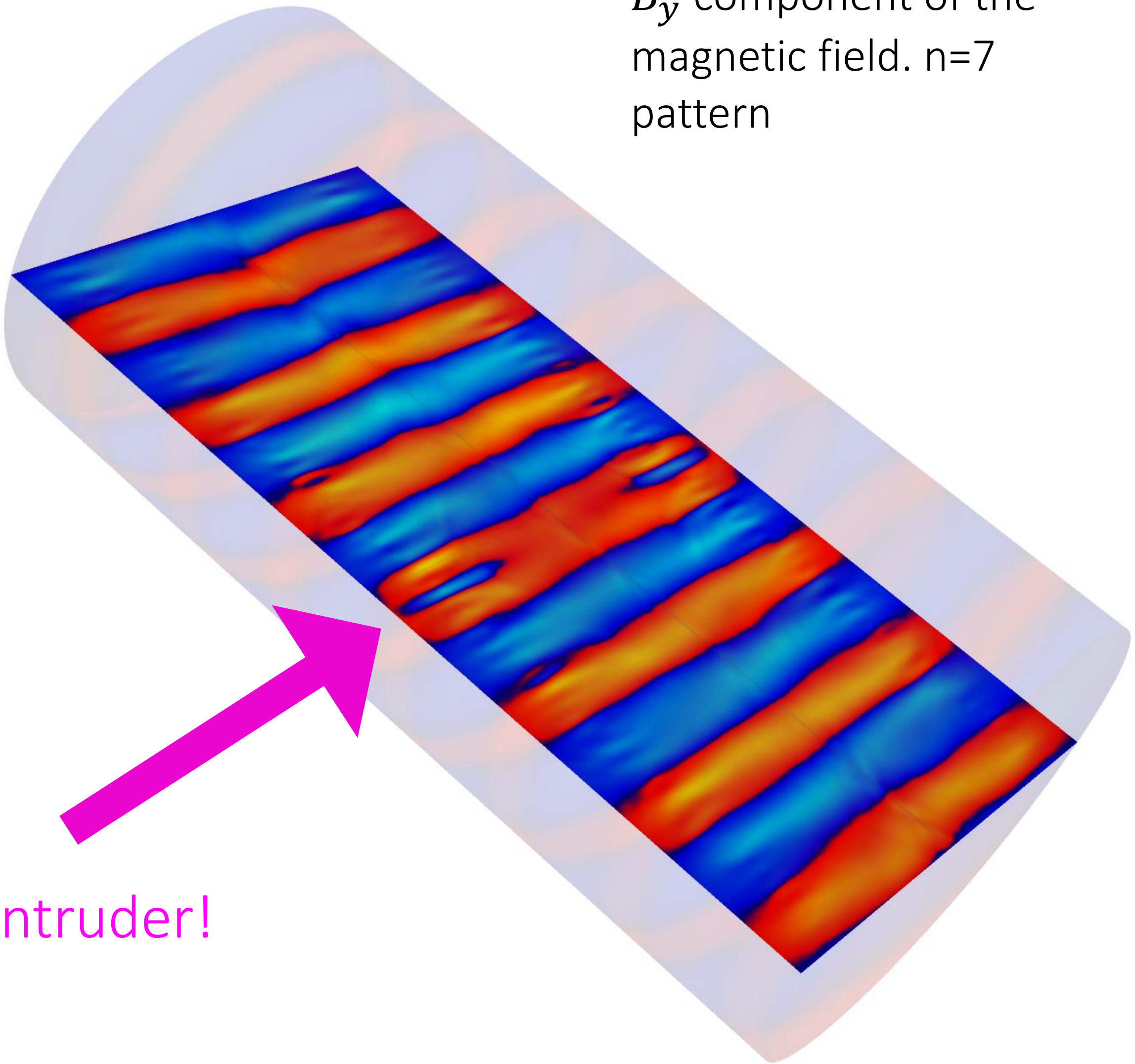
Fig. 7 from: Zuin, Vianello Spolaore et al **PPCF** 51 (2009)

at position with strong locking → strongest asymmetries



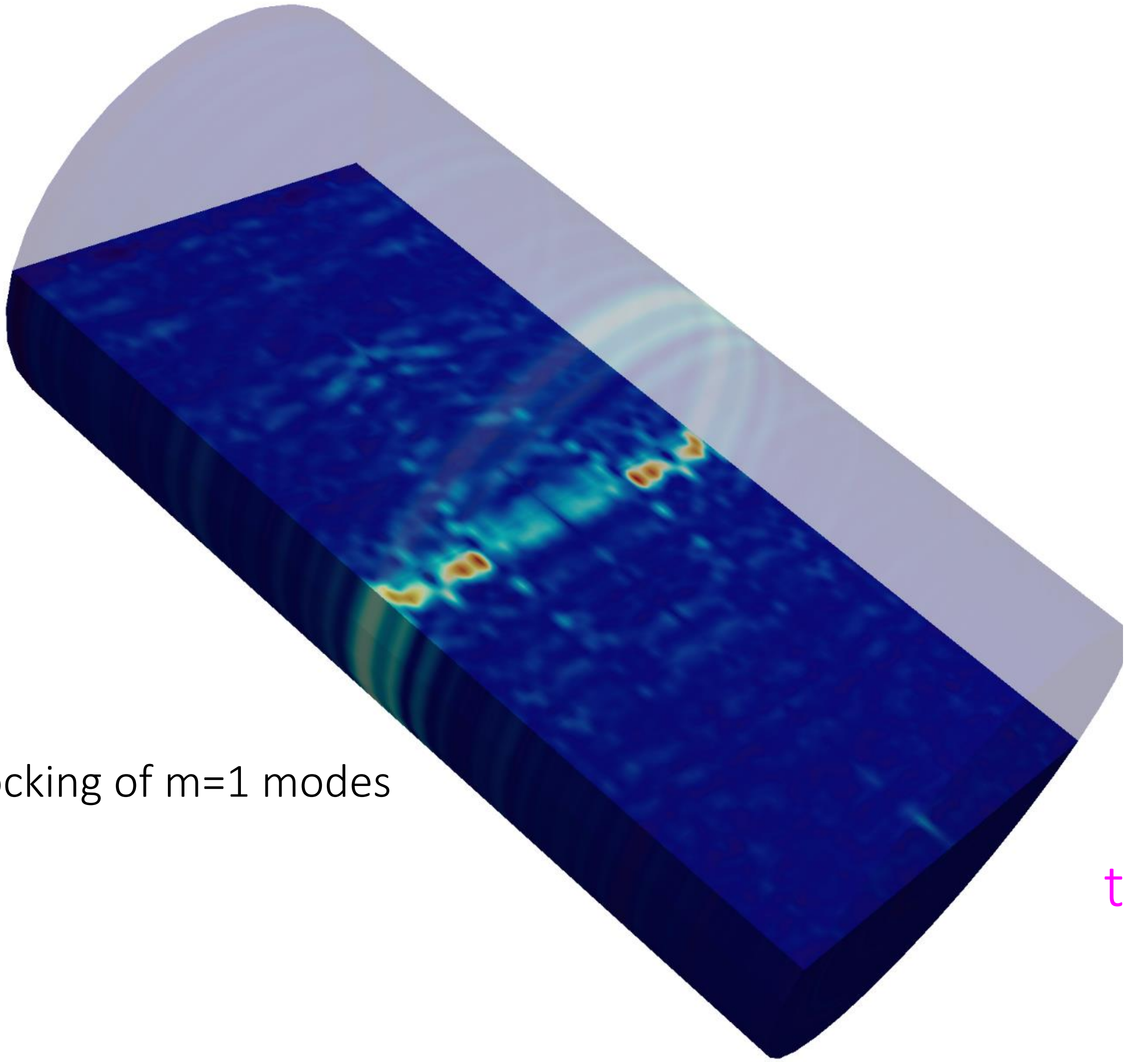
locking of m=1 modes

B_y component of the magnetic field. n=7 pattern

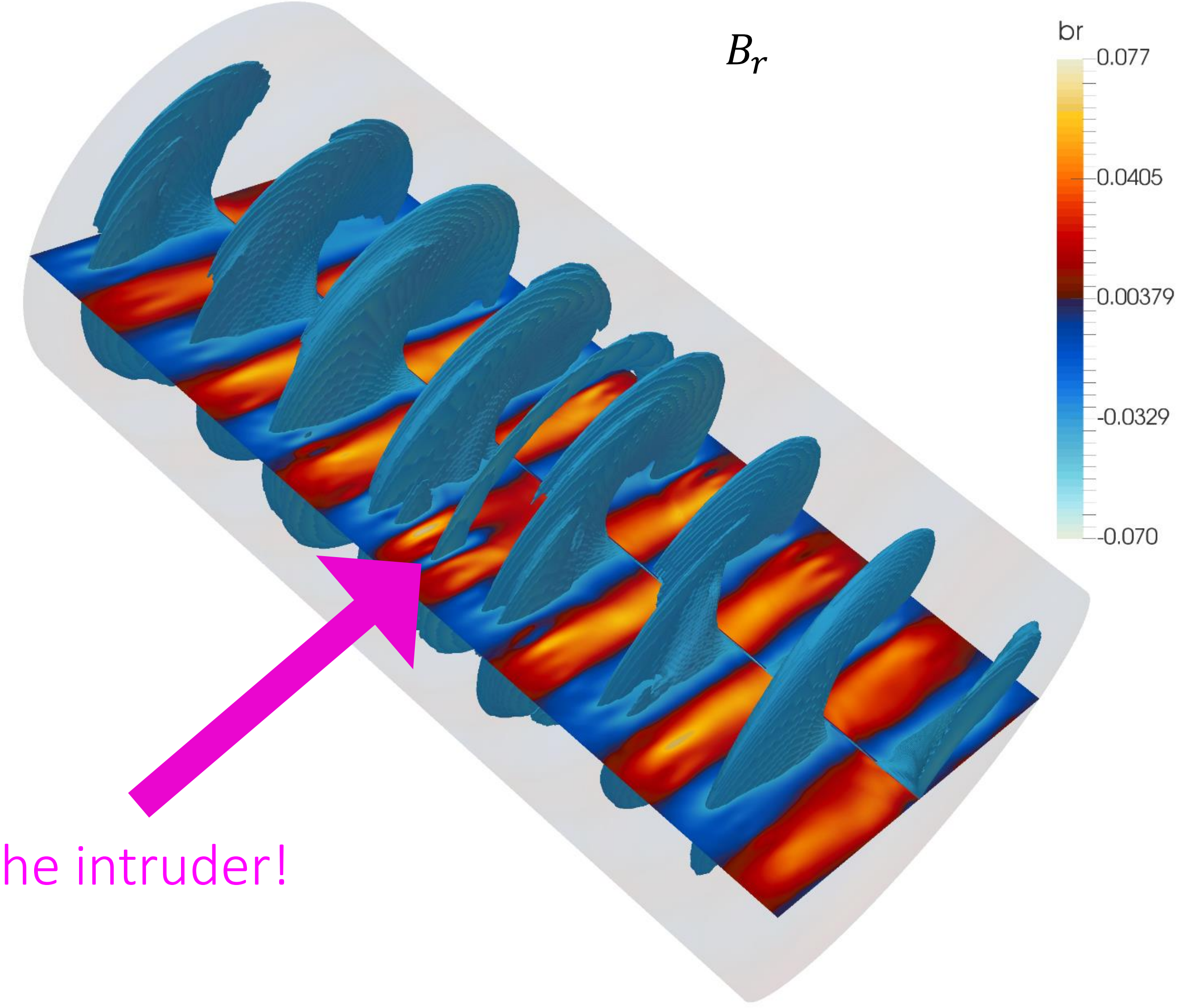


the intruder!

the helical features of B_r is ruined where MHD modes are locked: small asymmetry but relevant in creating a local burst of $\boldsymbol{J} = \nabla \times \boldsymbol{B}$

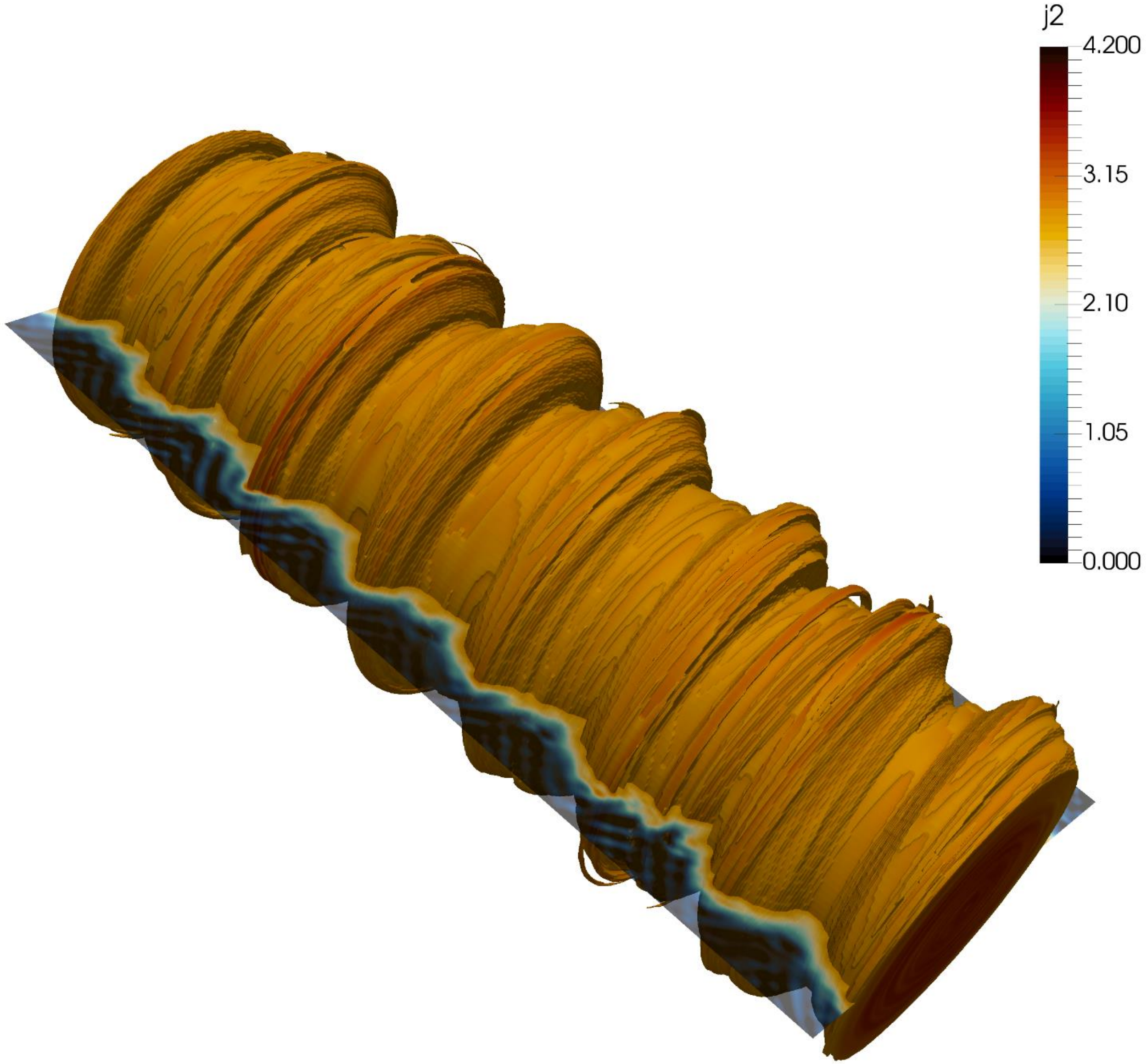


locking of m=1 modes



the intruder!

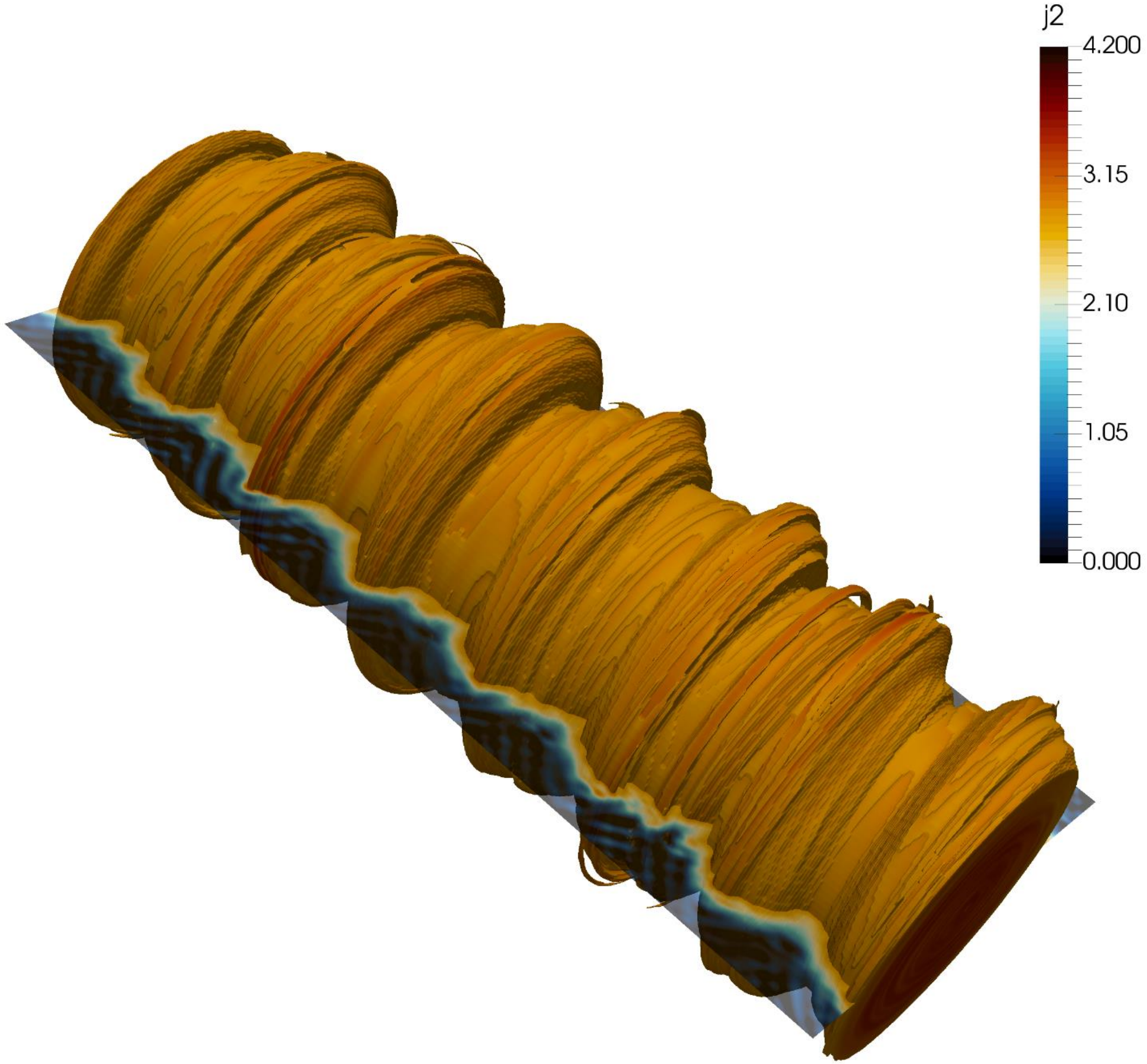
evolution of plasma current density. During QSH → helical pattern



we observe J^2
or also $J_{\parallel} = \frac{\boldsymbol{J}\cdot\boldsymbol{B}}{B^2}$

the latter quantity derives from the simplest possible force balance equation in a strongly current carrying plasma that is $\boldsymbol{J} \times \boldsymbol{B} = 0$

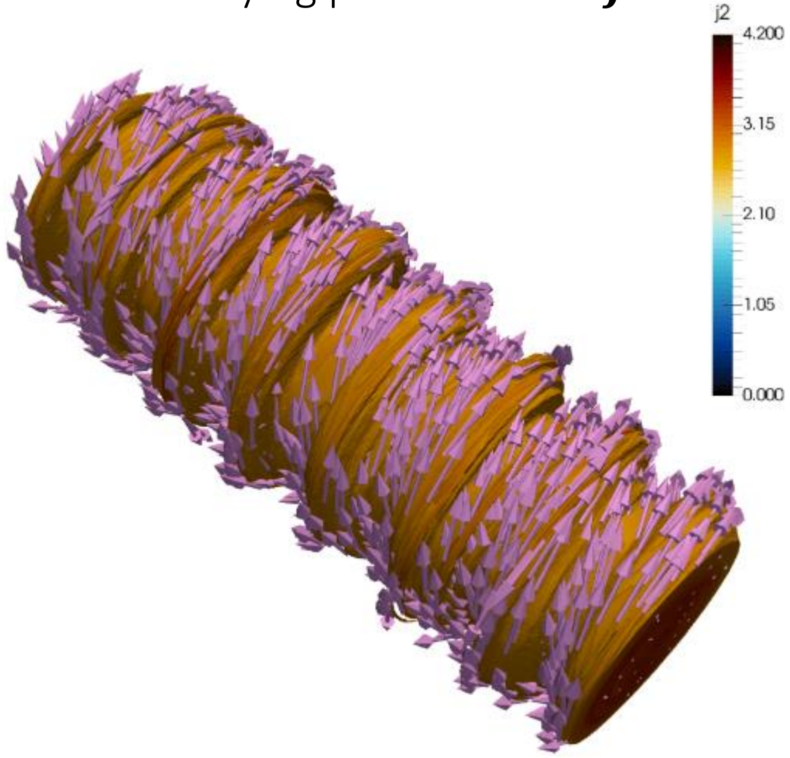
evolution of plasma current density. During QSH → helical pattern



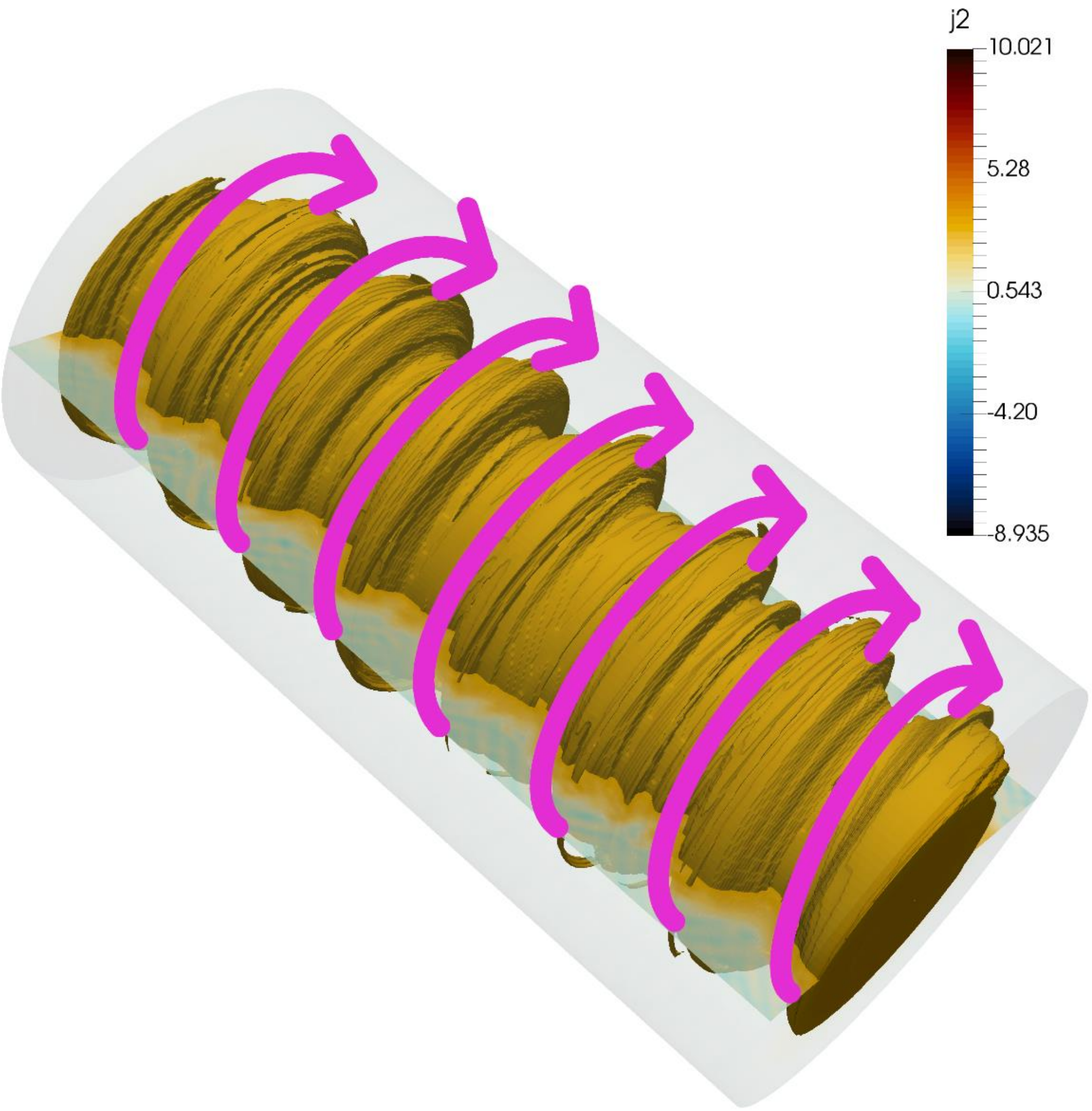
we observe J^2

or also $J_{\parallel} = \frac{\boldsymbol{J} \cdot \boldsymbol{B}}{B^2}$

the latter quantity derives from the simplest possible force balance equation in a strongly current carrying plasma that is $\boldsymbol{J} \times \boldsymbol{B} = 0$



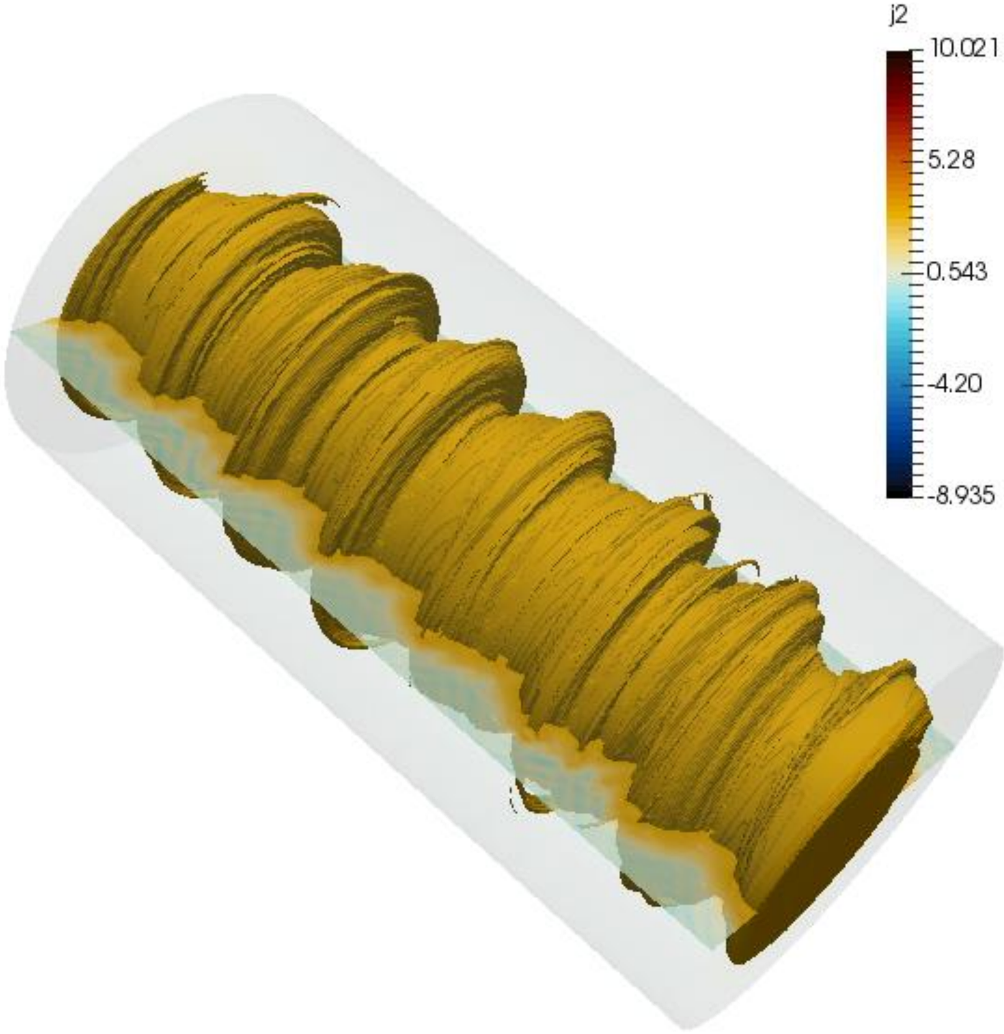
the n=7 QSH state is like a set of 7 coils with currents in same direction

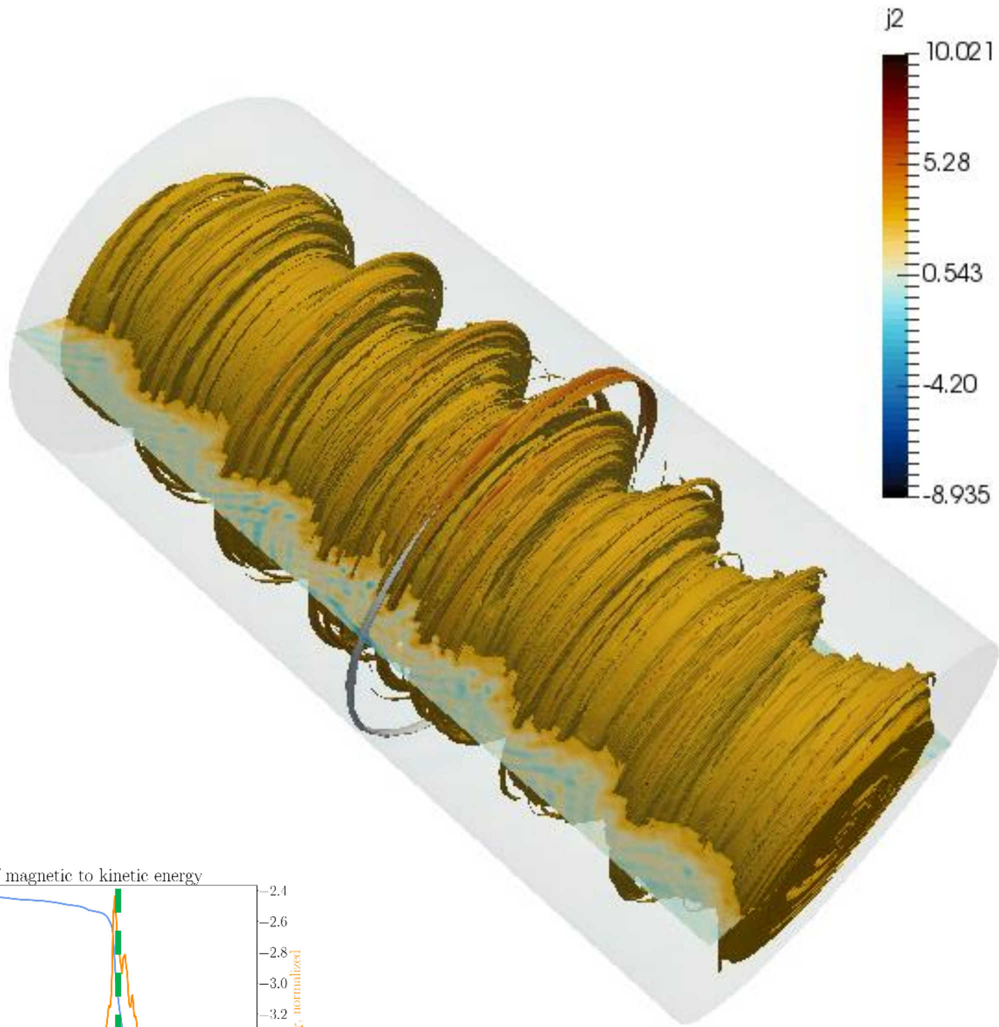


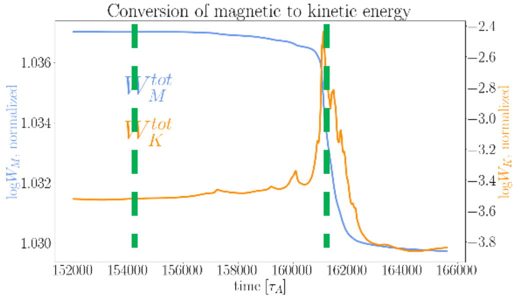
an unstable system, because co-currents tend to attract each other (Biot-Savart)

Escande, toy model

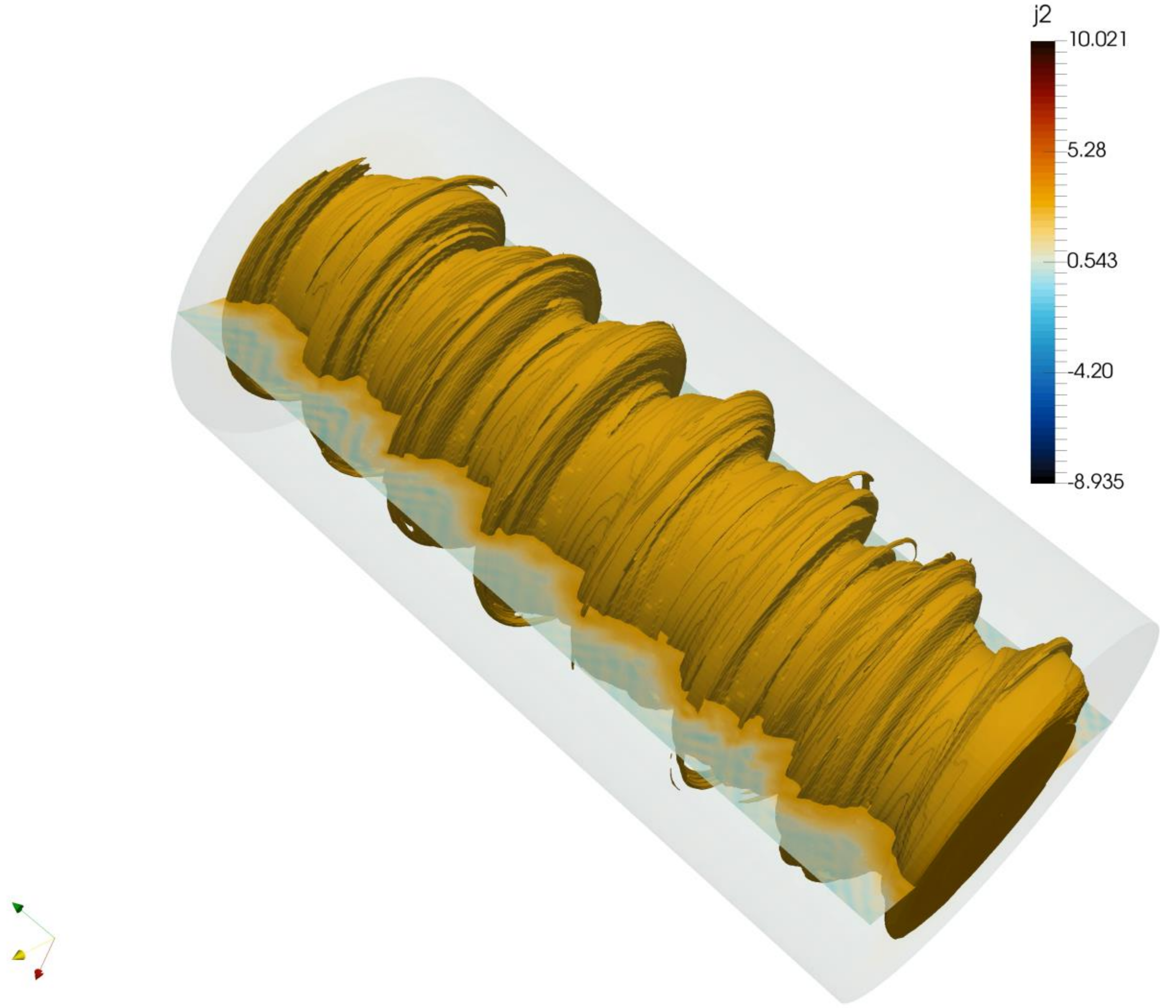
when asymmetries gets too strong: localized current sheet



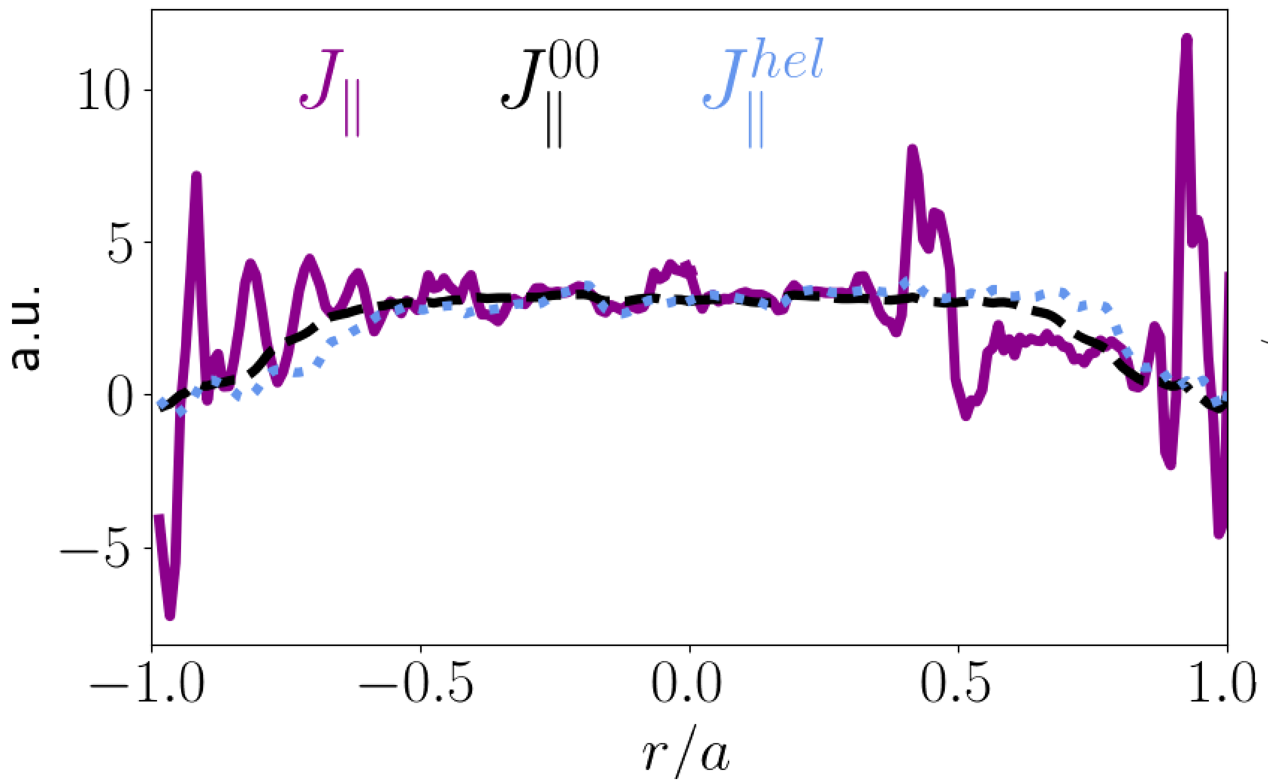


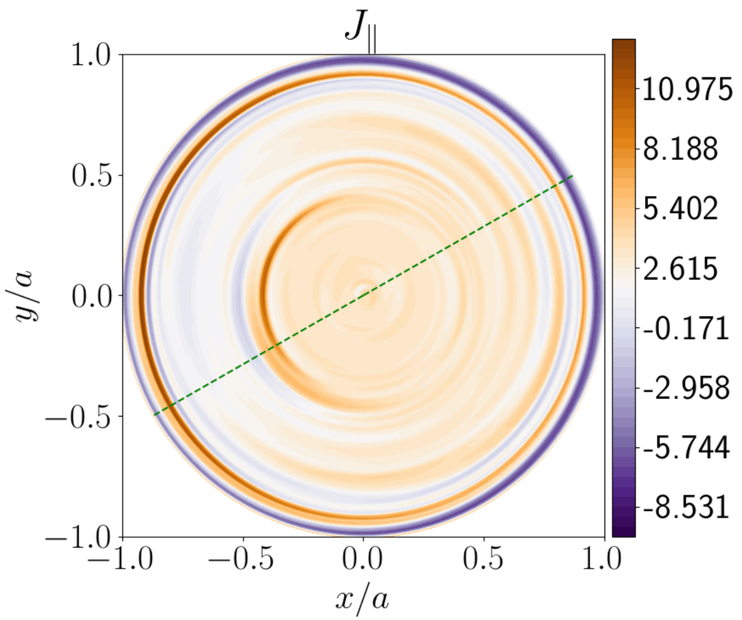


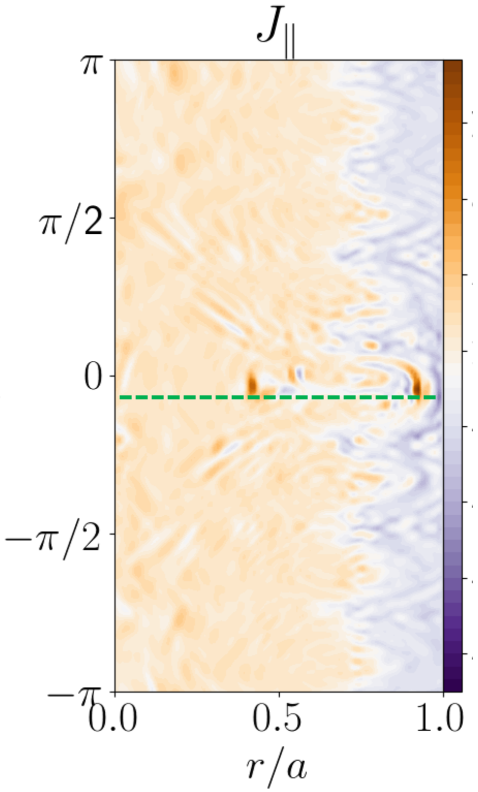
when the inhomogeneity due to locking increases, a current sheet develops, and the two closest helical coils coalesce

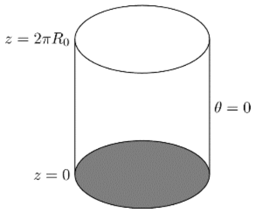


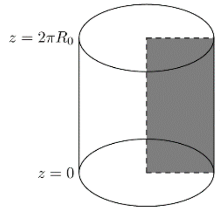
the parallel current is locally very peaked too, and the peaking is caused by all the MHD modes different from the axisymmetric and helical one







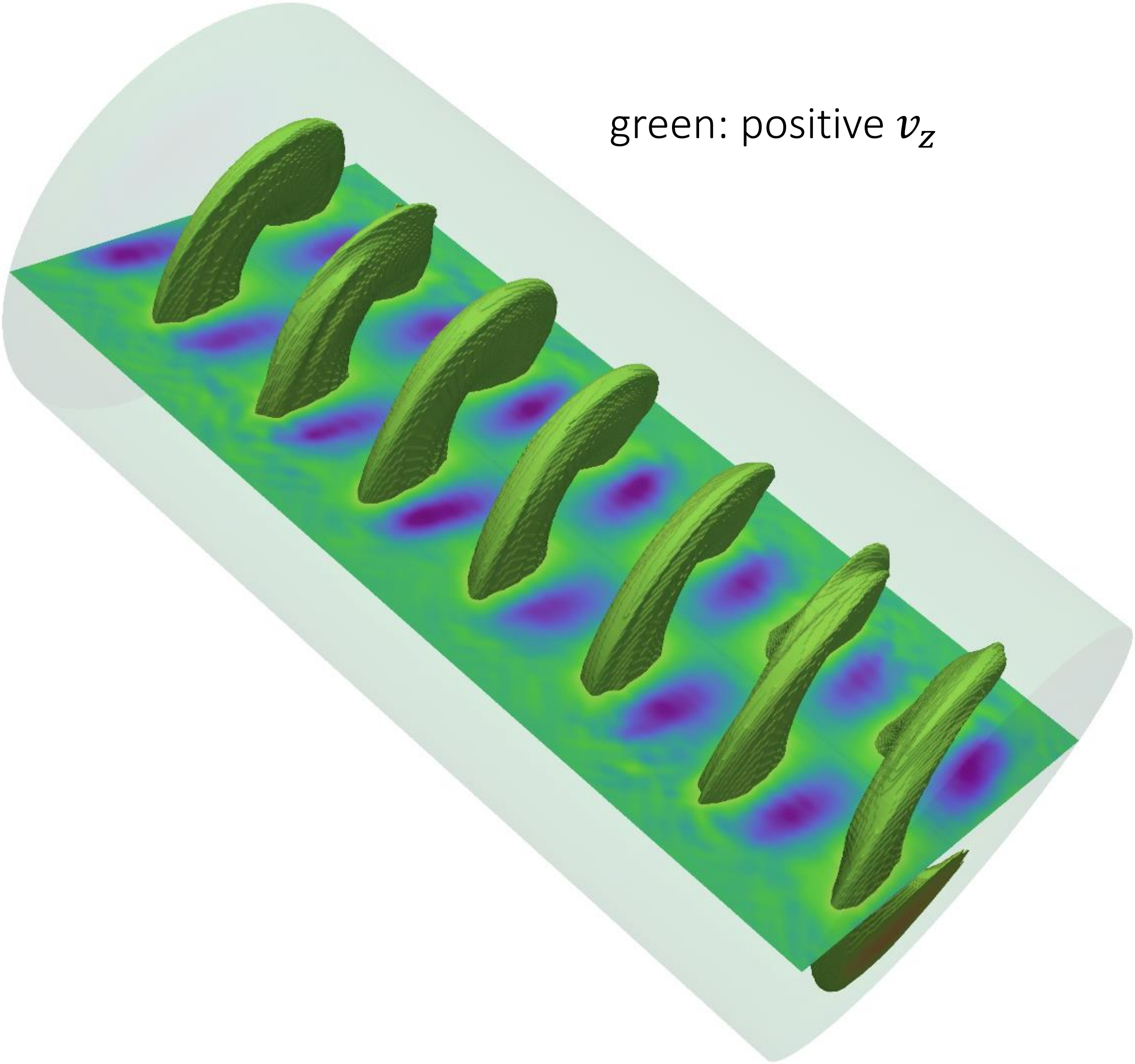


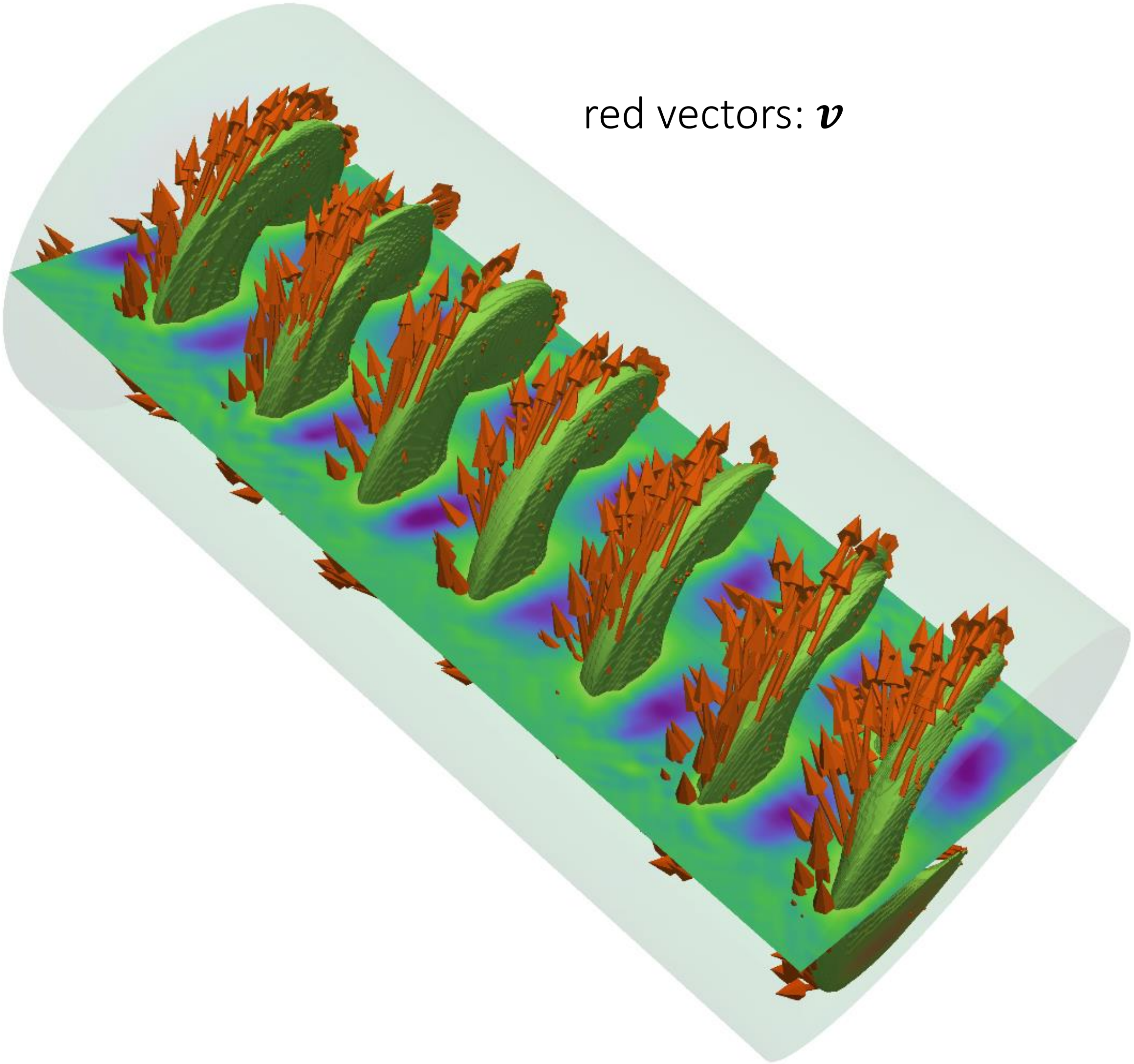


CONSORZIO RFX
Ricerca Formazione Innovazione

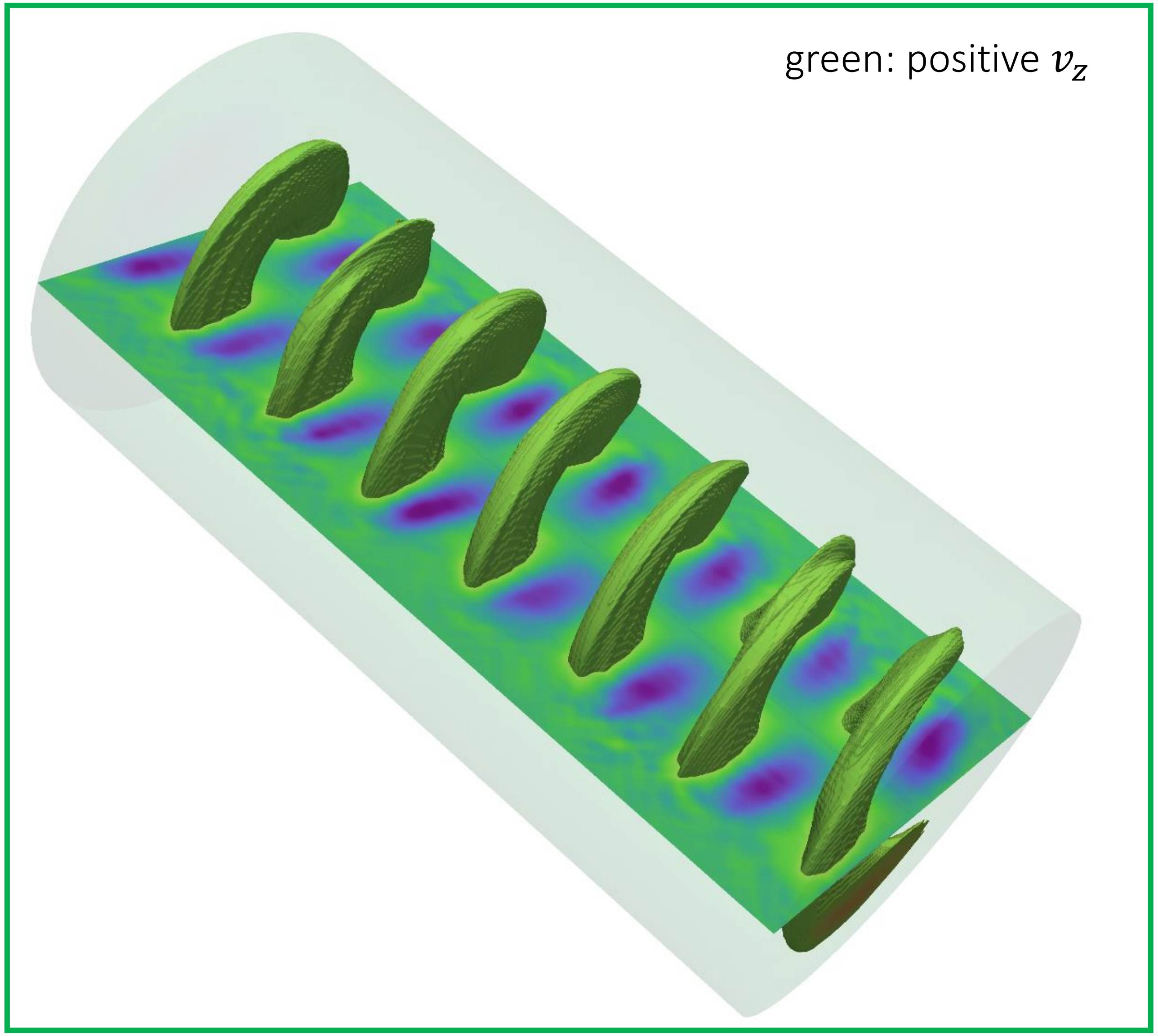
- the behaviour of the plasma flow when the helical structure coalesces
- Alfvén waves excitation
- the role of MPs in influencing the amplitude and frequency of the relaxation events
- possibility of controlling them

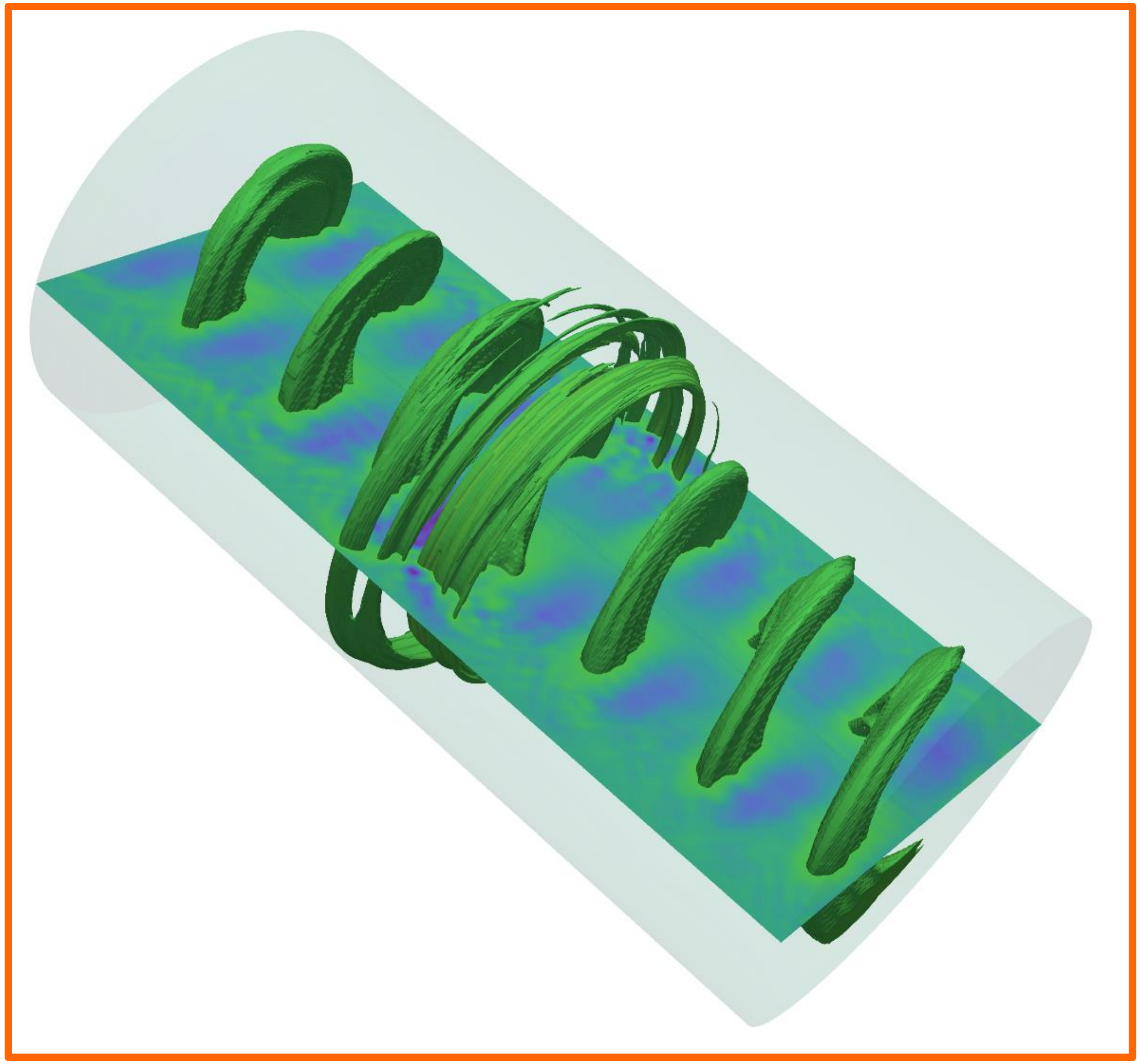
plasma flow during QSH state: ordered helical structure





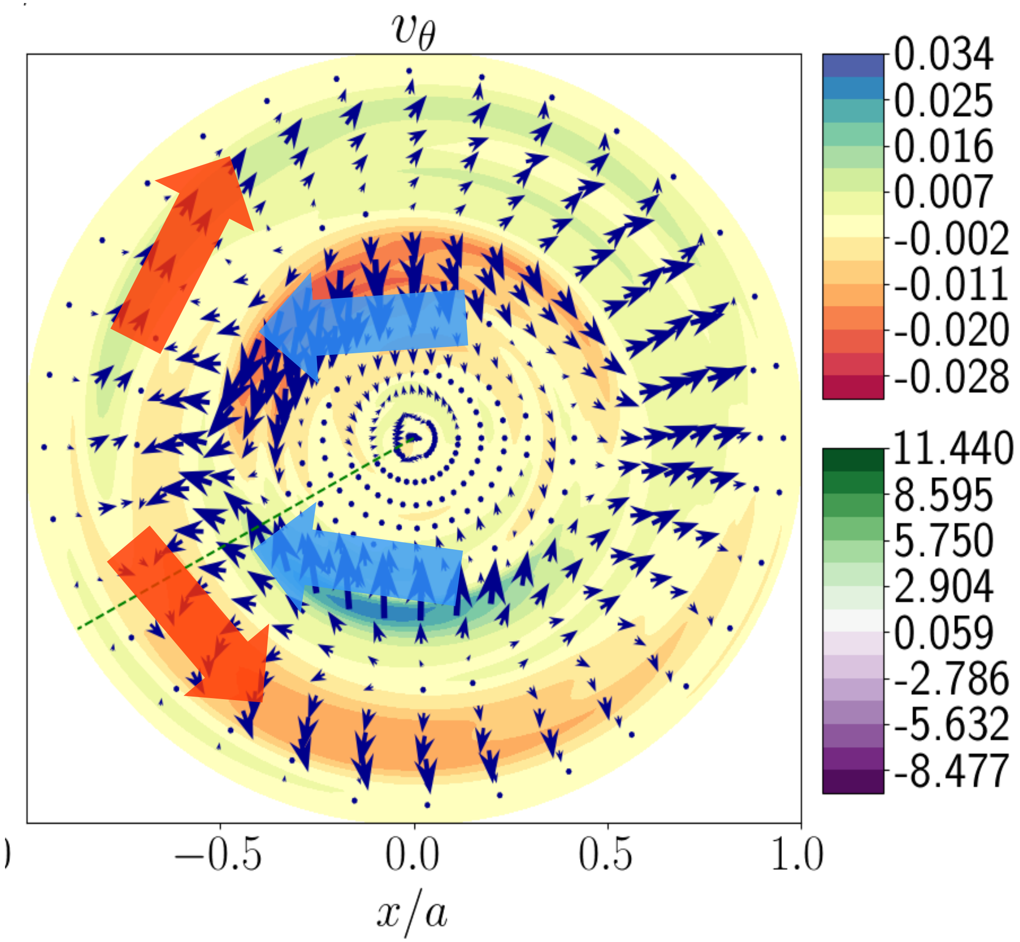
plasma flow during QSH state vs during coalescence (3D view)

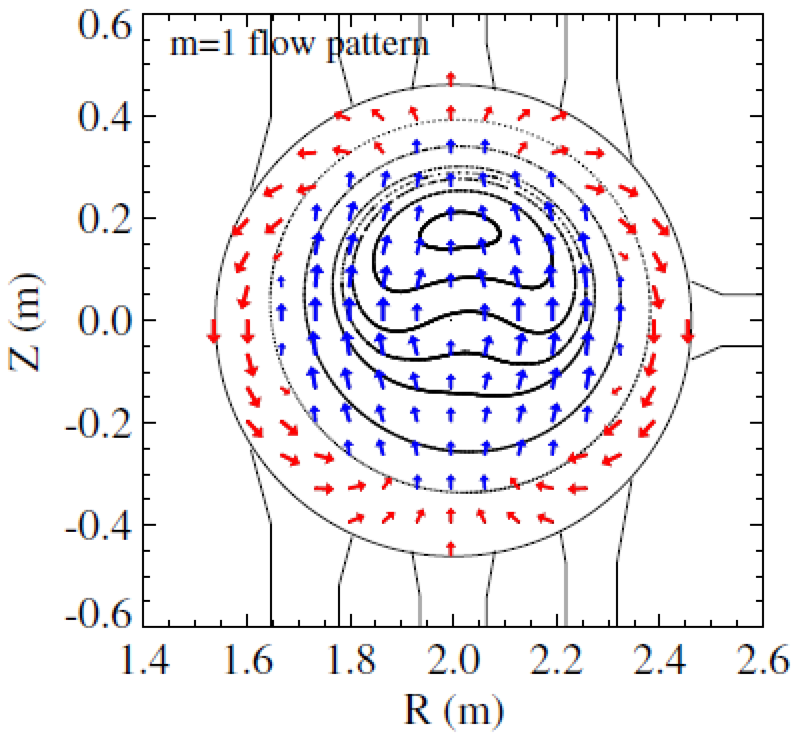




pattern of inflow outflow strongly correlated to current sheet presence

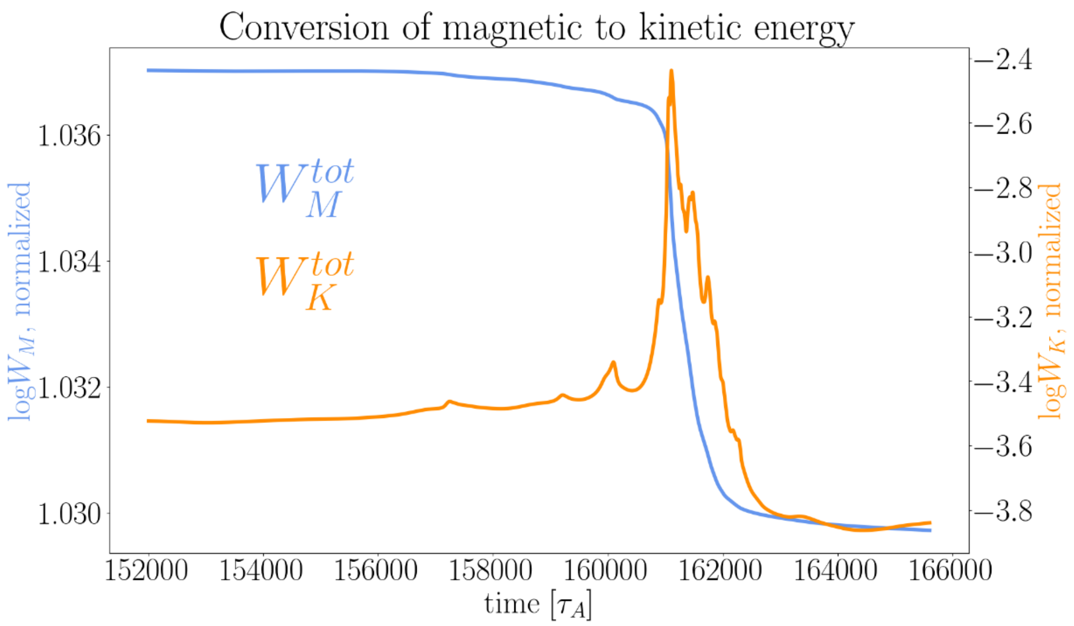
the pattern is reminiscent of the one measured in RFX-mod thanks to multichord Doppler spectroscopic diagnostic measuring Carbon (V) and Boron (V) impurities emission

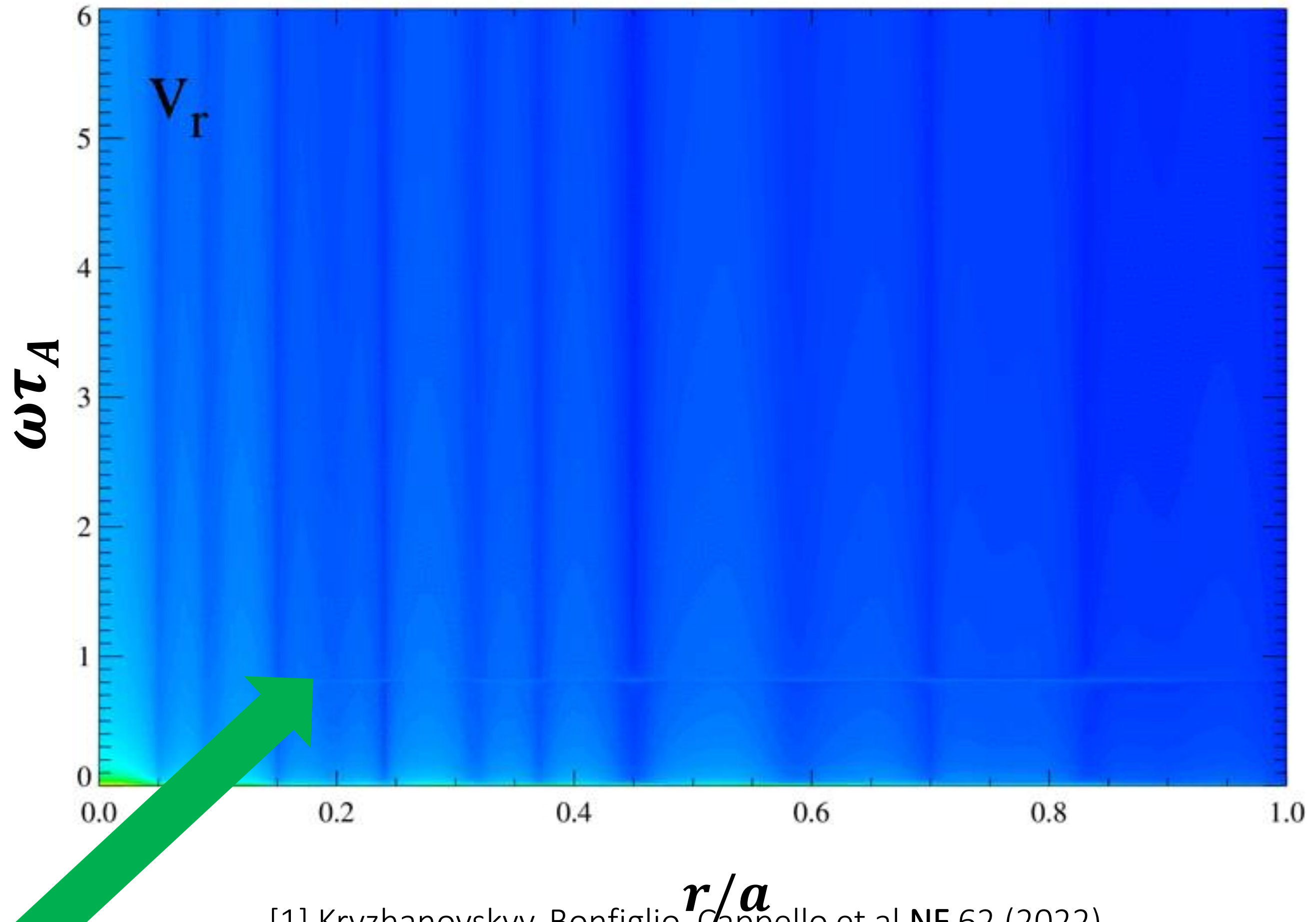




from Bonomo, Bonfiglio et al **NF** 51 (2011)

Alfvénic modes excited by the magnetic reconnection event both in RFPs [1] and in tokamaks [2]





Compressional Alfvén eigenmodes [1, in RFPs], Global Alfvén eigenmode are detected [2, in Tokamak simulations].

work in progress: compute ion heating using Hamiltonian model [3, 4].
Compare the resulting ion heating during MR with the values measured in the MST RFP experiment [5]

[1] Kryzhanovskyy, Bonfiglio, Cappello et al **NF** 62 (2022)
[2] Kryzhanovskyy, Bonfiglio, Cappello et al **NF** 64 (2024)
[3] Escande, Gondret, Sattin **Scientific Reports** 9 (2019)
[4] Sattin, Escande, **PRE** 107 (2023)
[5] G. Fiksel et al **PRL** (2009)

by unlocking the MHD modes it is possible to delay the onset of relaxation events

CONSORZIO RFX
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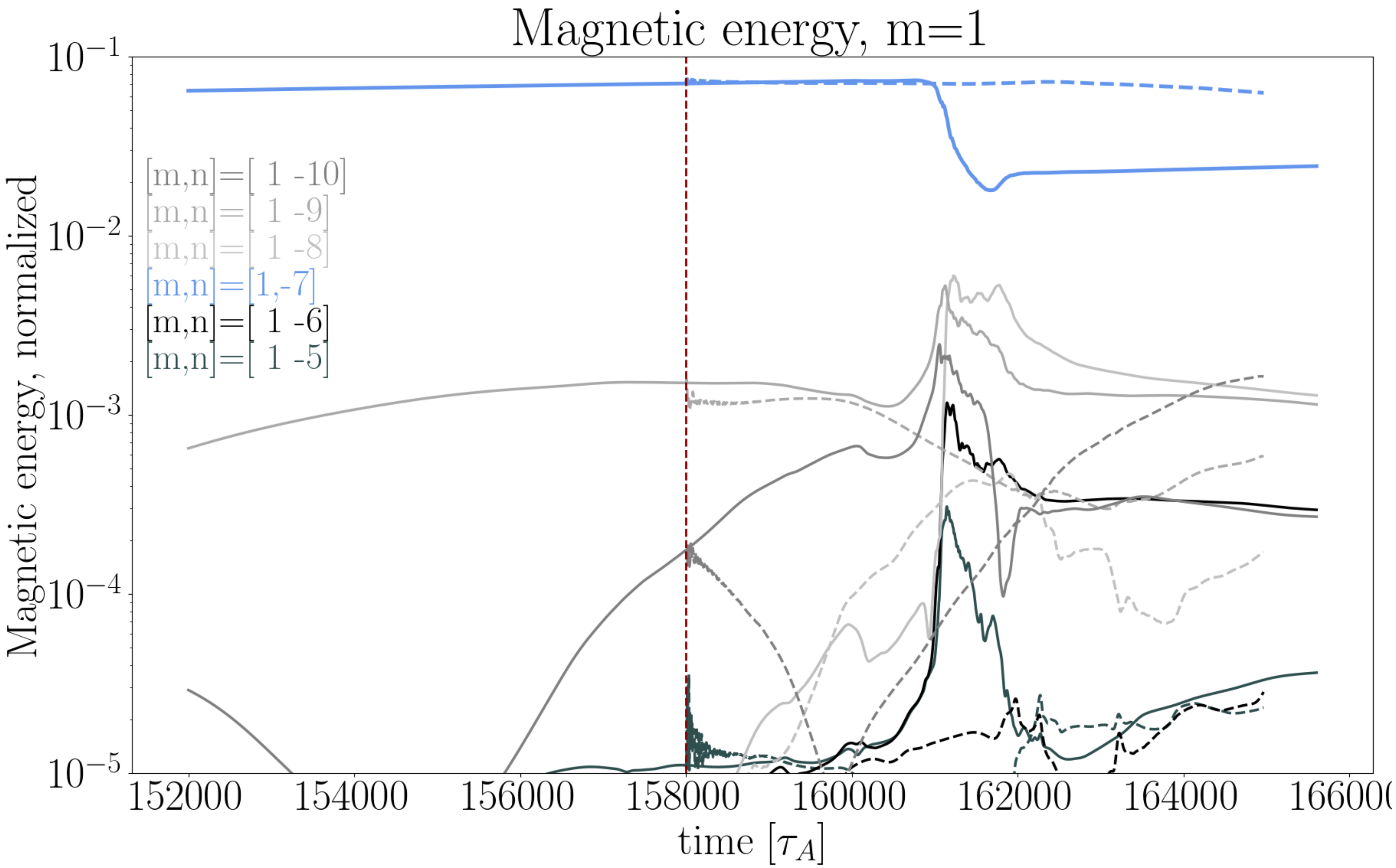
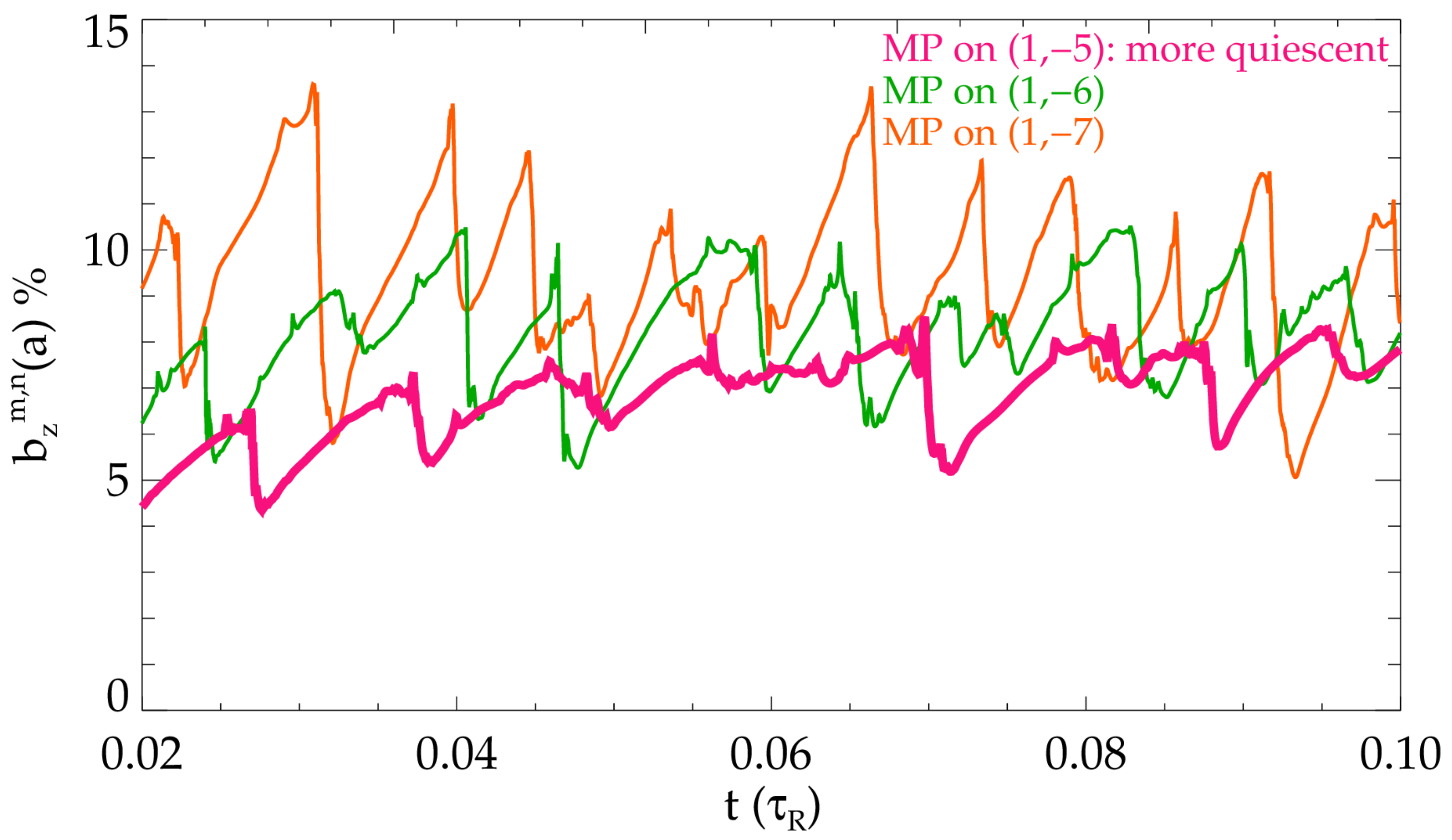


- possible form of control from external MPs?
- modes have been artificially unlocked at the red line
- here gained $5000\tau_A \sim 0.3ms$

more quiescent states with lover n_{MP}

n_{MP} = -7 → -6 → -5



MHD-code

$S=10^6$, $M=10^4$

Magnetic Perturbation Intensity = 4%

- The main features of 3D magnetic reconnection are observed in 3D MHD simulations of the Quasi-Helical RFP states:
  - abrupt conversion of magnetic to kinetic energy
  - current sheets formation
  - excitation of MHD waves
  - plasma flow localized burst
- control possibilities open-up
- ongoing work: whether the Alfvén waves can energize the ions