Overview of experimental results from RFX-mod

- 3D versus 2D -

David Terranova

and RFX-mod team

Consorzio RFX, Associazione EURATOM-ENEA sulla Fusione, Padova, Italy

Outline

- The RFP: from a 2D to 3D is a necessity.
- Experimental and numerical evidence of helical states:
  - Effects in the core.
  - Effect at the edge.
- Stability and transport in helical states.
- RFX-mod as a tokamak and 3D effects of external perturbations:
  - Active control of modes.
  - Effect on the flow.
- Summary.

The Reversed Field Pinch RFX-mod

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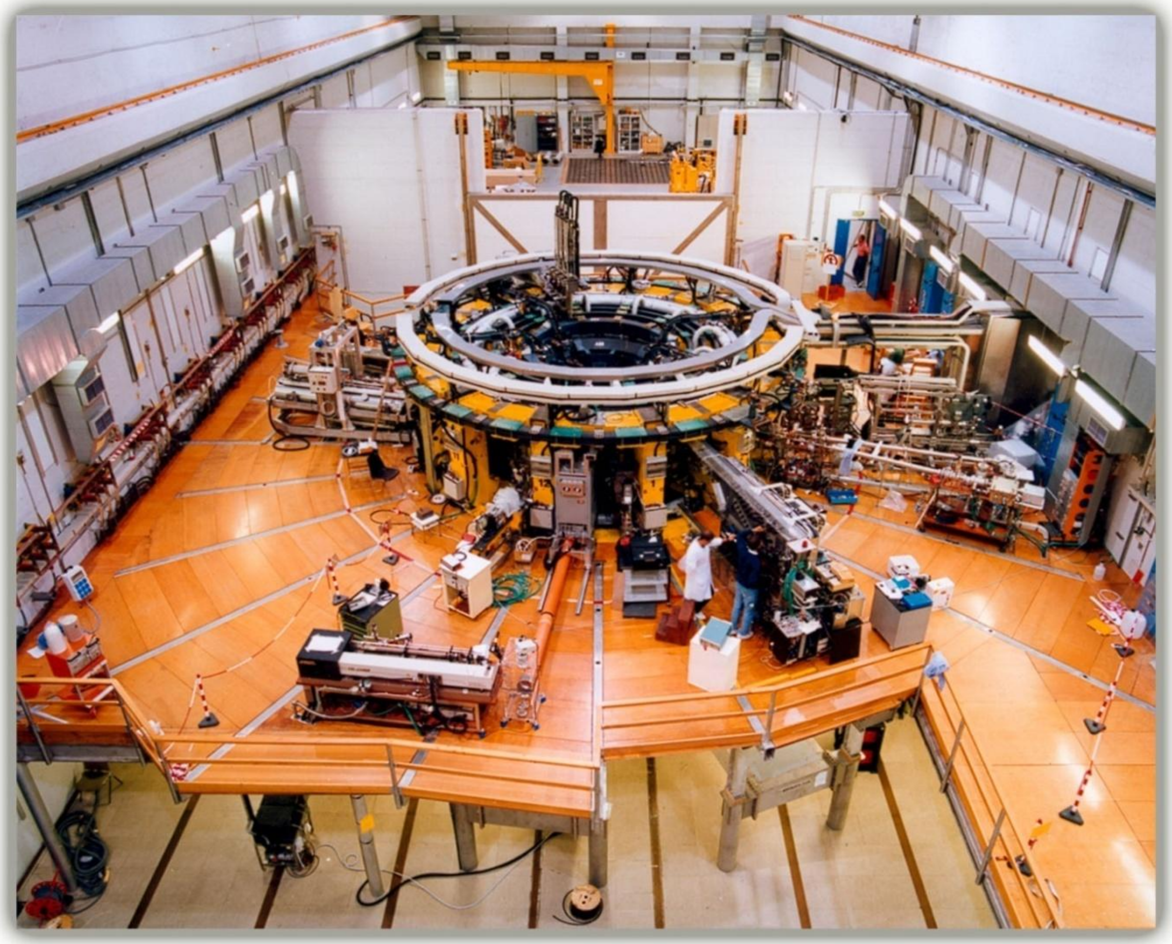
P. Sonato et al., *Fusion Eng. Des.* **66** (2003) 161

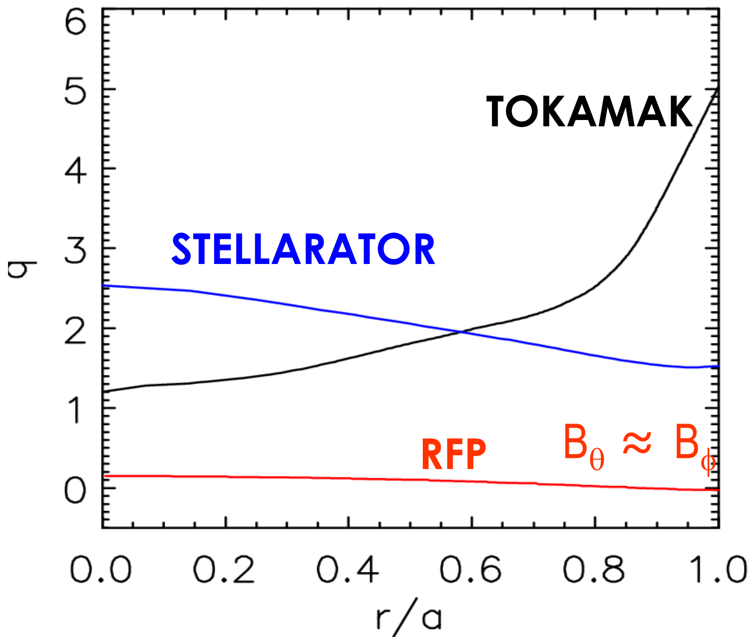


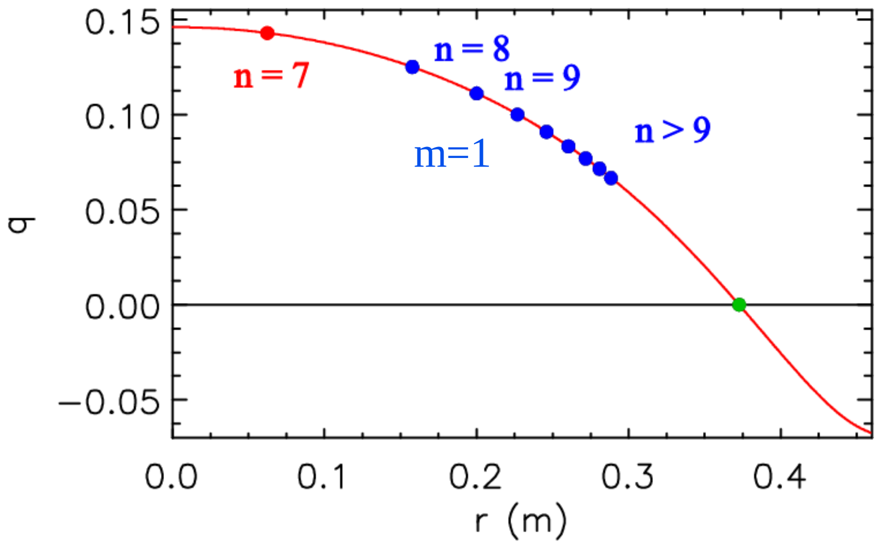
Major radius **2 m**
Minor radius **0.459 m**

Maximum magnetic field **0.7 T**
Maximum plasma current **2 MA**

Real-time control of both equilibrium and perturbations

Safety factor profiles

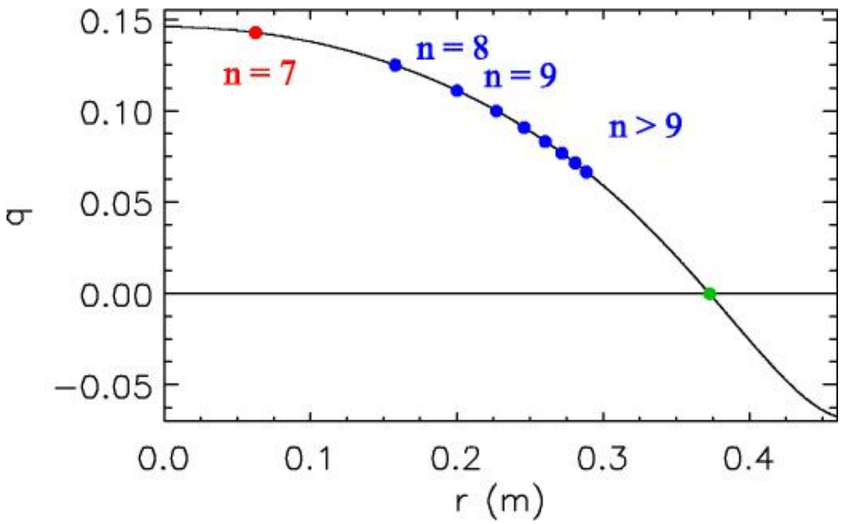


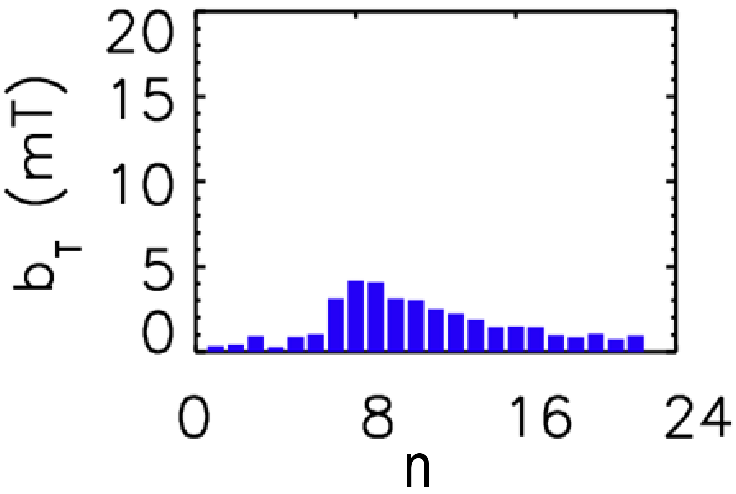


The RFP has to deal with many modes that are resonant inside the plasma.

RFP: intrinsically 3D

It is generally considered that a $q < 1$ configuration like the RFP would be intrinsically plagued by several instabilities at rational surfaces where ***q=m/n***.

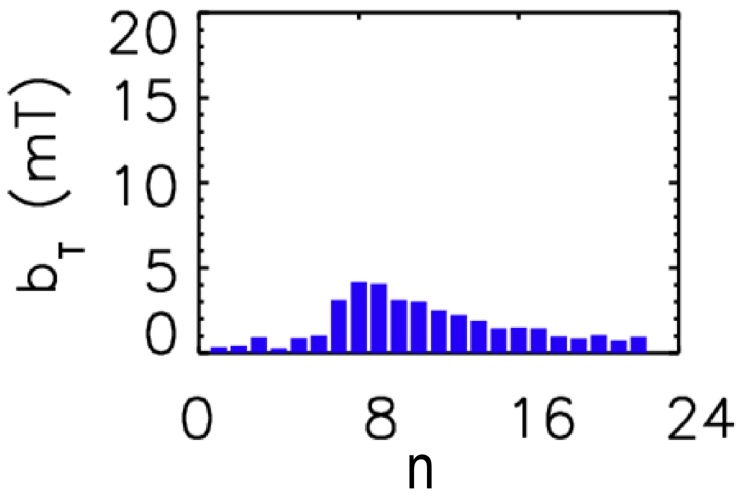


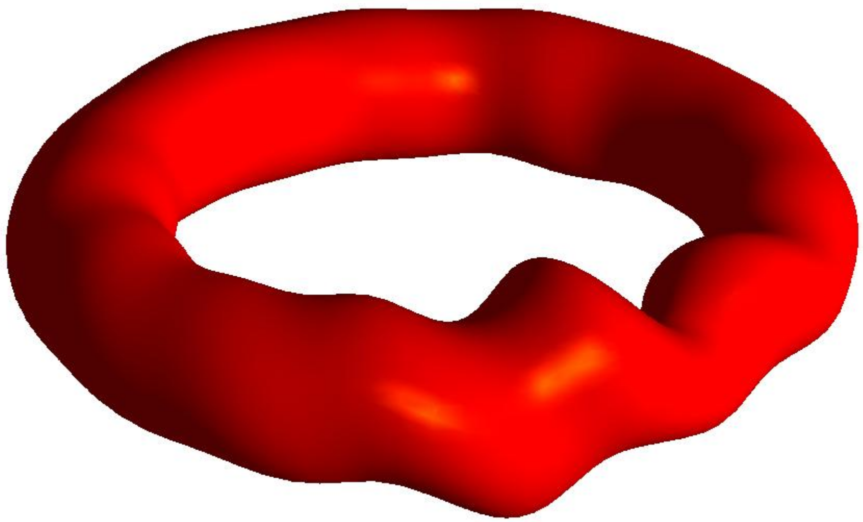


These instabilities are the drive sustaining the self-organization process of the RFP.

RFP: intrinsically 3D but not favourable

Multiple global tearing modes are not good for transport and PWI.



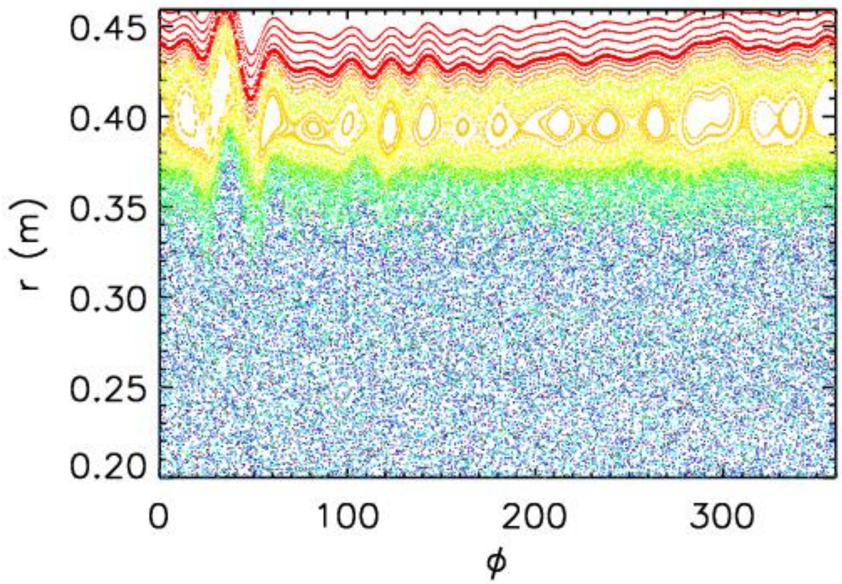


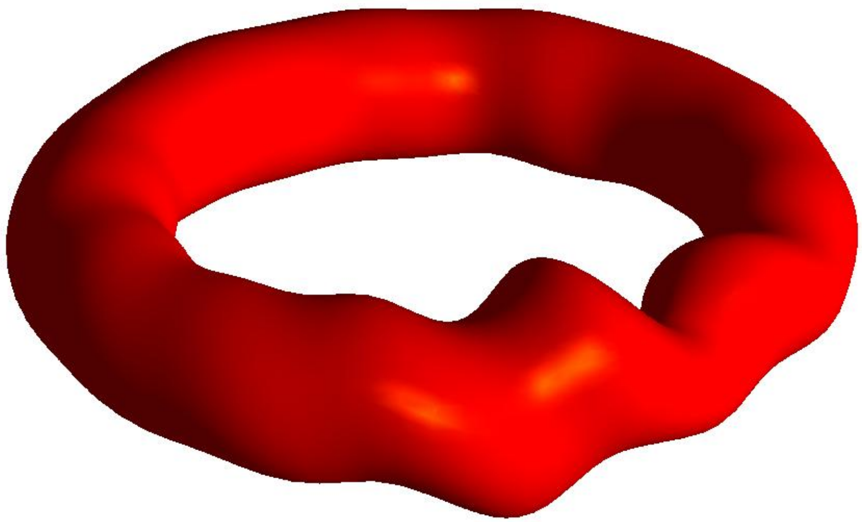
BROAD
spectrum in Fourier space

LOCALIZED
perturbation in the real space

RFP: intrinsically 3D but not favourable

Multiple global tearing modes are not good for transport and PWI.

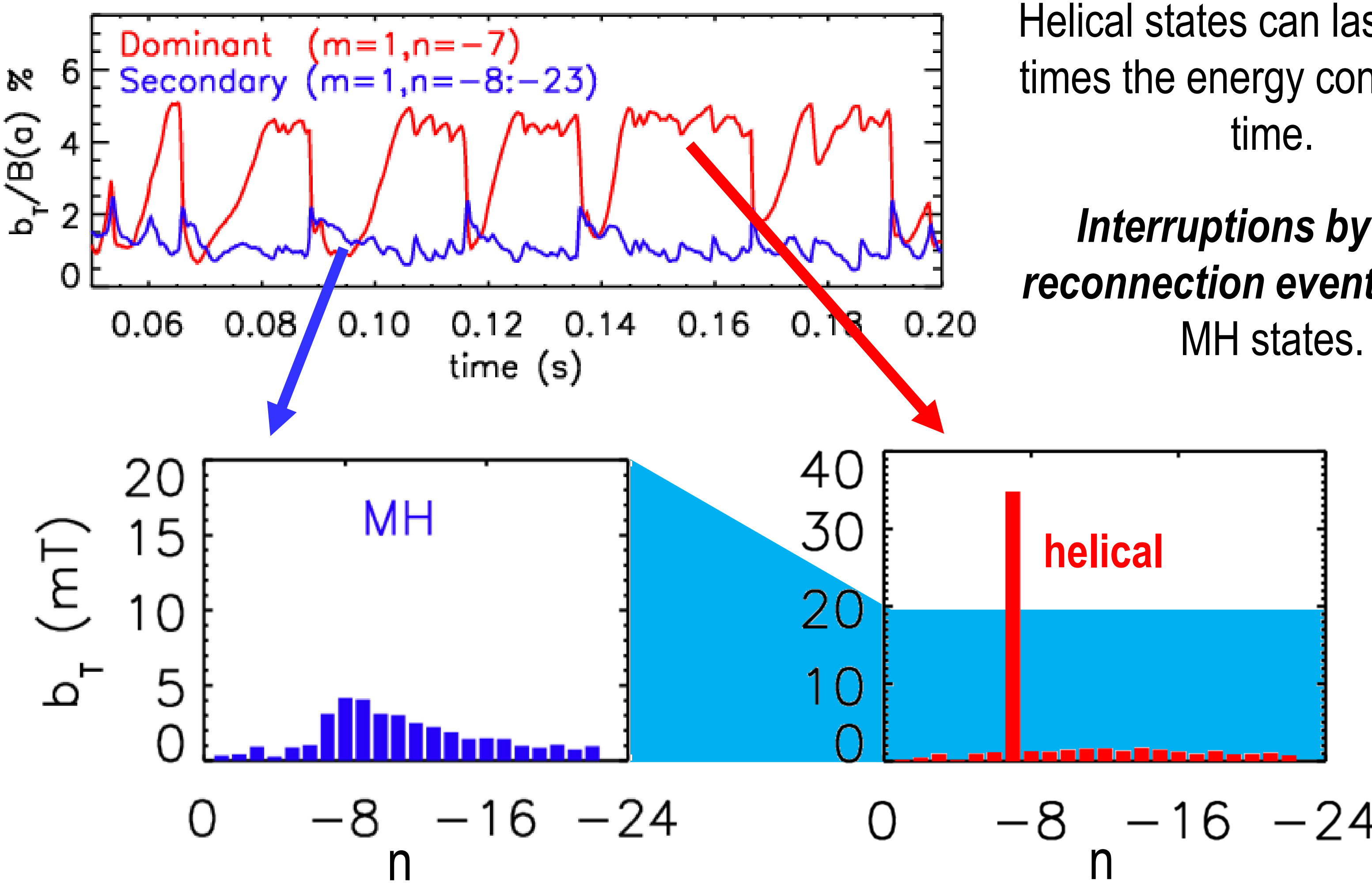




BROAD
spectrum in Fourier space

LOCALIZED
perturbation in the real space

3D evidence: MAGNETICS

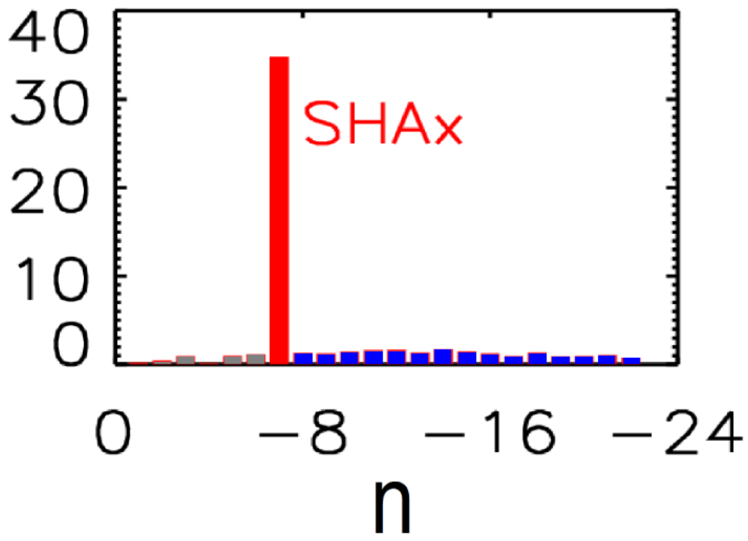


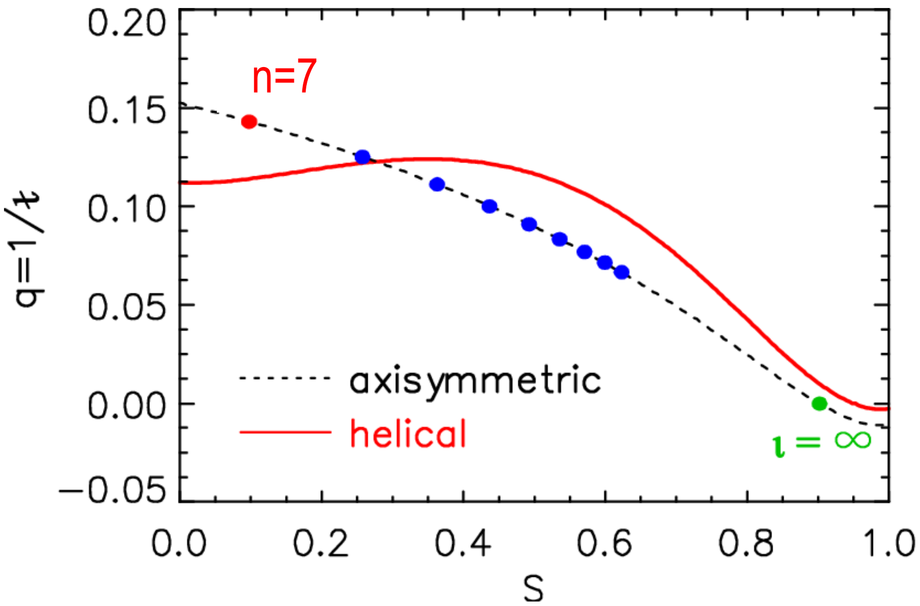
Helical states can last several times the energy confinement time.

Interruptions by MHD reconnection events lead to MH states.

The dominant mode is the most internally resonant tearing mode.

q profile in helical states





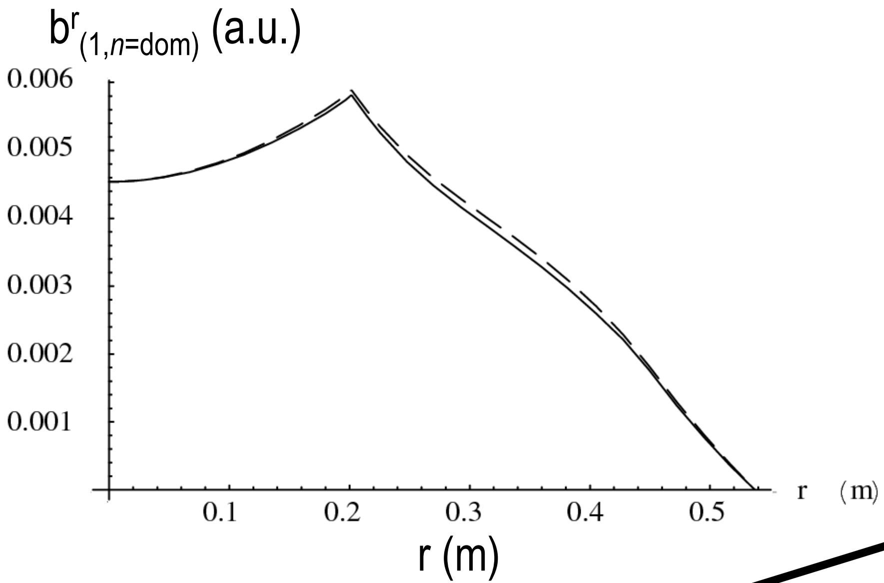
The **core resonance disappears** resulting in a **NON-monotonic** safety factor profile.

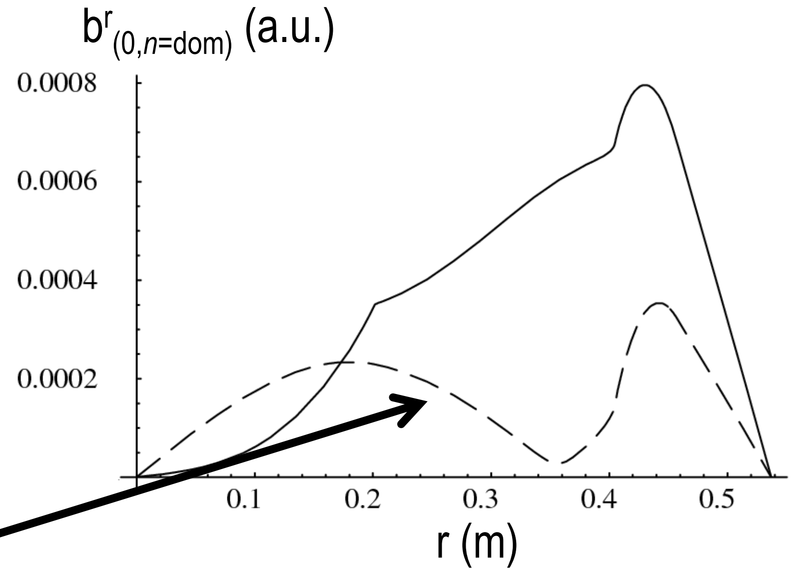
- Cowling compliant (axis-symmetry is broken).
- Helical equilibrium.
- Low magnetic chaos.

E. Martines *et al.*, PPCF **53** (2011) 035015

R. Lorenzini *et al.*, Nature Physics **5** (2009) 570-574

Eigenfunctions in the torus





$$\hat{b}^{r\,m,n} = \left(\frac{1}{\sqrt{g}}\right)^{0,0} \hat{b}^{r\,m,n} + \left(\frac{1}{\sqrt{g}}\right)^{1,0} \hat{b}^{r\,m-1,n} + \left(\frac{1}{\sqrt{g}}\right)^{-1,0} \hat{b}^{r\,m+1,n}$$

NCT code: solves the Newcomb equation. Linear perturbative approach in toroidal geometry, force-free.

P. Zanca & D. Terranova, PPCF **46** 1115 (2004)

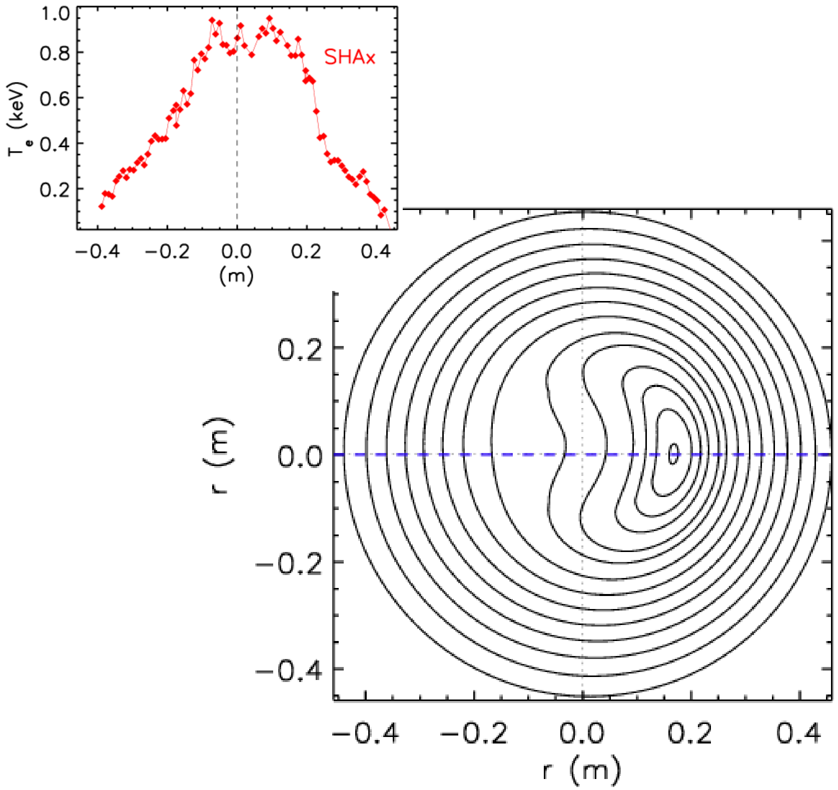
Toroidal helical equilibrium (ideal MHD)

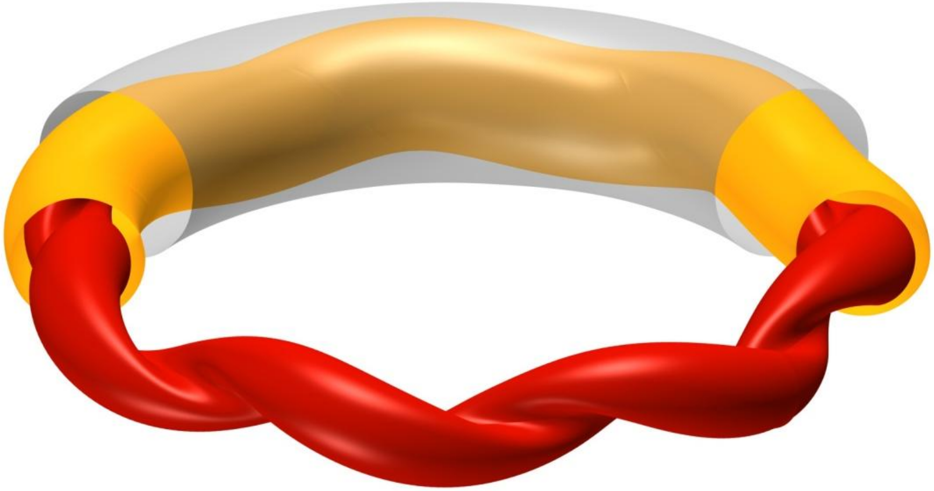
- **SHEq**: uses **NCT** which solves the **inverse problem** with information from magnetics only: E. Martines et al., Plasma Phys. Control. Fusion **53** (2011) 035015

$$\chi^{m,n}(r,\vartheta,\phi) \equiv \underbrace{m\Psi_0(r) - nF_0(r)}_{\text{Axi-symmetric}} + \Big(\underbrace{m\psi^{m,n}(r) - nf^{m,n}(r)}_{\text{Dominant mode}}\Big)\times e^{i(m\vartheta - n\phi)}$$

	Toroidal flux	Poloidal flux
Order-0	F_0	Ψ_0
Frist-order (*m*,*n*) mode	$f^{m,n}$	$\psi^{m,n}$

Helical equilibrium





Constant helical flux surfaces define the topology of plasma equilibrium: all measured quantities can be correctly interpreted in terms of the dominant helicity.

R. Lorenzini *et al.*, Nature Physics **5** (2009) 570-574

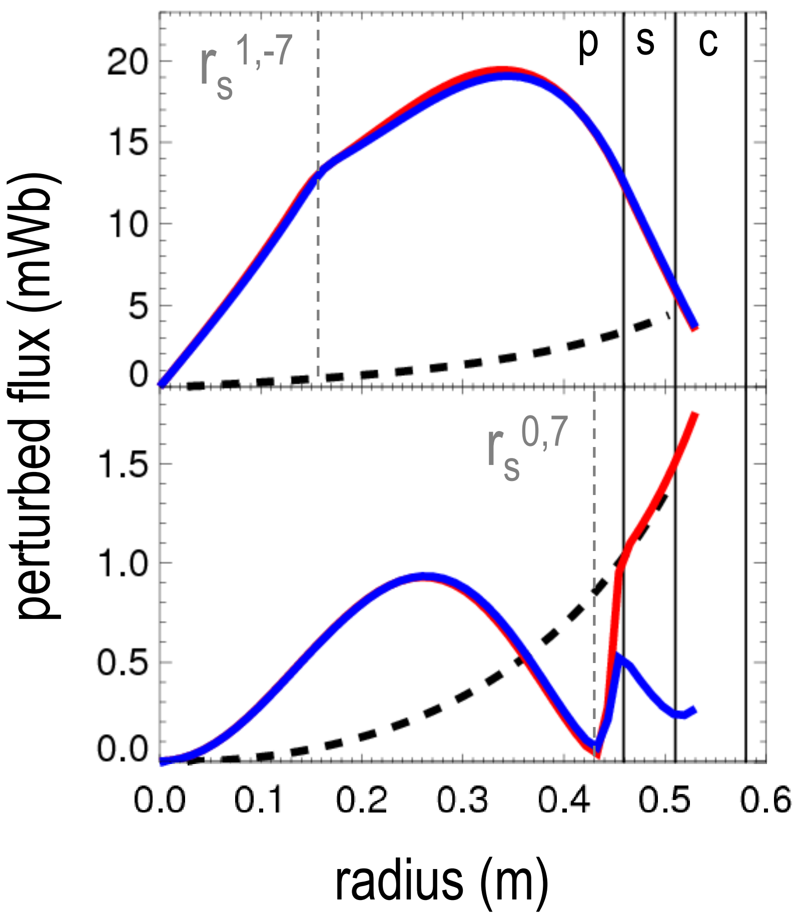
Plasma response to magnetic field errors

Plasma response to *n*=7 error field harmonic computed from toroidal Newcomb equation.

- - vacuum field

— plasma (#28784)

— plasma + dynamic decoupling (#28765)



m=1, *n*=-7
dominant harmonic of the helical equilibrium

m=0, *n*=7
edge resonant, partly due to toroidal coupling

3D equilibrium (ideal MHD)

- **SHEq**: linear perturbative, toroidal geometry, force-free. Solves the inverse problem with information from magnetics only.

$$\chi^{m,n}(r,\vartheta,\phi) \equiv \underbrace{m\Psi_0(r) - n\mathrm{F}_0(r)}_{\text{Axi-symmetric}} + \left(\underbrace{m\psi^{m,n}(r) - nf^{m,n}(r)}_{\text{Dominant mode}}\right) \times e^{i(m\vartheta - n\phi)}$$

E. Martines et al., Plasma Phys. Control. Fusion **53** (2011) 035015

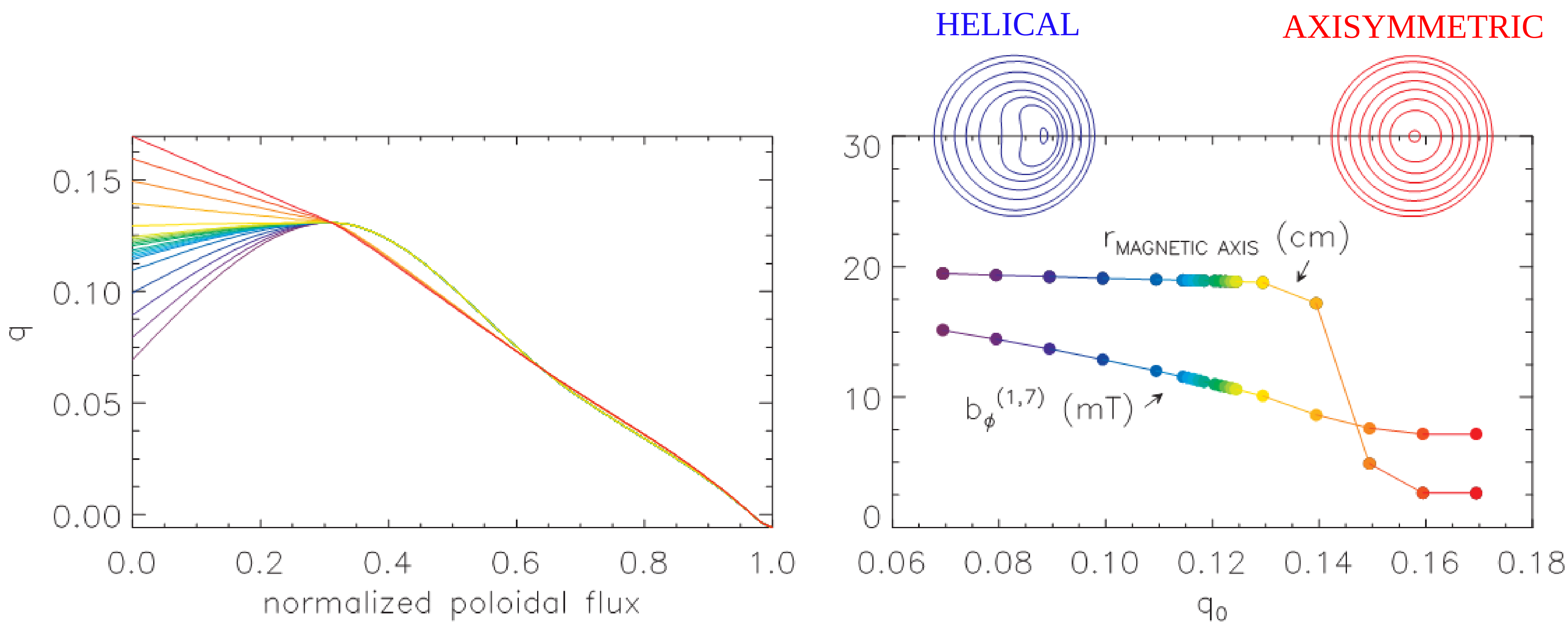
- **VMEC**: non-linear, with pressure, fully 3D. Solves the direct problem.

S.P. Hirshman and J.C. Whitson, *Phys. Fluids* **26** (1983) 3554

- **V3FIT**: solves the inverse problem with diagnostics (magnetic and kinetic). Uses **VMEC** as equilibrium solver.

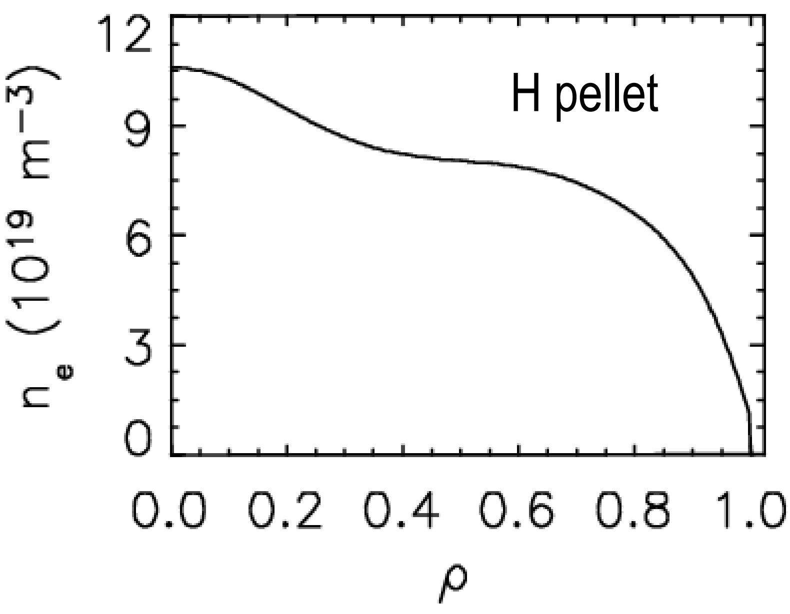
J.D. Hanson et al., *Nucl. Fusion* **49** (2009) 075031

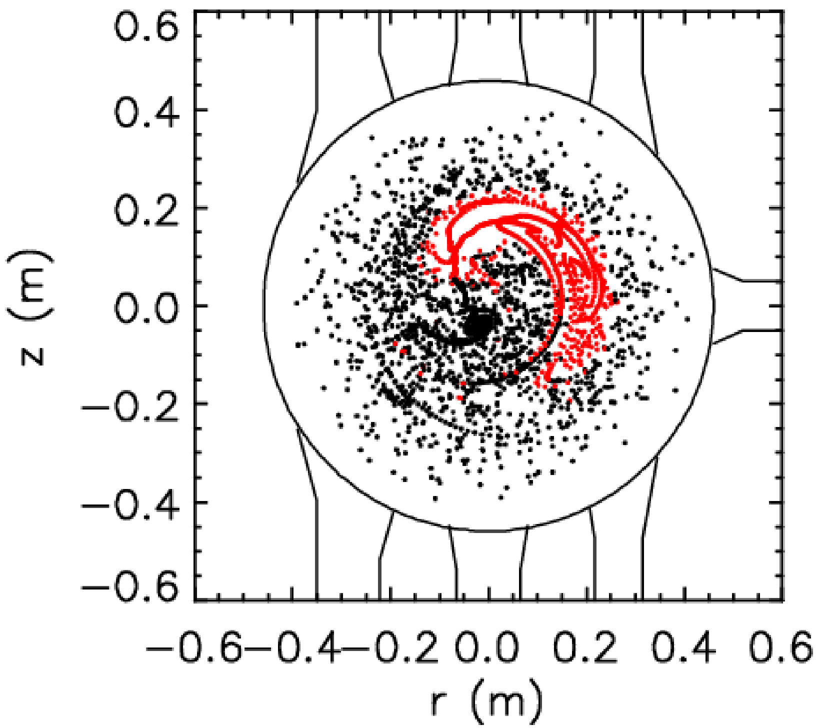
Effect of q profile



Helical states are characterized by the reversed shear in the core.

Particle transport studies with pellet injection

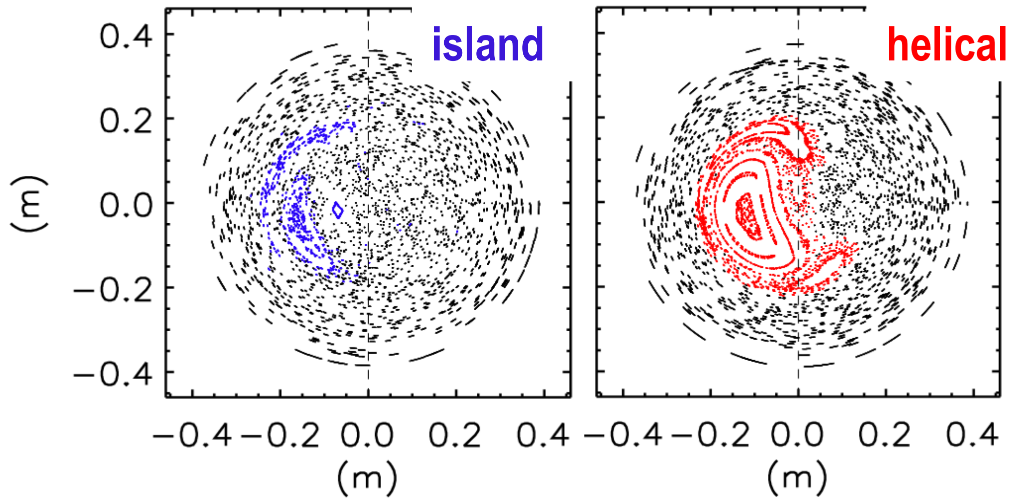




Pellet *particles are bound to the helical shape* of the plasma

And are confined inside the helical core.

Helical state is 'more' chaos resilient

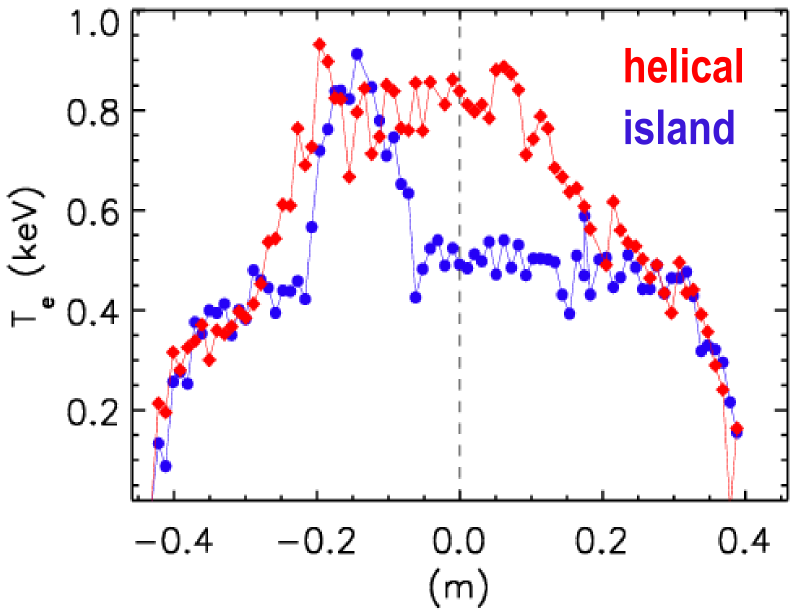


Poincaré plot of two states having analogous values of secondary mode energy.

- The increased resilience to the residual magnetic chaos explained by the lack of the X-point.

  D.F. Escande *et al.*, PRL. 85, 3169 (2000)

- The hot part of the thermal structure is larger in helical states.



Resilience to chaos and MHD spectrum

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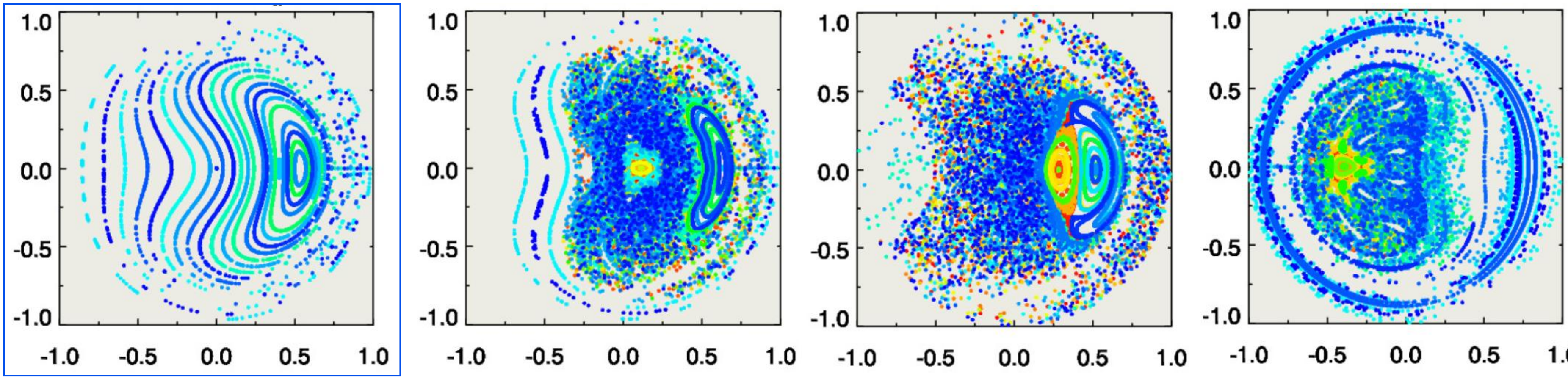


Starting case resilient to chaos

Remove one secondary mode

Phase flip for a secondary mode

Phase flip for dominant mode

The resilience to chaos is sensitive to the q profiles in the core and to the features of the spectrum of magnetic fluctuations.

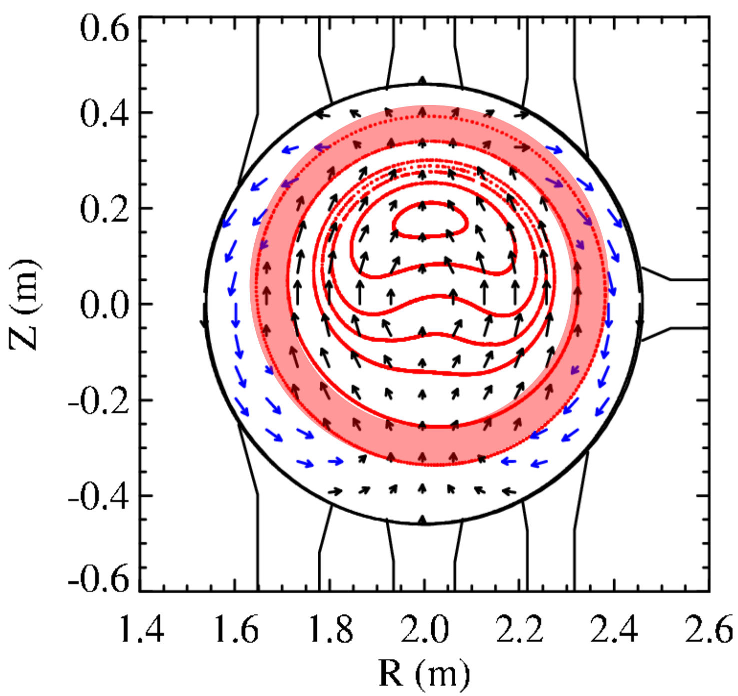
M. Veranda *et al.*, EPS-ICPP 2012

SpeCyl code: 3D cylindrical, nonlinear, visco-resistive.
Nemato for line tracing.

Cappello and Biskamp NF 1996
Finn, Chacon, PoP 2005

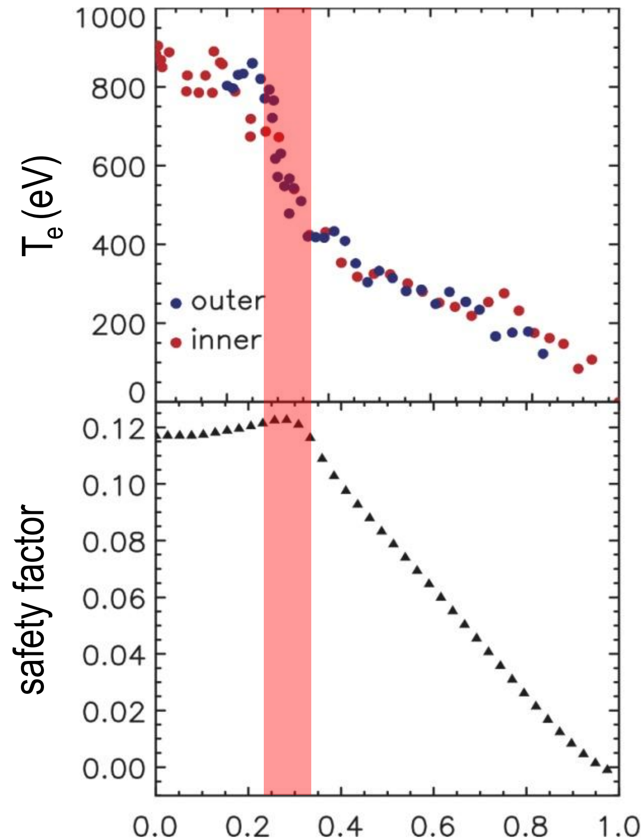
Magnetic and flow shear: ITB formation

- ITB forms where magnetic shear vanishes.
- Flow has helical pattern with maximum flow shear (10^4-10^5 s^{-1}) near ITB radius.
- Strong similarity with tokamak and stellarator.



2D map of flow from multi-chord passive Doppler spectroscopy

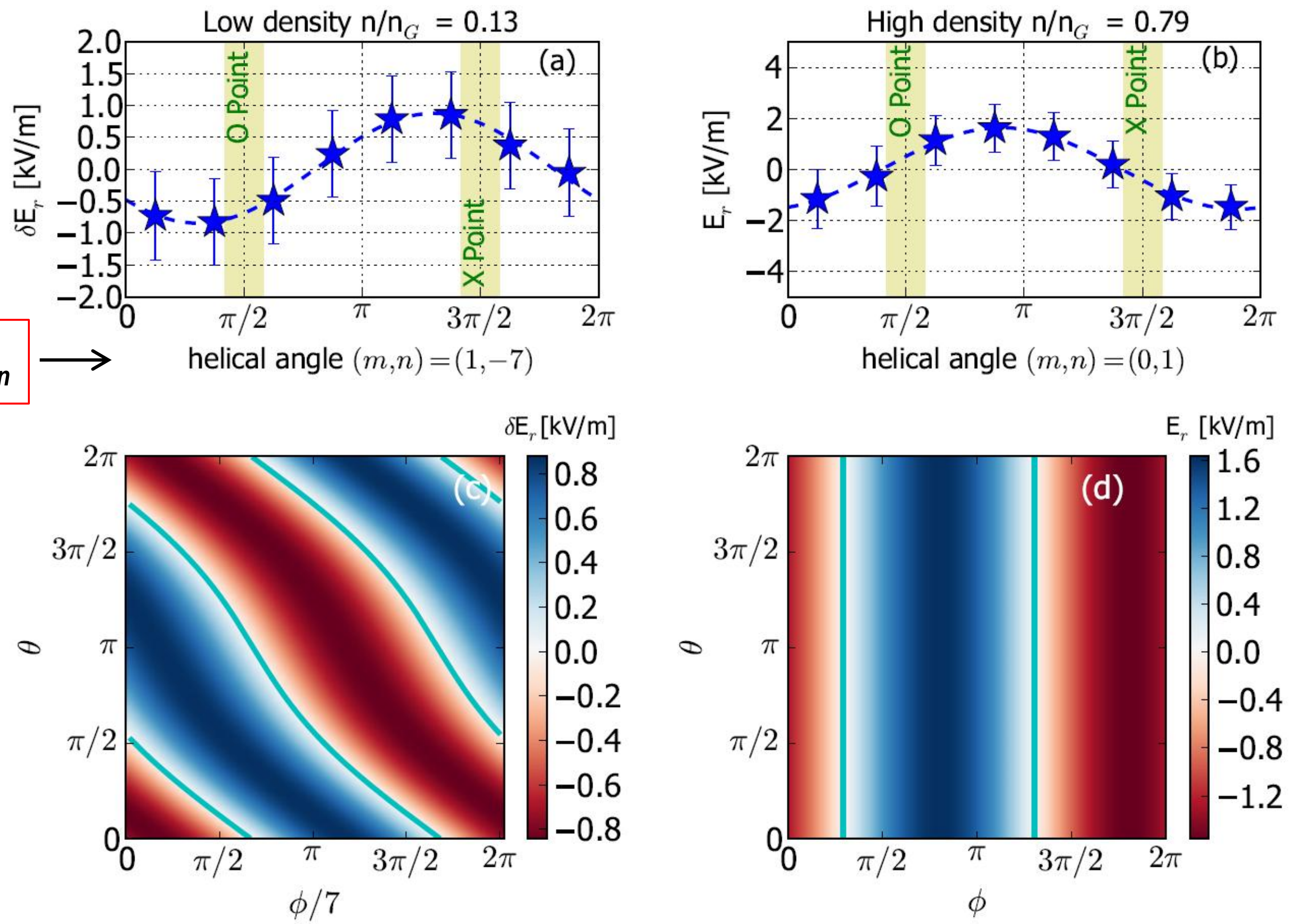
F. Bonomo *et al.* NF 2011



M. Gobbin *et al.* PRL 2011

3D Edge properties

$$u_{m,n} = m\theta - n\varphi - \Phi_{m,n}$$



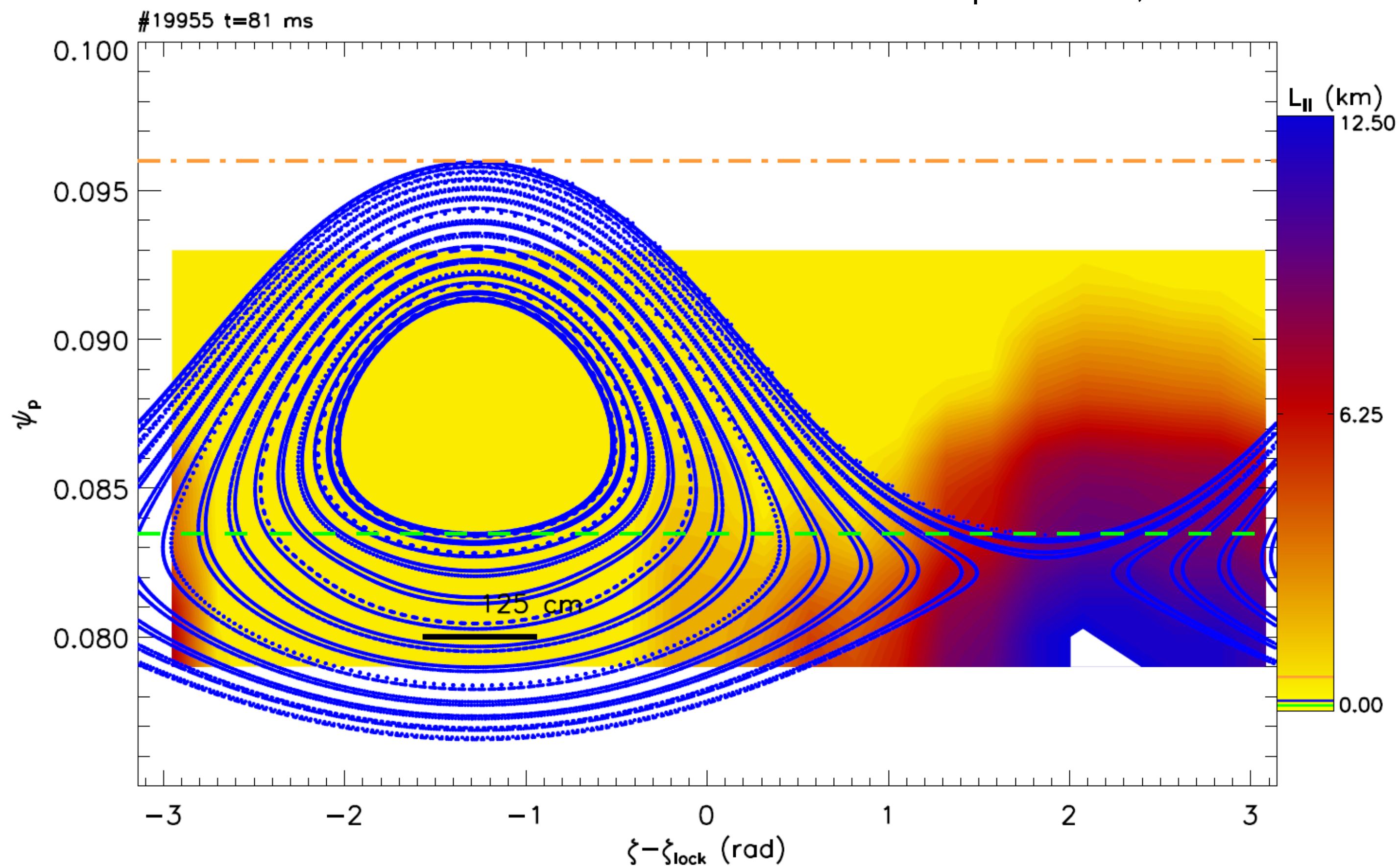
The small helical ripple modulates all the kinetic properties of the plasma and the plasma wall interaction.
The edge E^r is consistent with the applied helicity.

N. Vianello *et al.* 24th IAEA (2012), EX-P8-02

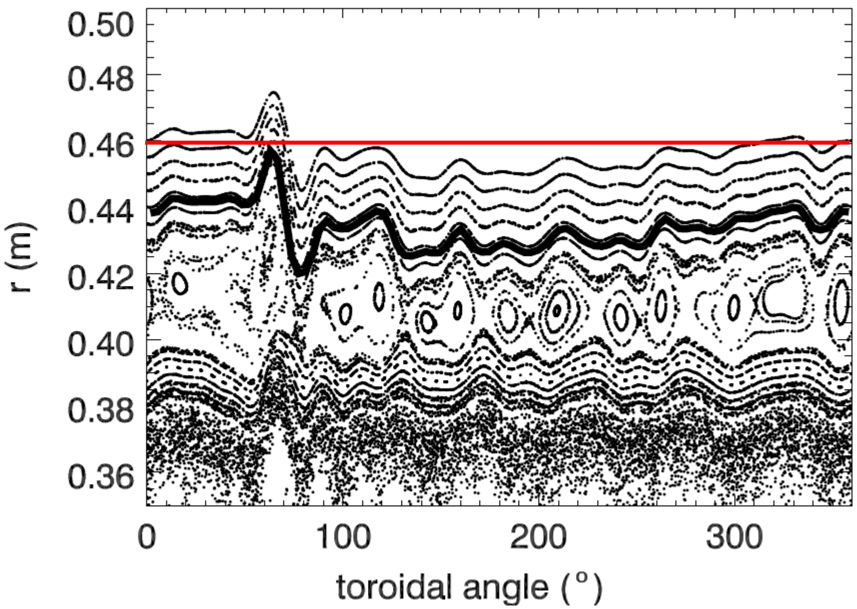
Simulations with the GC code Orbit

- Parallel electron **connection length** to the wall (or, equivalently, electron transit time) shows **3 orders of magnitude difference** along *u* (in the figure, a 0/1 island).
- Ions possess larger drifts and do not show a modulation along the helical angle *u*.

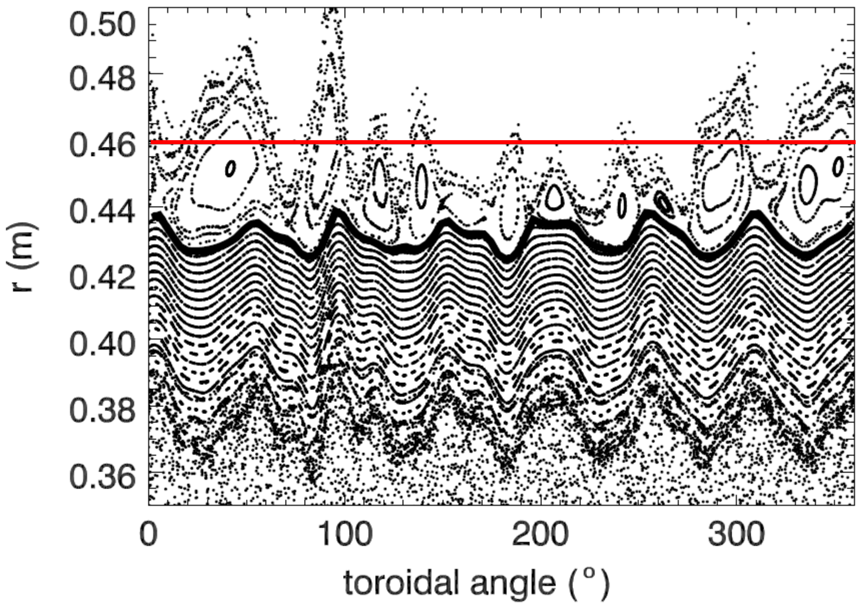
G.Spizzo et al., Nucl. Fusion **52** (2012) 054015



RFX-mod boundary



Limiter-like *configuration*
deep reversal



divertor-like *configuration*
shallow reversal

The plasma boundary in high current helical RFP plasmas could be exploited for building a divertor by locating divertor plates with appropriate pumping in the regions of strong interaction (more and more regular as the amplitude of secondary modes reduces as plasma current is increased).

Such RFP "helical-divertor" would be more similar to the ***island divertor in stellarators*** *than to the tokamak divertor.*

E. Martines *et al. Nucl. Fusion* **50** (2010) 035014

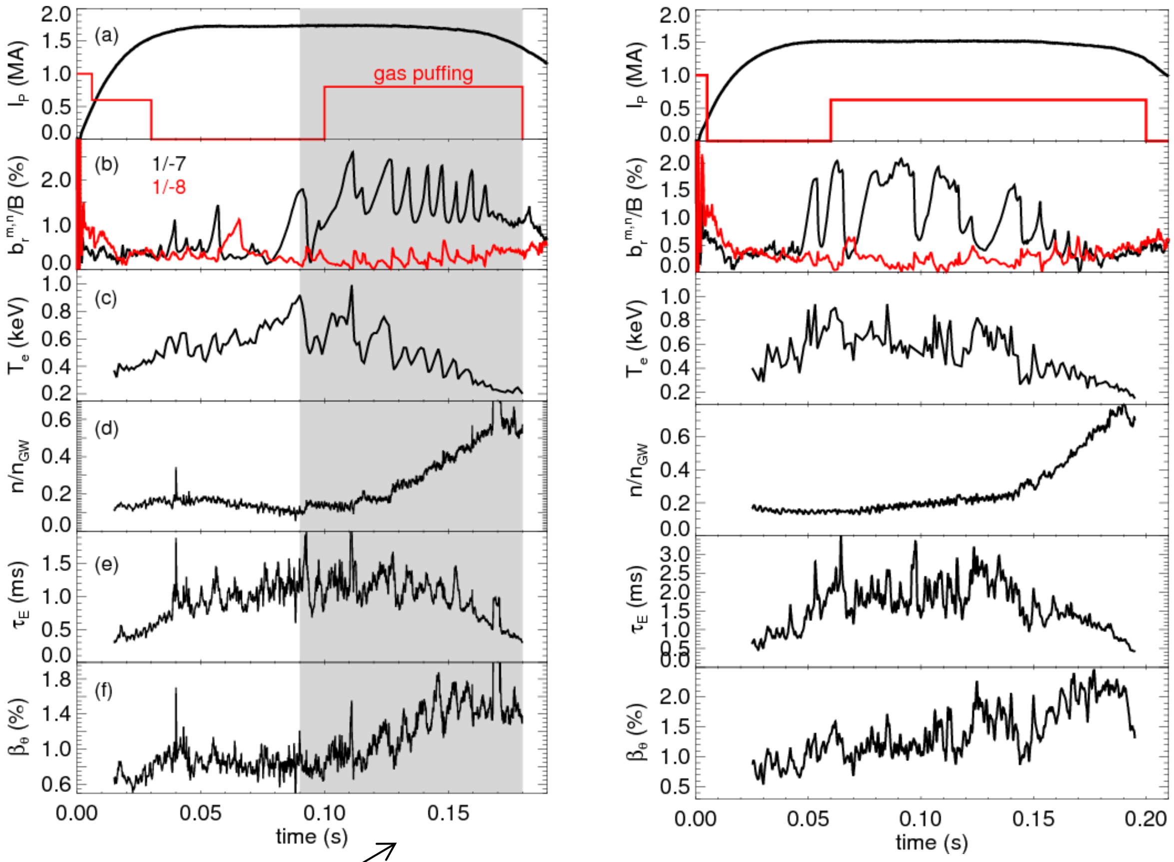
High density helical regimes

Helical shaping allows **extending** the **density range** where helical states exist.

The energy confinement does not change with helical shaping, as long as $b_r^{1,-7}(a)/B<2\%$.

Some confinement degradation occurs at the highest density reached ($n/n_{GW}\approx0.5$).

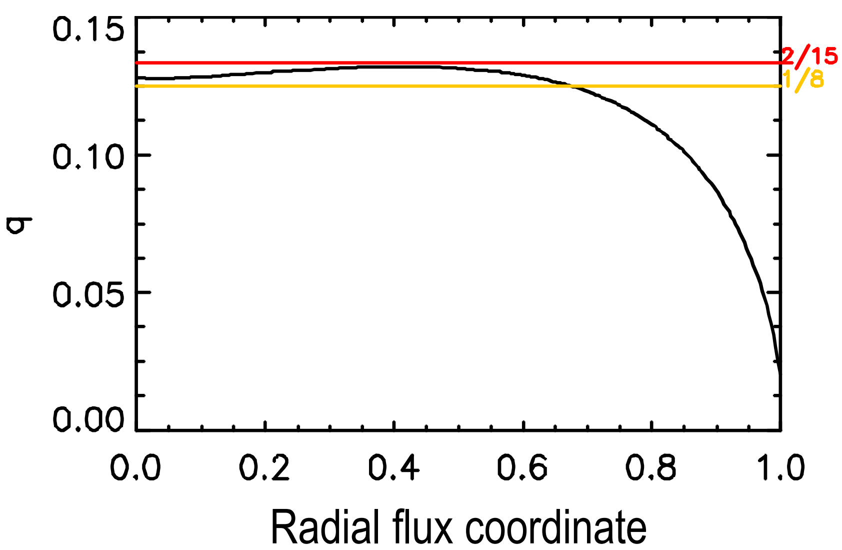
DENSITY INCREASES MAINLY DUE TO GAS PUFFING

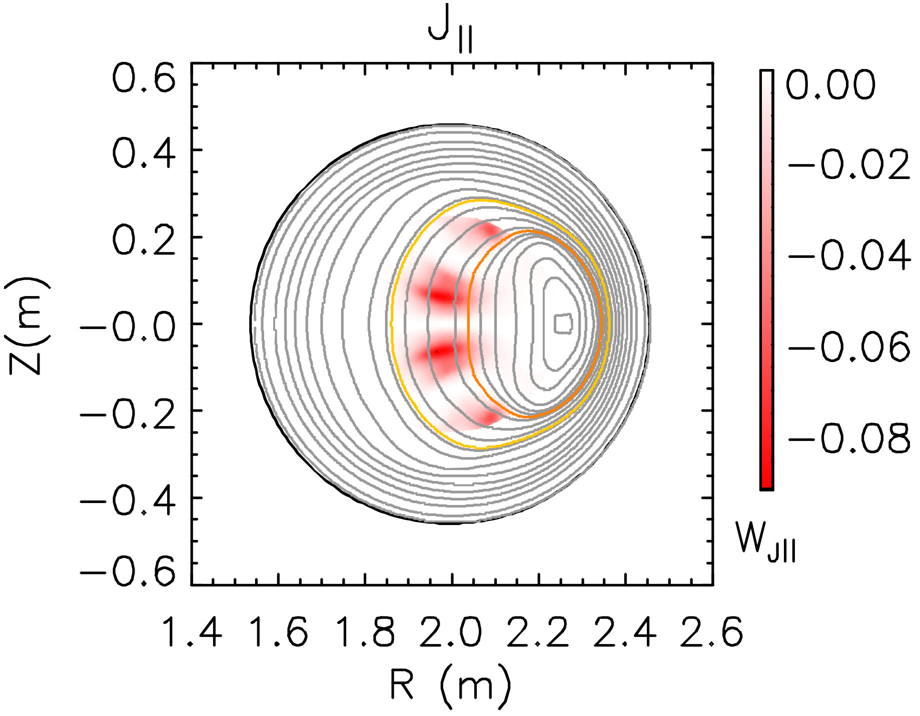


Shaded area **helical boundary ON**

Ideal linear stability analysis

Periodicity symmetry breaking modes: dominantly the *m*=1,*n*=8 coupled with the *m*=2,*n*=15 modes.





Both magnetic shear and double resonances play a role in breaking the symmetry.

Terpsichore code: W.A. Cooper (CRPP)

Heat transport in helical states

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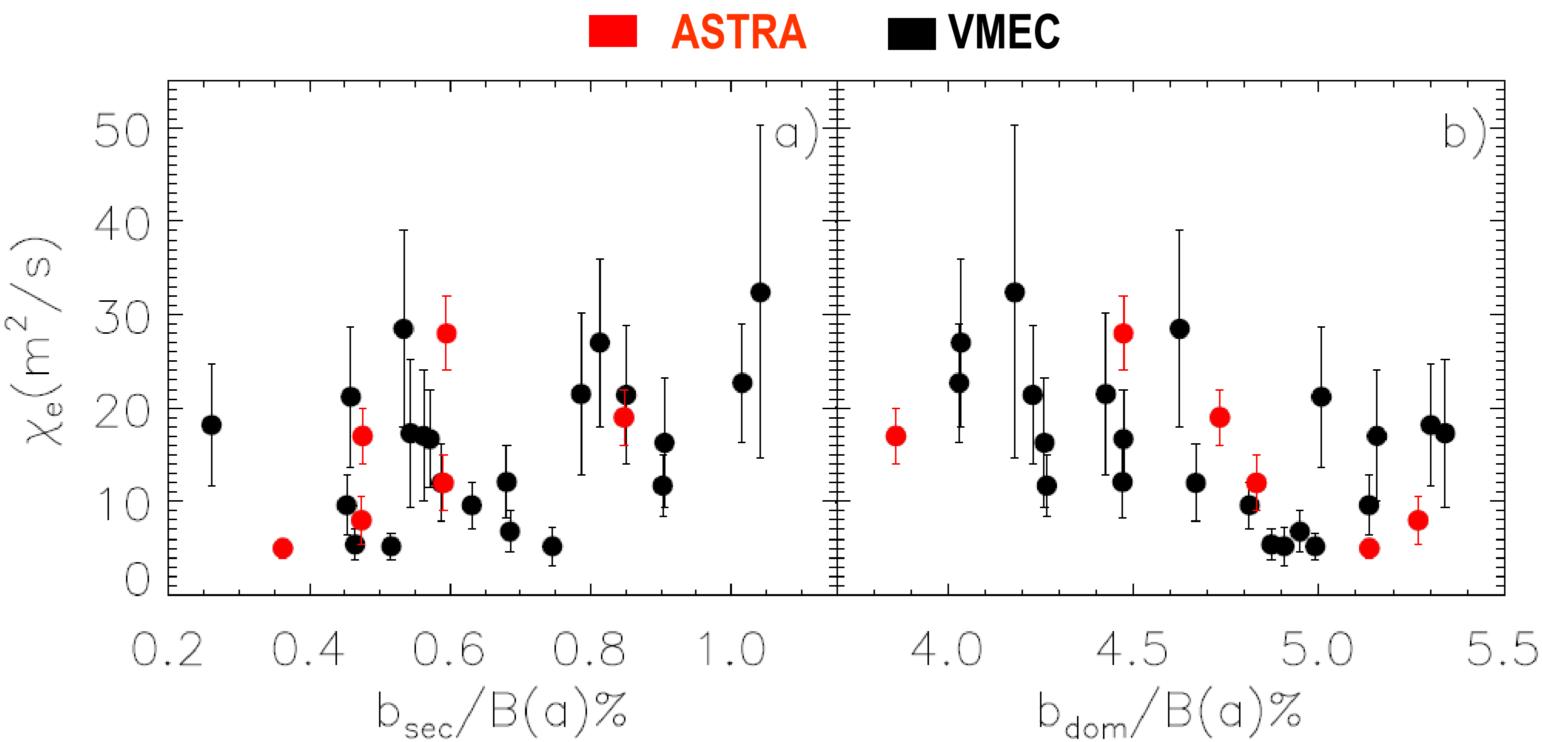
Minimum value of χ_e computed from VMEC equilibrium and with ASTRA.



χ_e values **below 10 m^2/s** only for high dominat mode or low secondary modes (<0.8%).

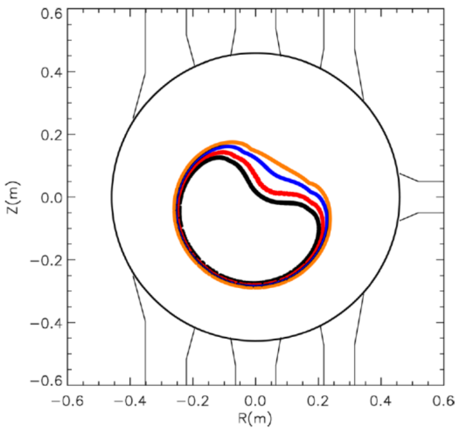
χ_e has larger spread for low secondary modes. This could imply **other mechanisms for energy transport?**

M. Gobbin *et al.*, EPS 2012

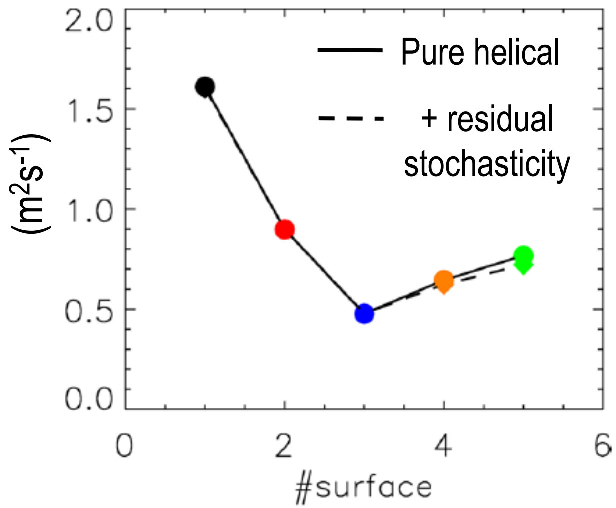
Effect of residual stochasticity and turbulence

- Residual stochasticity at the ITB has an effect only on electron particle transport.

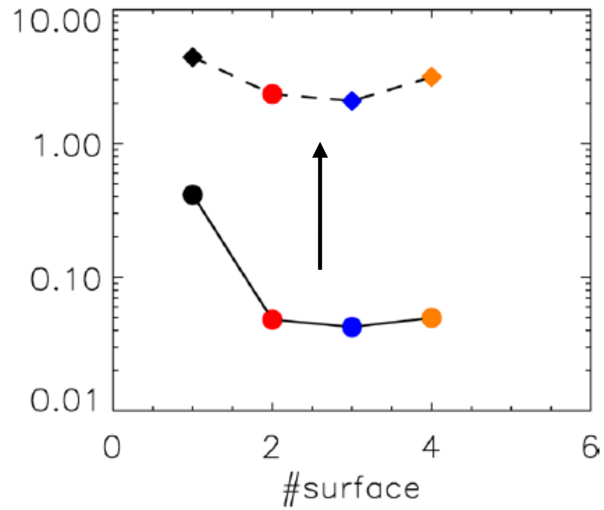
M. Gobbin *et al.* PPCF 2009 and PoP 2011



D_i, ion diffusivity (m^2s^{-1})



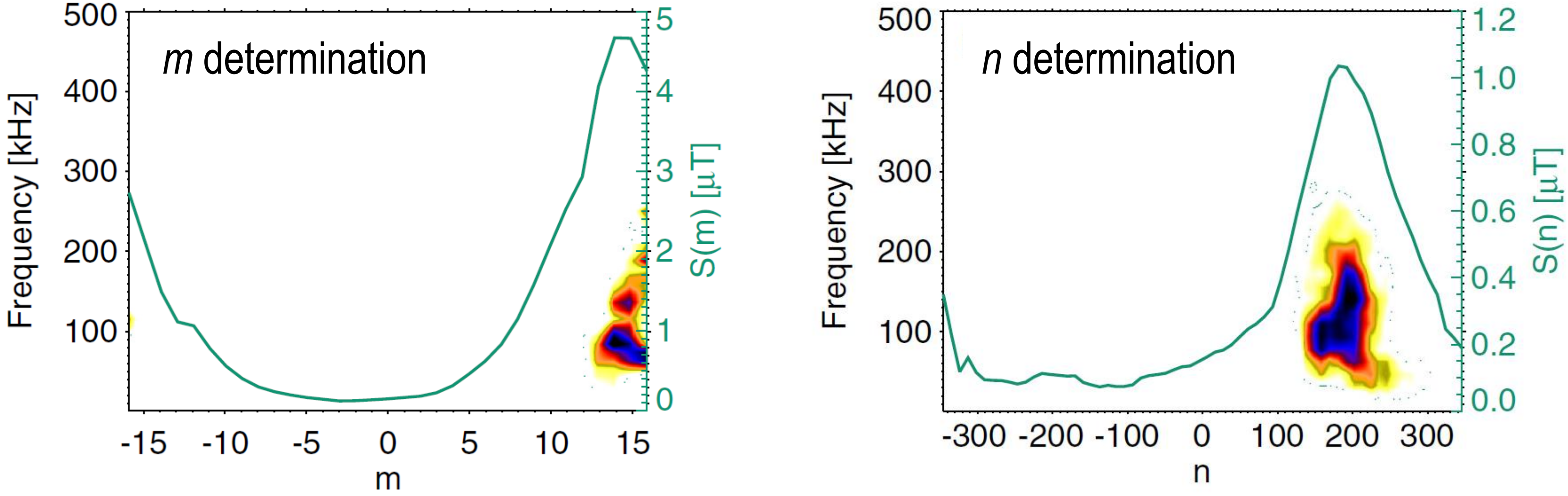
D_e, electron diffusivity (m^2s^{-1})



- Other instabilities may also play a role: Microtearing modes recently observed and modelled with GS2.

M. Zuin *et al.* PRL 2013

Micro-tearing instability

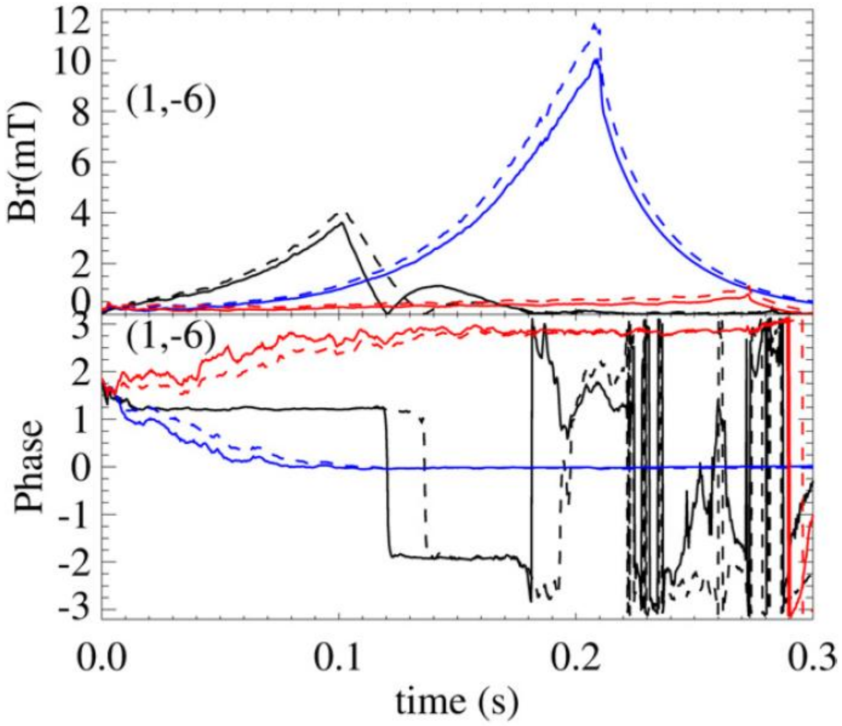


The spectrum structure is deduced by a two-point analysis using two magnetic coils poloidally separated.

The structure of the instability is centered around (*m*,*n*) = (15,190)
This **corresponds to a resonant condition** for q at minor radius $r_{res}/a \approx 0.6$, which is in the **region** of the **maximum T_e gradient**.

M. Zuin *et al.* PRL 2013

Reduced set of coils

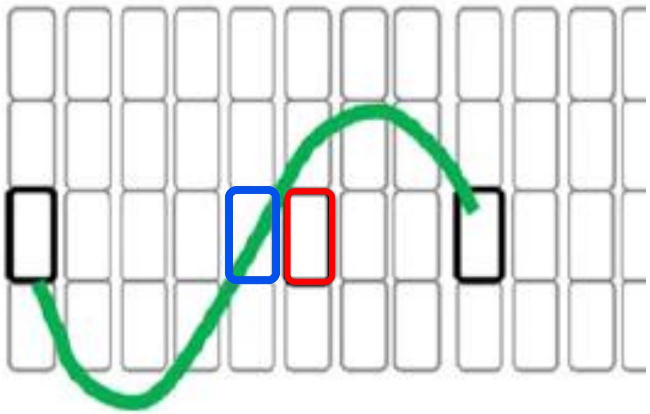


48x4 (full system)

12x1 (evenly spaced)

12x1 (un-evenly spaced)

with sideband subtraction



Good **RWM control** with a reduced set of coils **was also possible in the low-q_{edge} tokamak** configuration: operation at q_{edge} = 1.7 with the use **of just six coils** located **in the outboard mid-plane**.

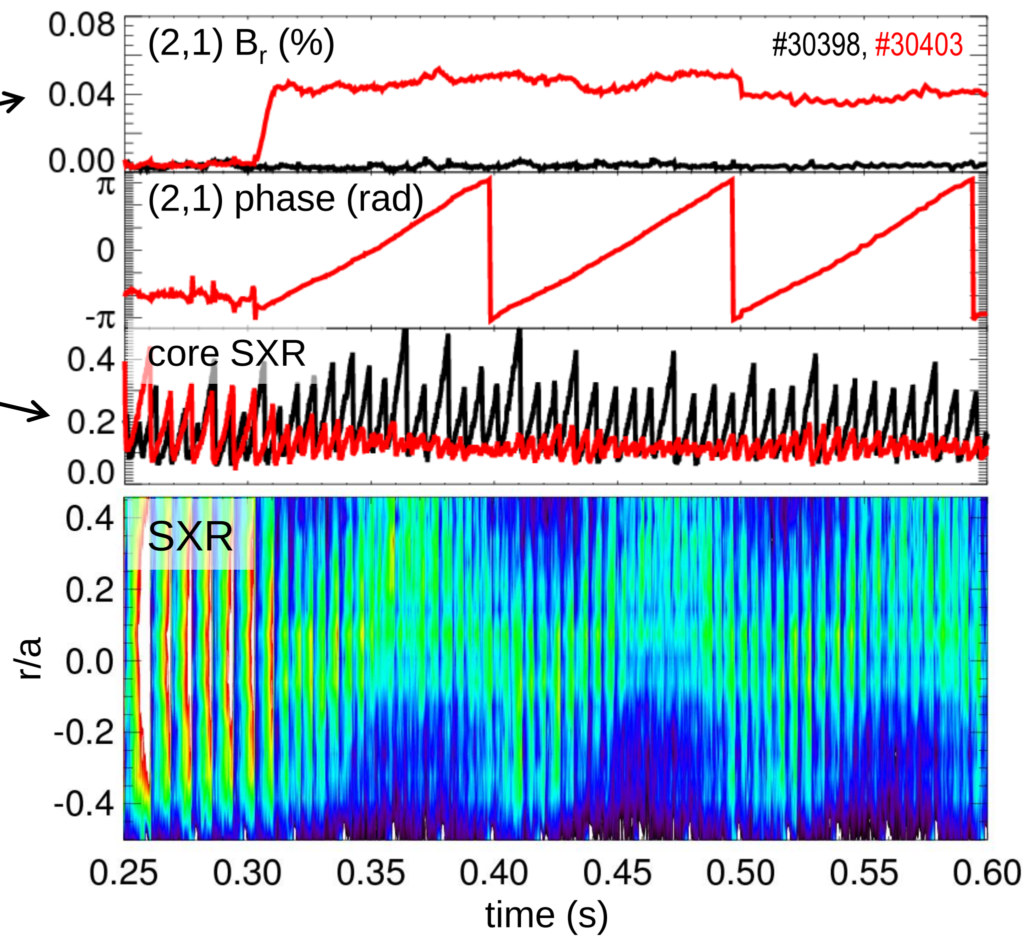
M. Baruzzo *et al.* Nucl. Fusion **52** (2012) 103001

Control of a n=1 tokamak equilibrium

(2,1) RWM maintained at finite amplitude by feedback control.

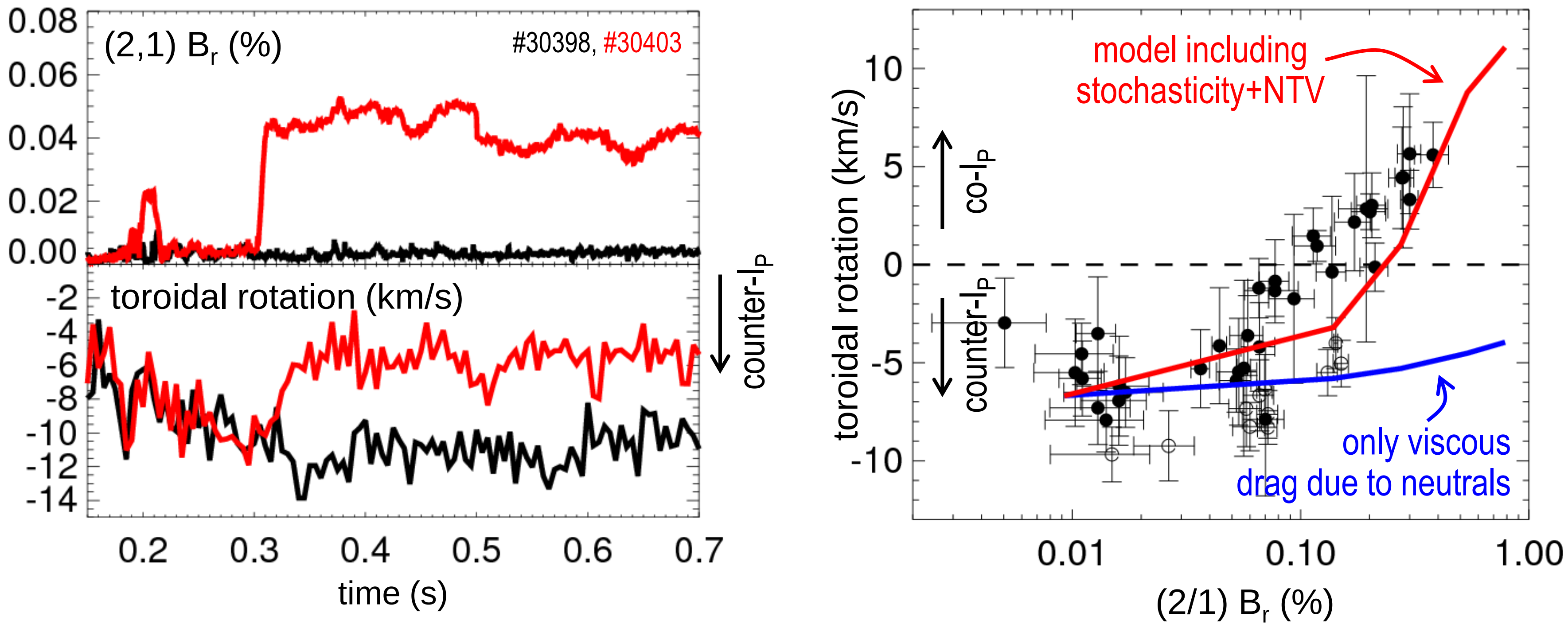
Sawtooth amplitude significantly reduced.

Sawtoothing (1,1) internal kink replaced by a more continuous (1,1) helical core.



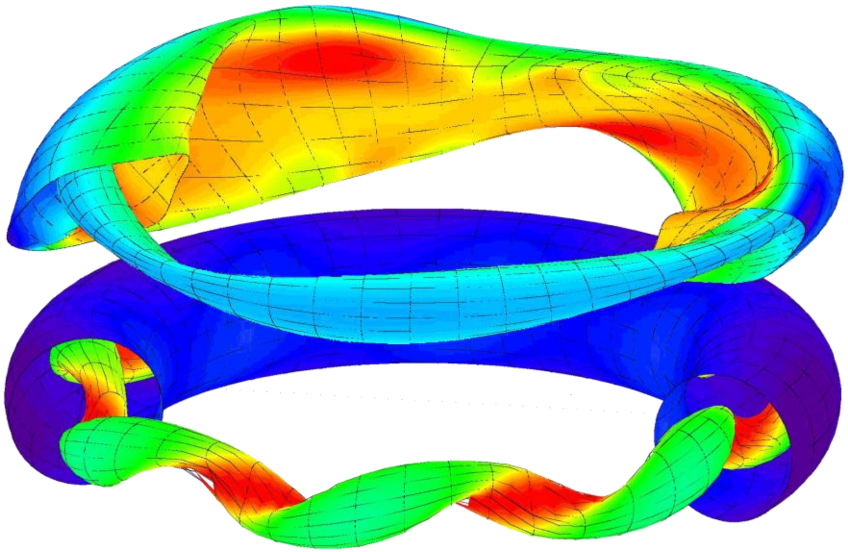
3D effects on toroidal rotation in tokamak

- The non-resonant (2,1) mode affects toroidal rotation. L. Piron *et al.* 2012
- Results interpreted by a 1D momentum balance model including torques due to stochasticity and neoclassical toroidal viscosity.



Summary

- The **3D nature** of the RFP is quite different in **MH** and **QSH** states: it is necessary to look at the plasma in **adequate coordinates**, to correctly describe and give an interpretation of experimental data.
- The **helical structure affects** all aspects of the **plasma**: level of chaos, PWI, edge properties, stability and transport.
- **External perturbations** can **help** the sustaiment of helical states in particular states such as in **high plasma density**.
- **Need to understand** more precisely the link between MHD and temperature dynamics in helical states as well as **the interruption** of such states.
- RFX-mod can run also as a **low current tokamak**:
  - RWM control can be obtained with a reduced set of coils.
  - External action on the (2,1) mode affects plasma core, sawteeth dynamics and flow.



Joint 19th ISHW and 16th RFP workshop

September 16-20, 2013

Padova, Italy - Centro Culturale S. Gaetano

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email: ish_rfp_ws2013@igi.cnr.it