Self-organized helical equilibria in the RFX-mod reversed field pinch

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and the RFX-mod team

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Outline

- Self-organized helical equilibria: experimental evidence
- Equilibrium reconstruction:
  - – Perturbative approach (NCT)
  - – 3D approach (VMEC): issue of magnetic flux and q
- VMEC for the RFP
- Conclusions

RFX-mod a Reversed Field Pinch experiment

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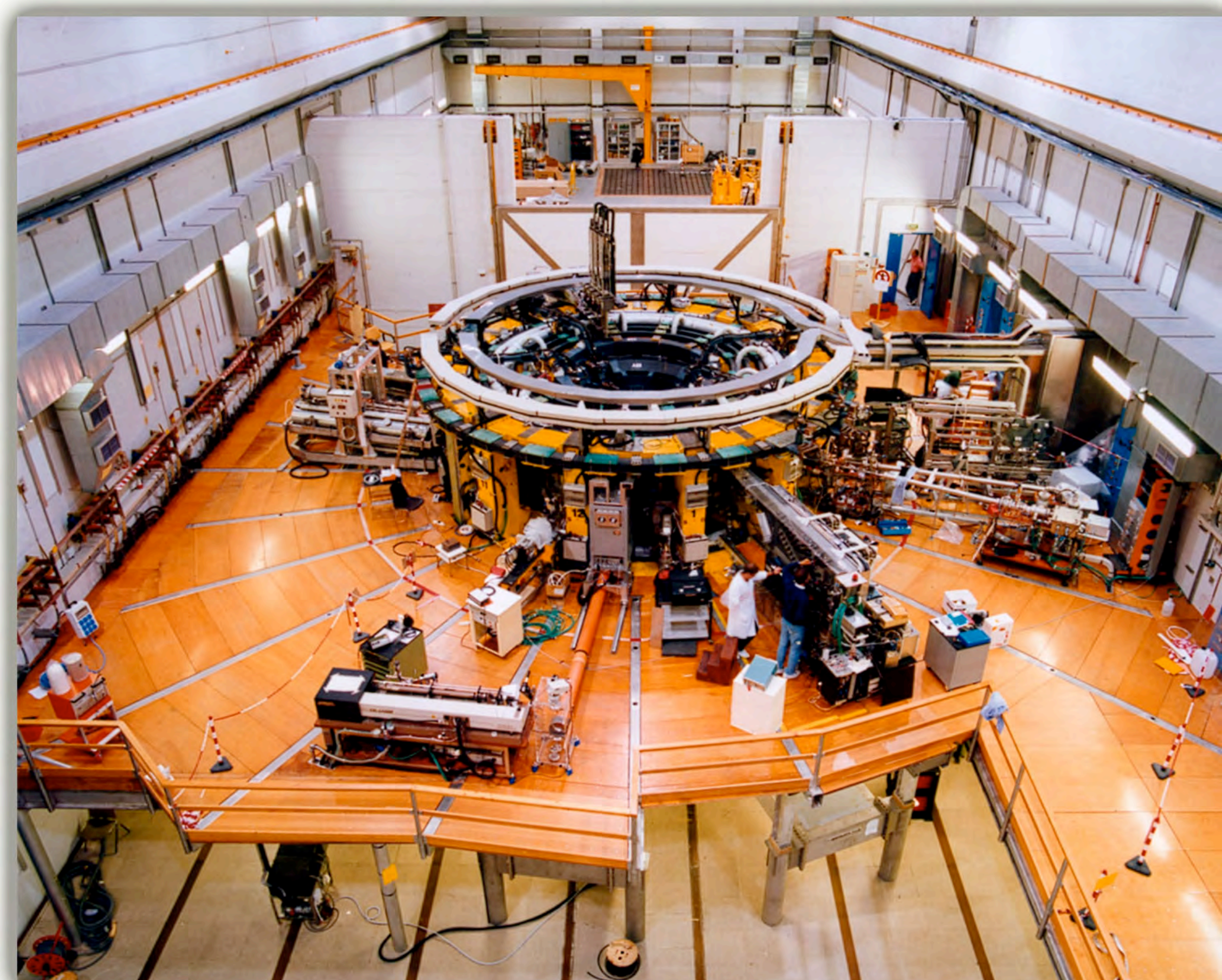
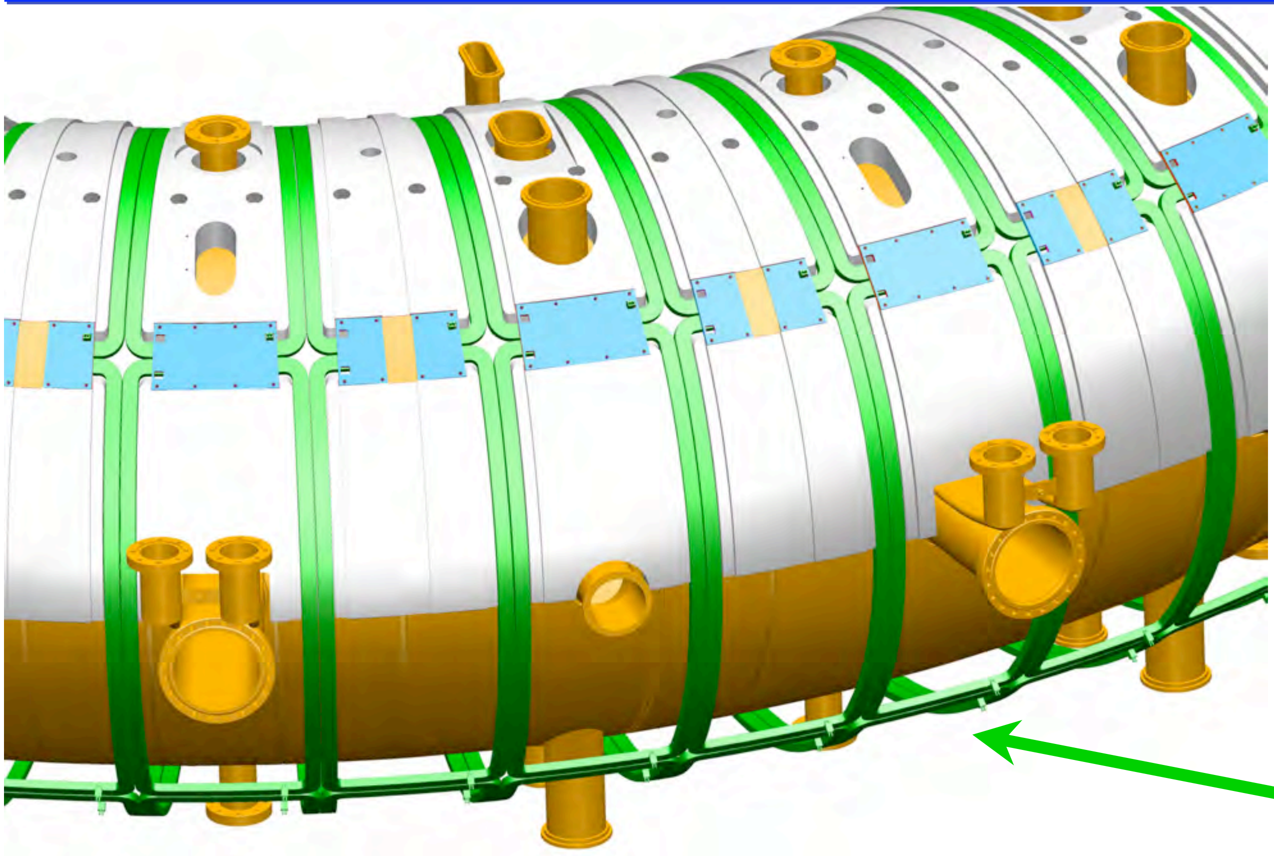


Largest RFP:

R_0 = 2 m
a = 0.46 m

Max I_p = 2 MA
Max B_T = 0.7 T

RFX-mod magnetic boundary: active coils



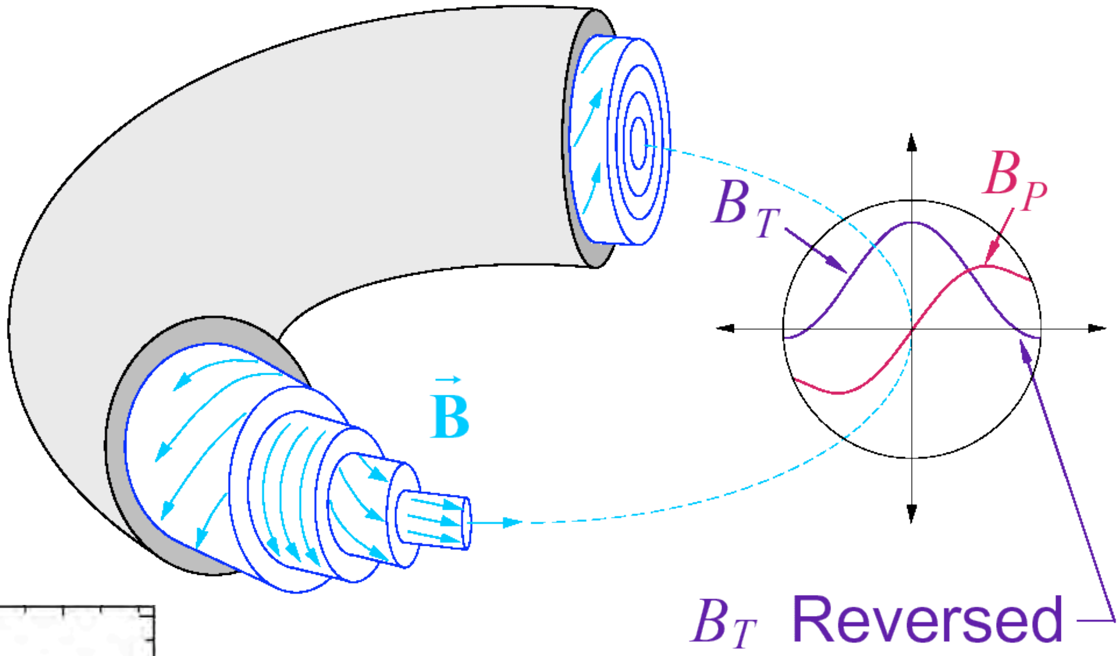
Maximum radial field that can be produced:

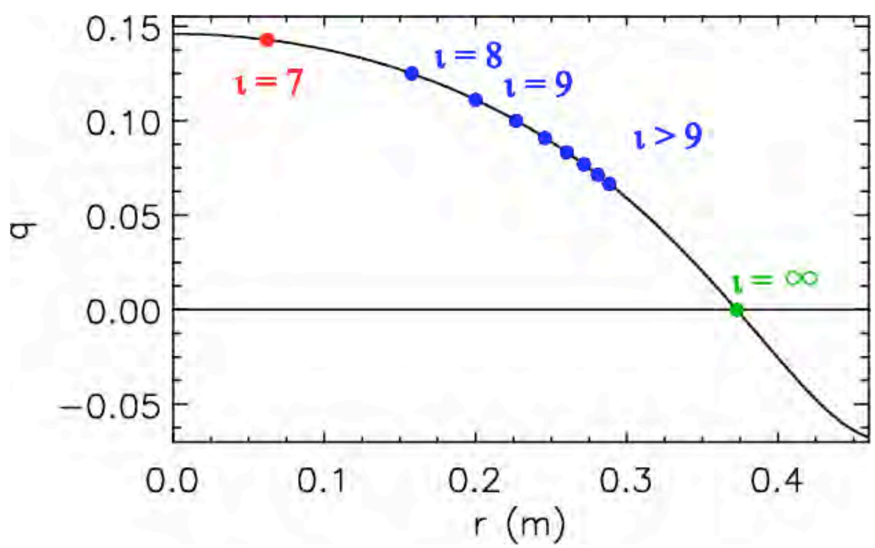
b_r = 50 mT (DC)
b_r = 3.5 mT (100 Hz)

192 independently controlled coils covering the whole torus. Digital Controller with Cycle frequency of 2.5 kHz.

RFP axisymmetric equilibrium profiles

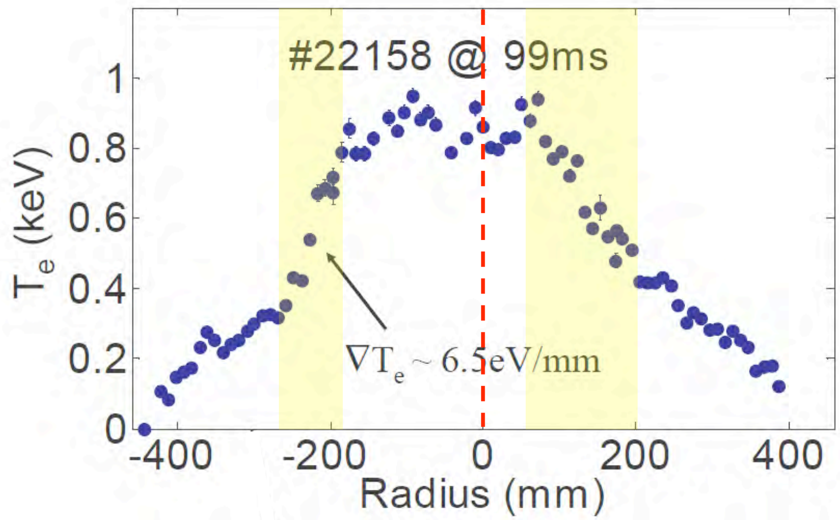
- Strongly paramagnetic plasma with B_T reversal at the edge.
- Strong magnetic shear.
- Safety factor is q<1 everywhere.

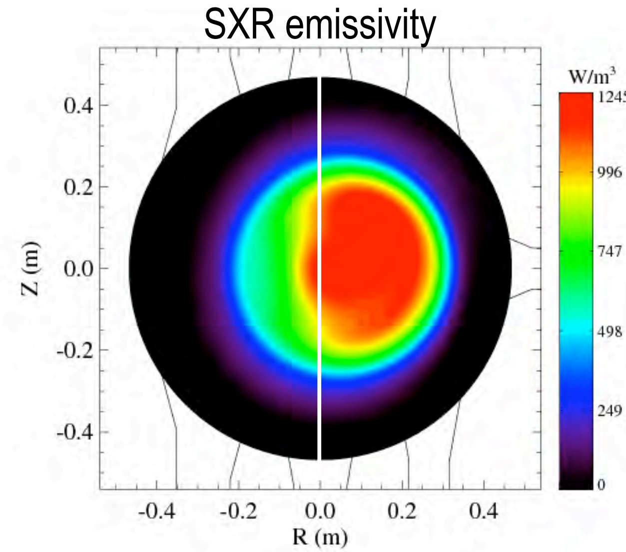


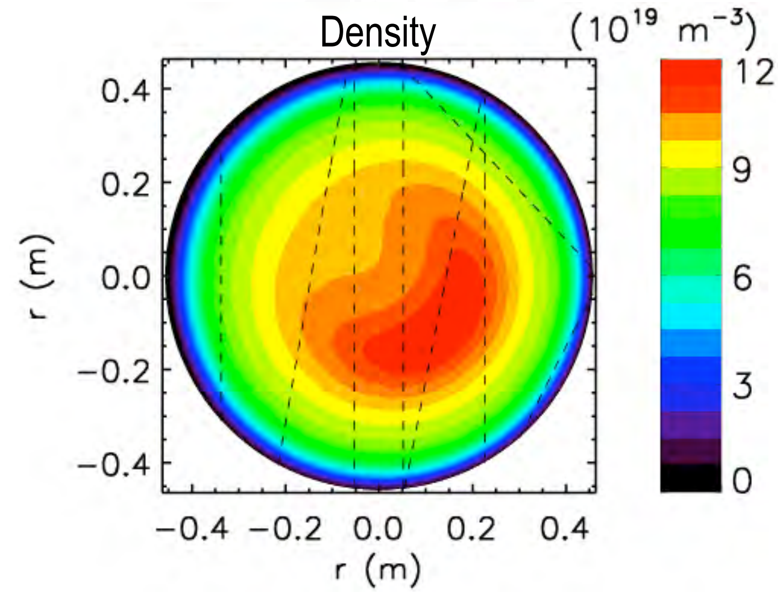


In RFX-mod equilibria
ι is always > 6

Helical states: kinetic evidence





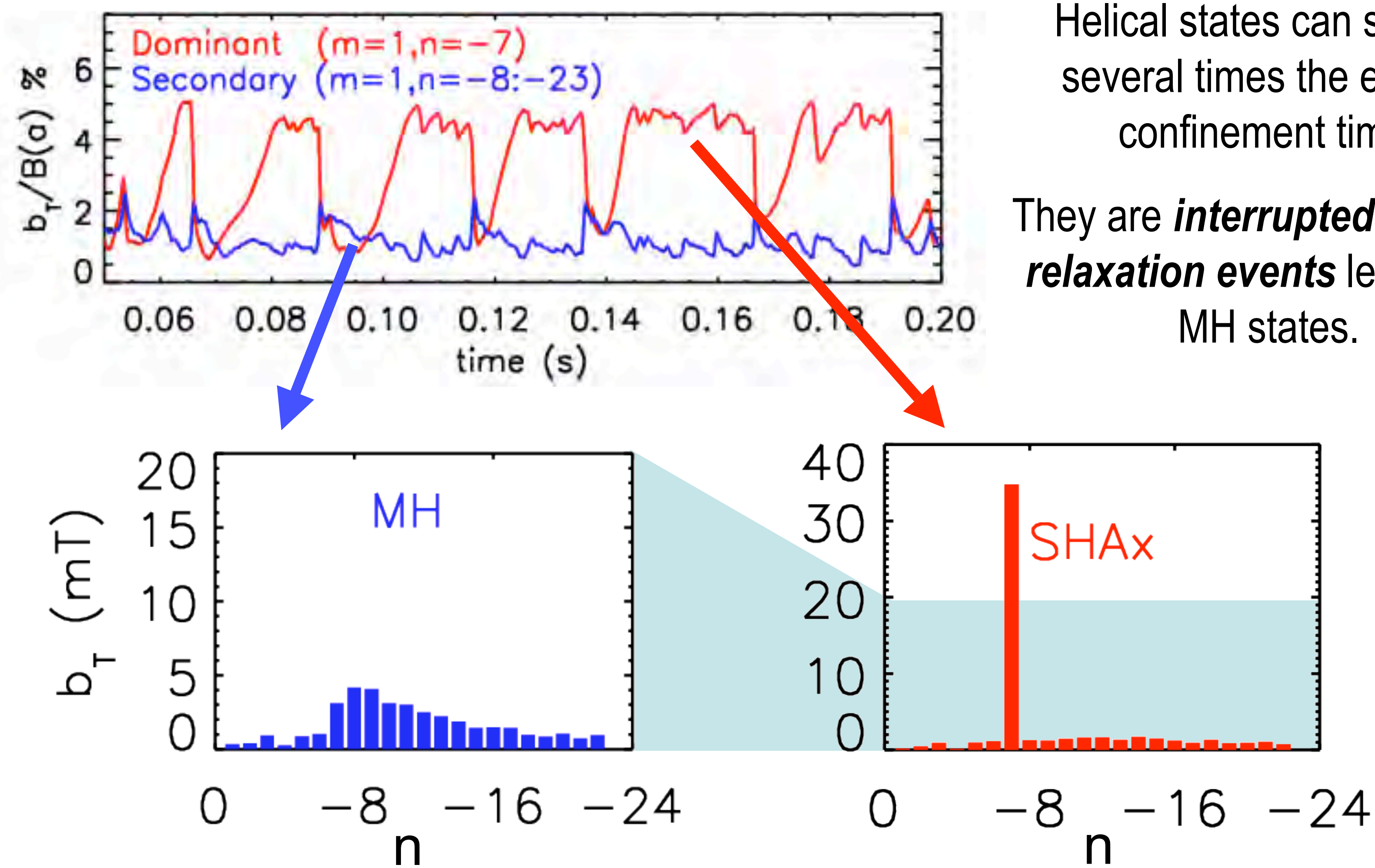


A bean shaped thermal structure is visible in the tomographic reconstruction of **SXR emissivity**.

T_e gradients are associated to a dominant mode in the spectrum of the toroidal magnetic field.

The structure can **confine particles**.

Helical states: magnetic fluctuations evidence



Helical states can survive several times the energy confinement time.

They are ***interrupted by MHD relaxation events*** leading to MH states.

The dominant mode is the most internally resonant tearing mode.

WE NEED A 3D EQUILIBRIUM (1/2)

A perturbative approach in toroidal geometry

A helical equilbrium needs a helical coordinate

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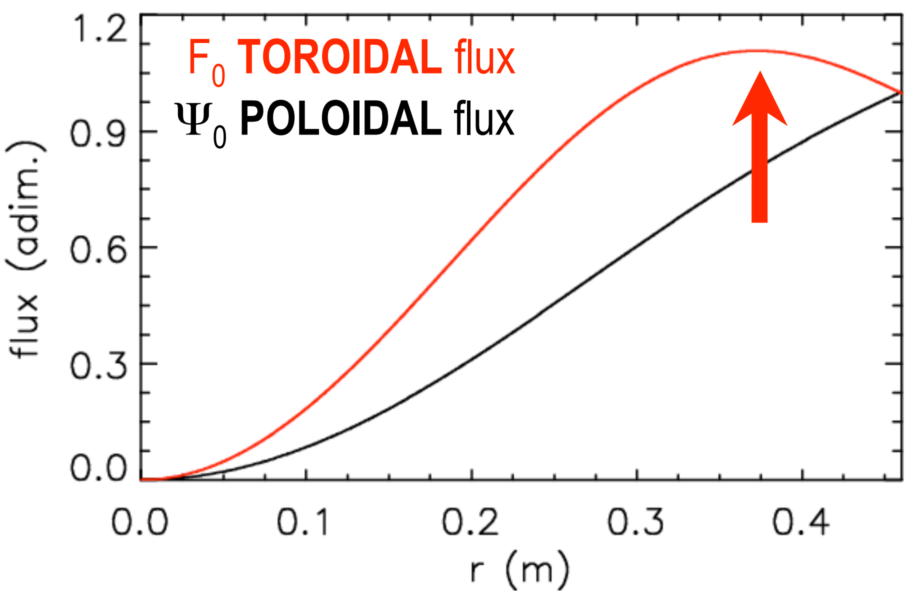
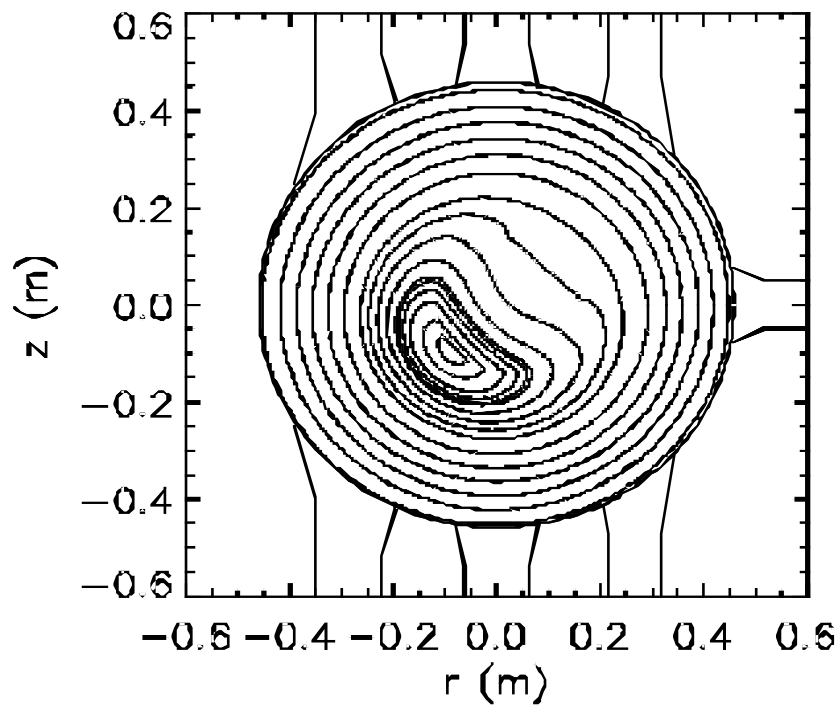
The SHAx state is well described in terms of a helical flux χ_{mn} with m=1,n=7:

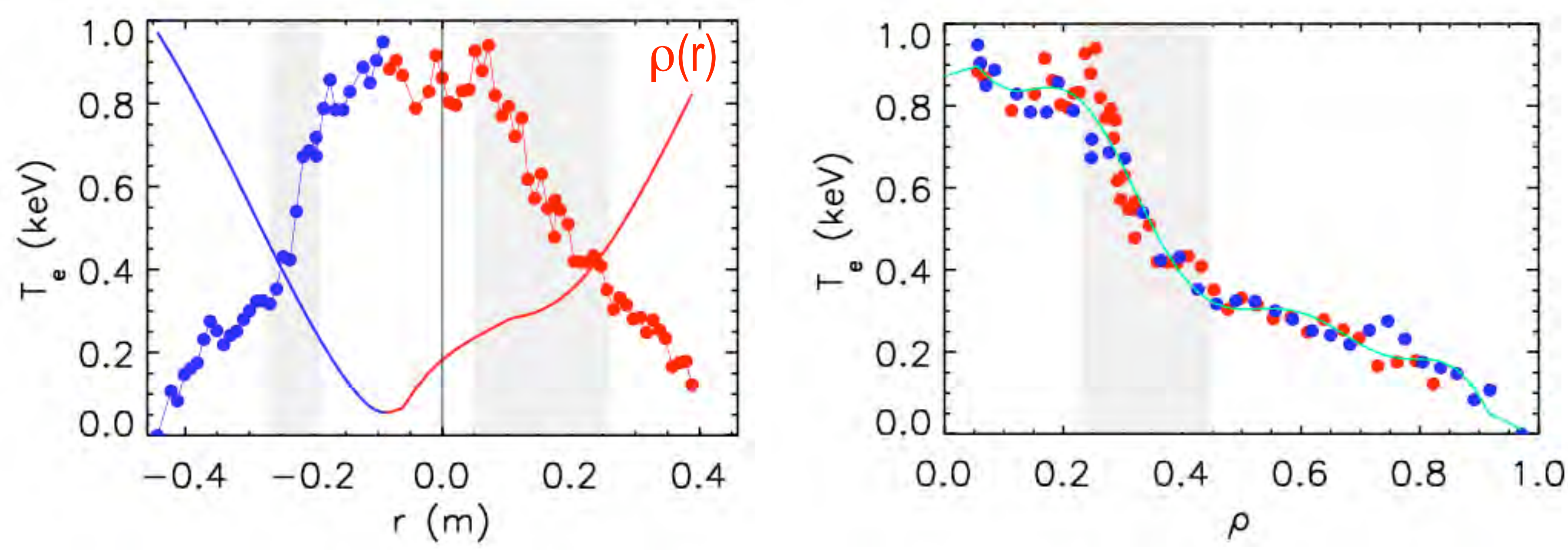
$\chi^{m,n}(r,\vartheta,\phi) \equiv$ [redacted] − [redacted] + [redacted] − [redacted]

Axi-symmetric — **Dominant mode**





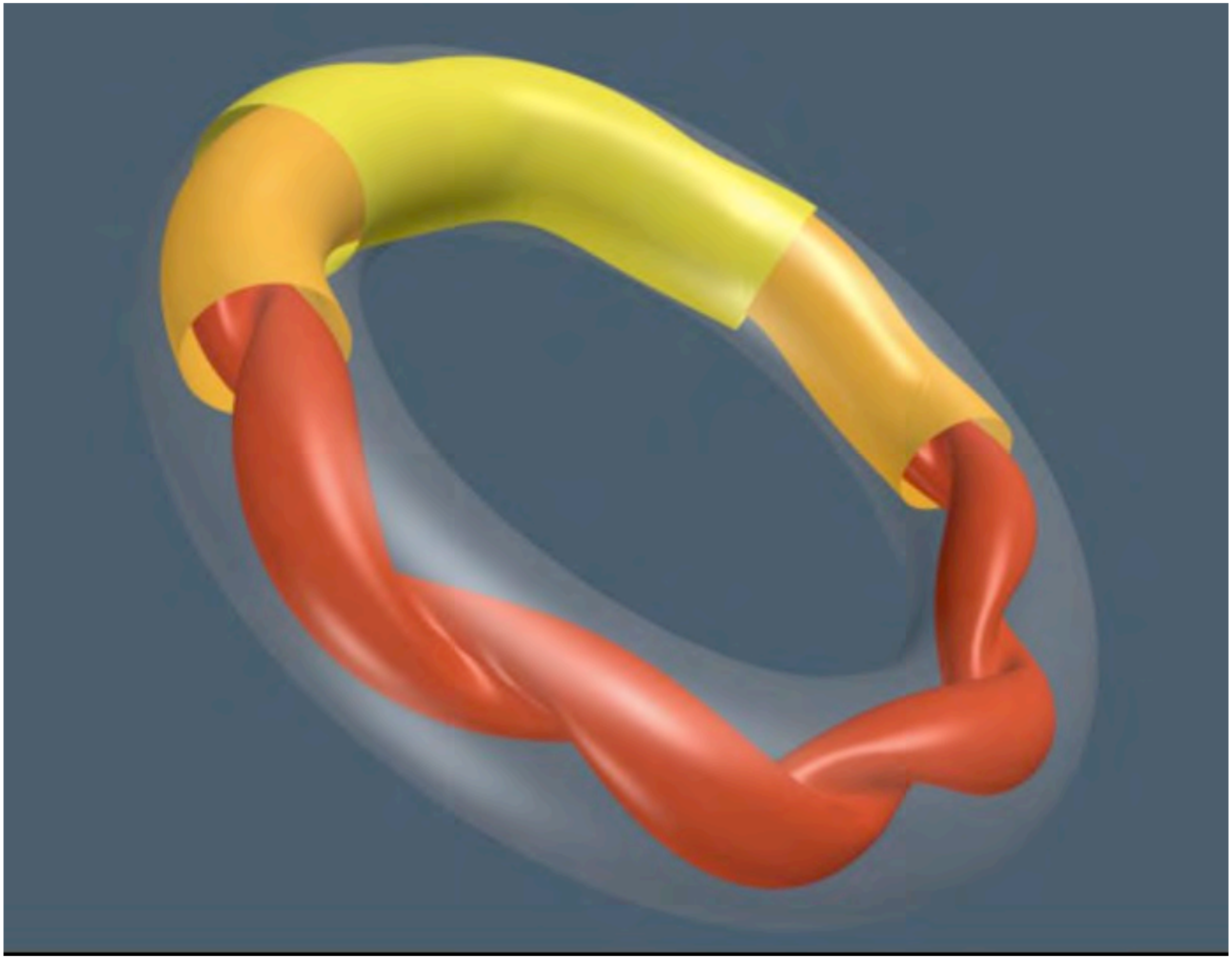
Mapping T_e on helical flux



- **T_e** profiles are non-axisymmetric in **r** but not in ρ: $T_e = T_e(\rho)$.
- The transport barrier is due to the presence of “almost-invariant” helical flux surfaces.

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

Flux surfaces in RFX-mod helical equilibria



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

Flux surfaces in toroidal devices

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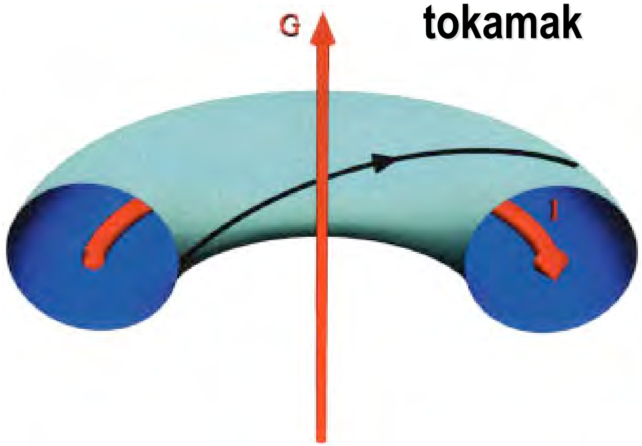
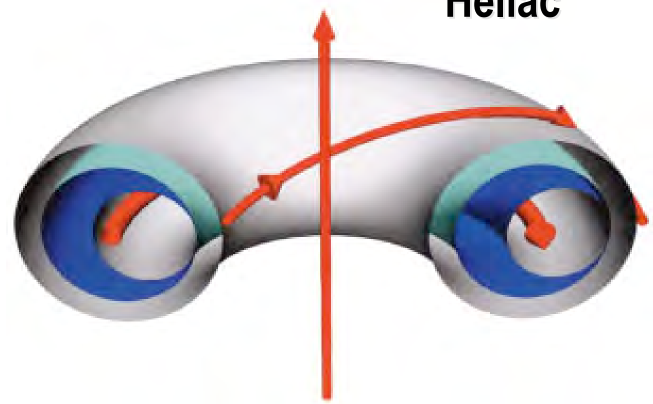
tokamak

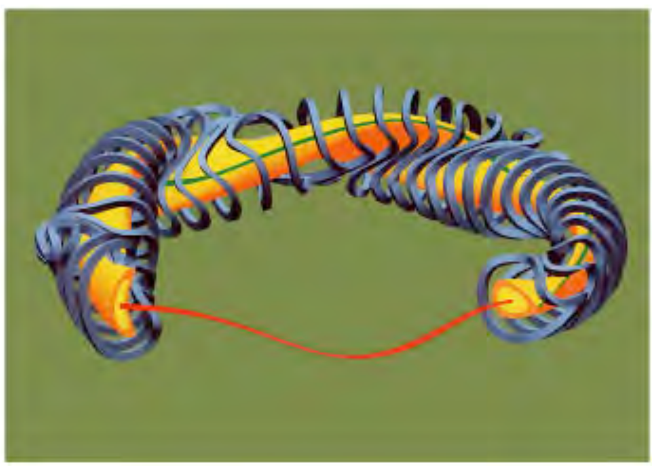


Heliac



A. Boozer, Phys. Plasmas **5** (1998) 1647

W7-X



RFX-mod in helical state

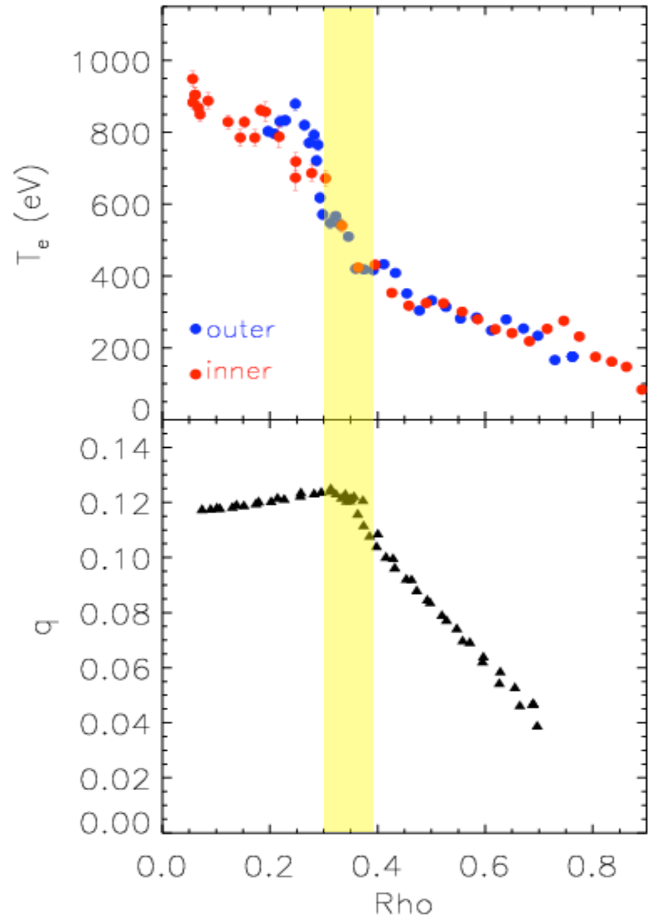
The q profile: experimental finding

The helical equilibrium is obtained ***spontaneously with an axi-symmetric boundary***,

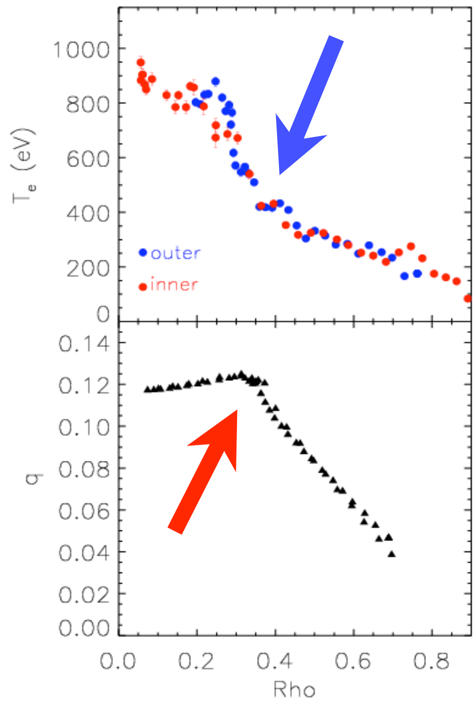
BUT

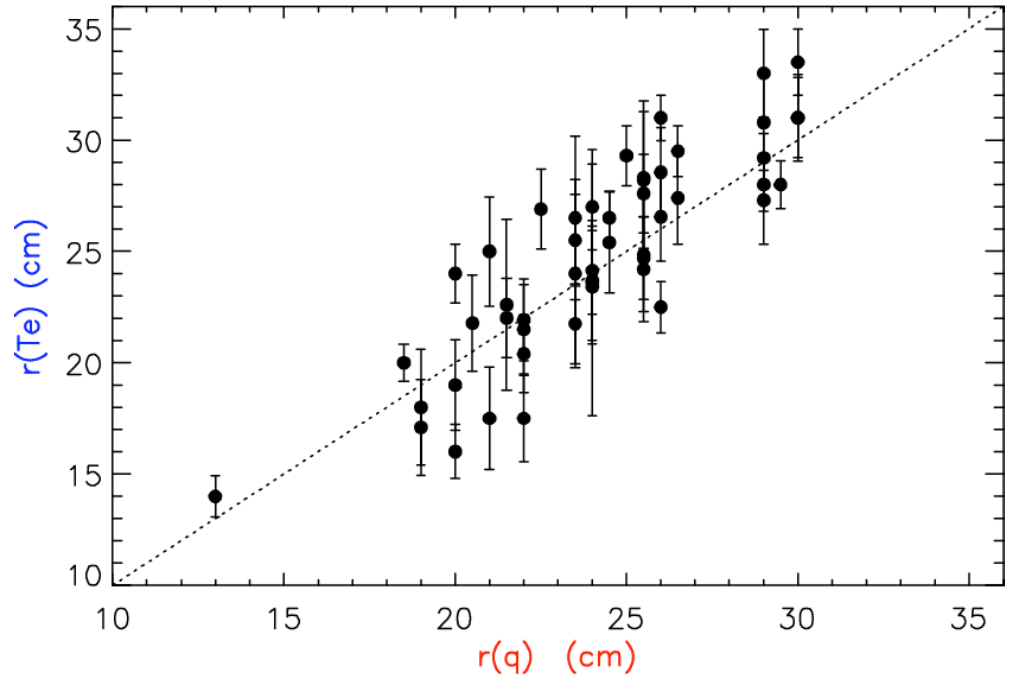
the ***calculated q profile*** has a ***particular shape***, quite different form the axisymmetric one:

q is not monotonic.



q profile and temperature barriers





RFP and Tokamaks

- Experiments with ***reverse shear*** in Tokamaks shows a transition corresponding to the region inside the radius where q'=0 (***a minimum***).
- In RFX-mod confinement improves in the region inside the radius where q'=0 (***a maximum***).

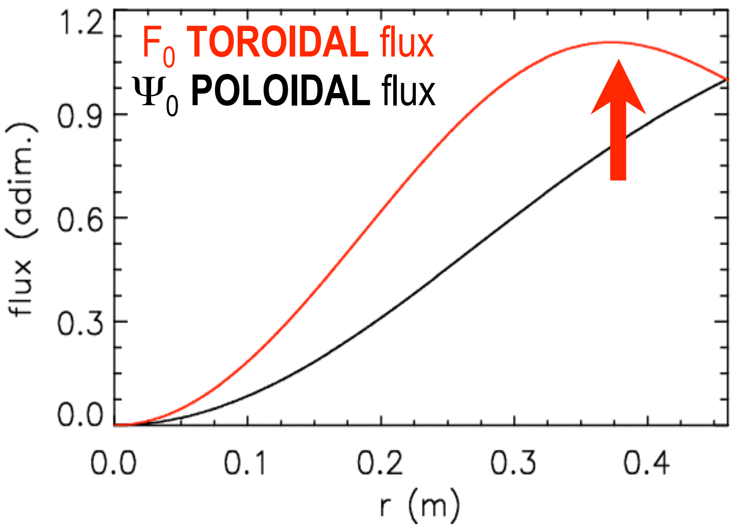
WE NEED A 3D EQUILIBRIUM (2/2)

A full 3D code

VMEC for the RFP

Code modification thanks to S.P. Hirshman

From ***toroidal*** flux to ***poloidal*** flux



VMEC Axisymmetric and Helical equilibria

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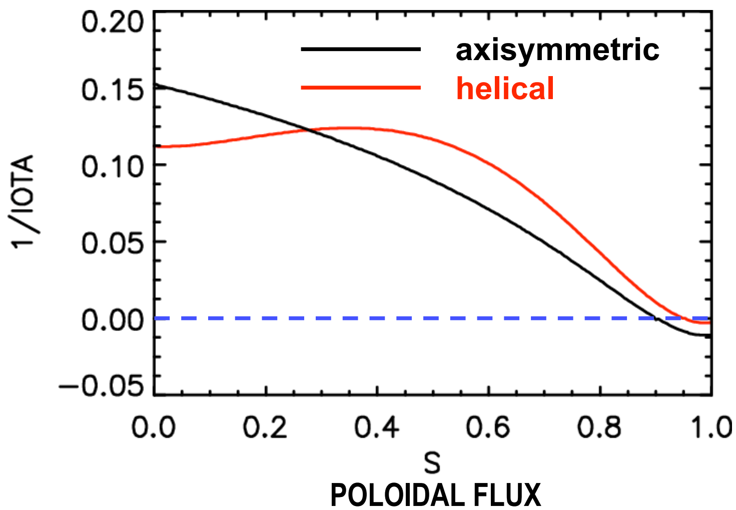


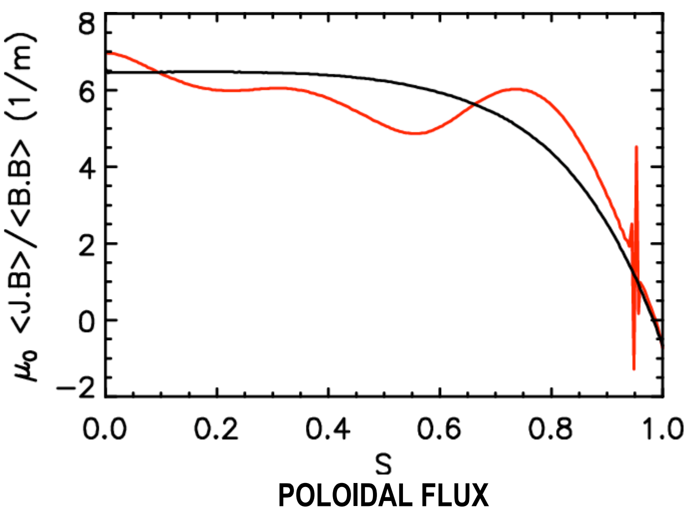
INPUT PARAMETERS:

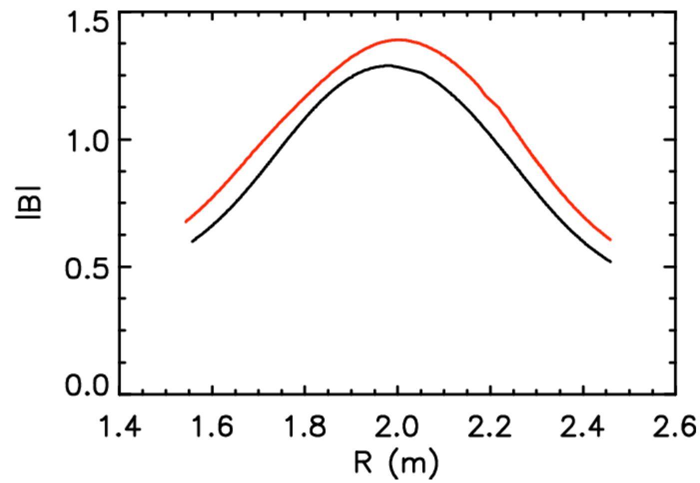
q(s) = 1/ι(s)

β = 0

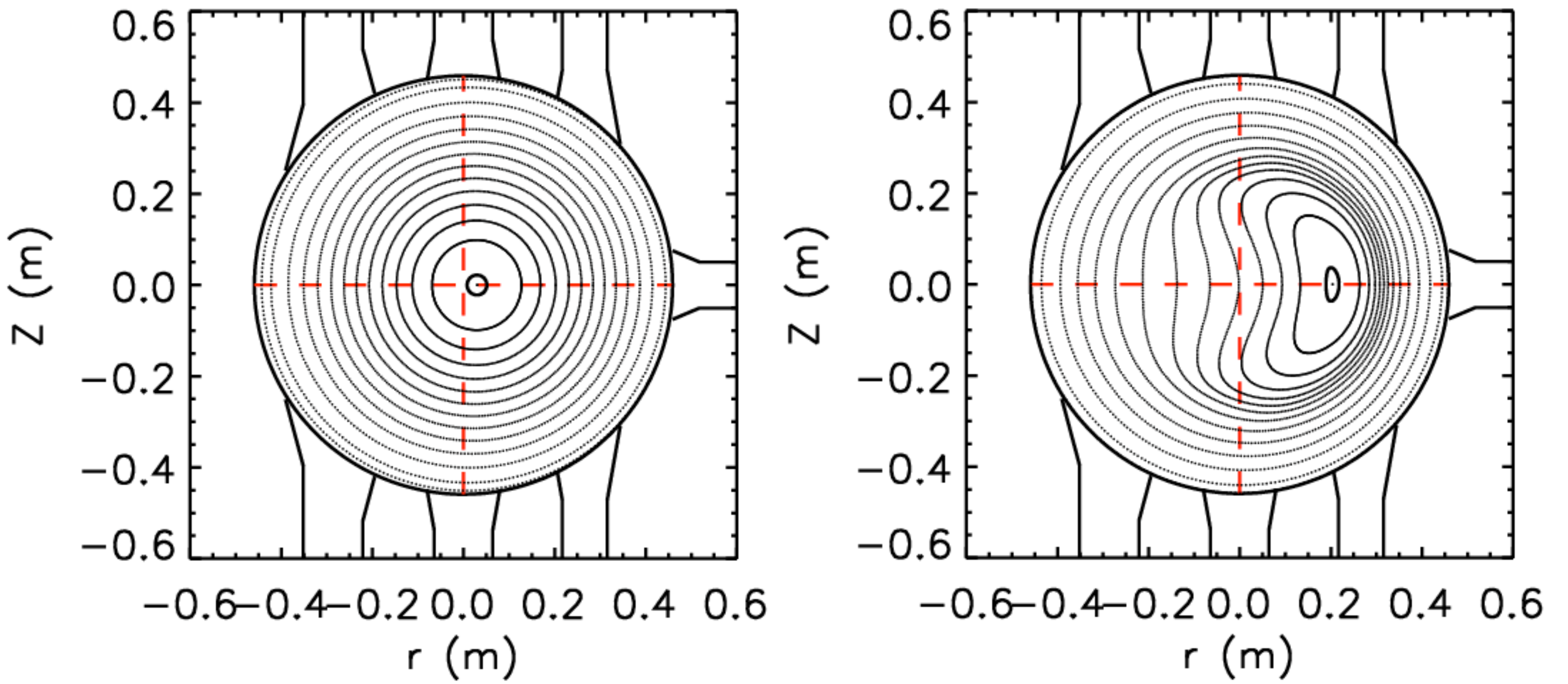
circular and axi-symmetric LCFS

(fixed boundary)



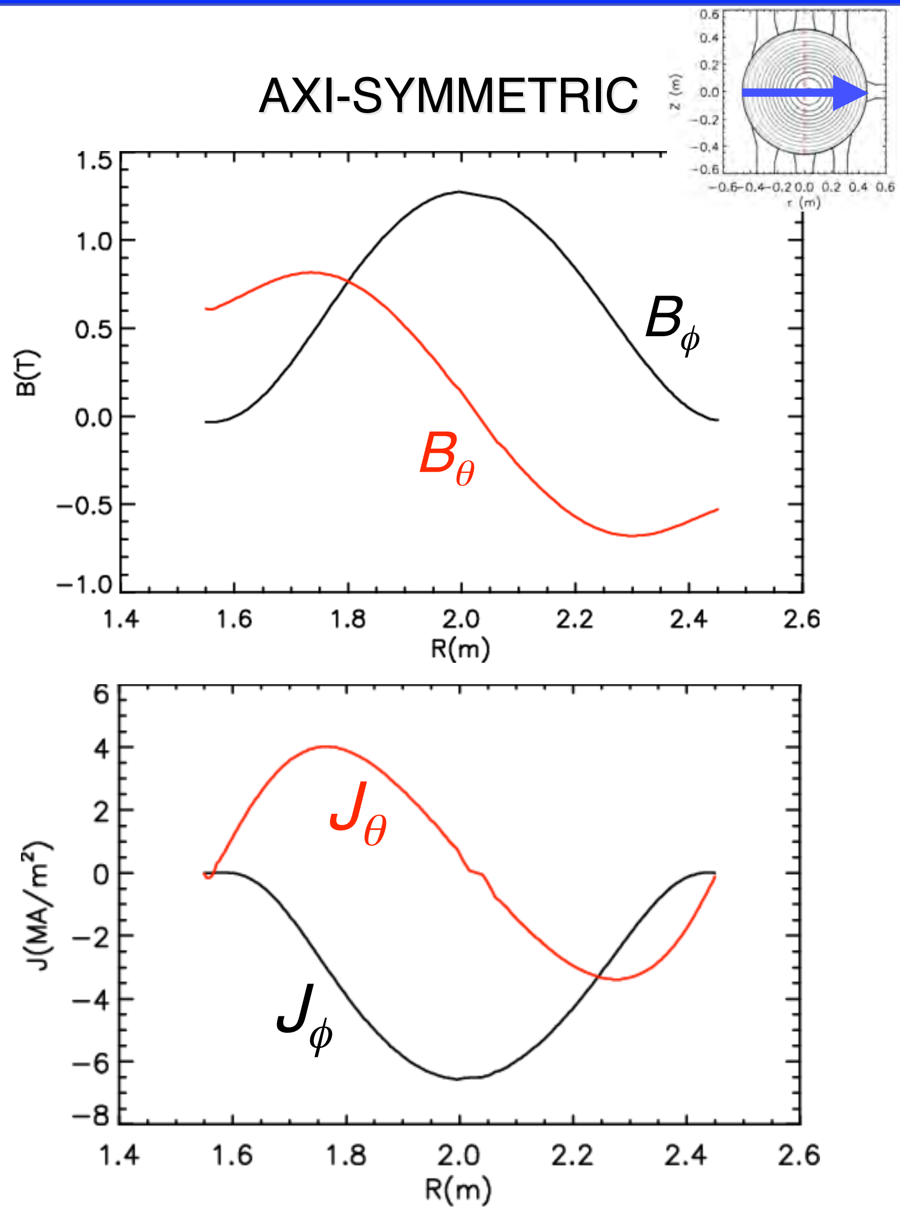


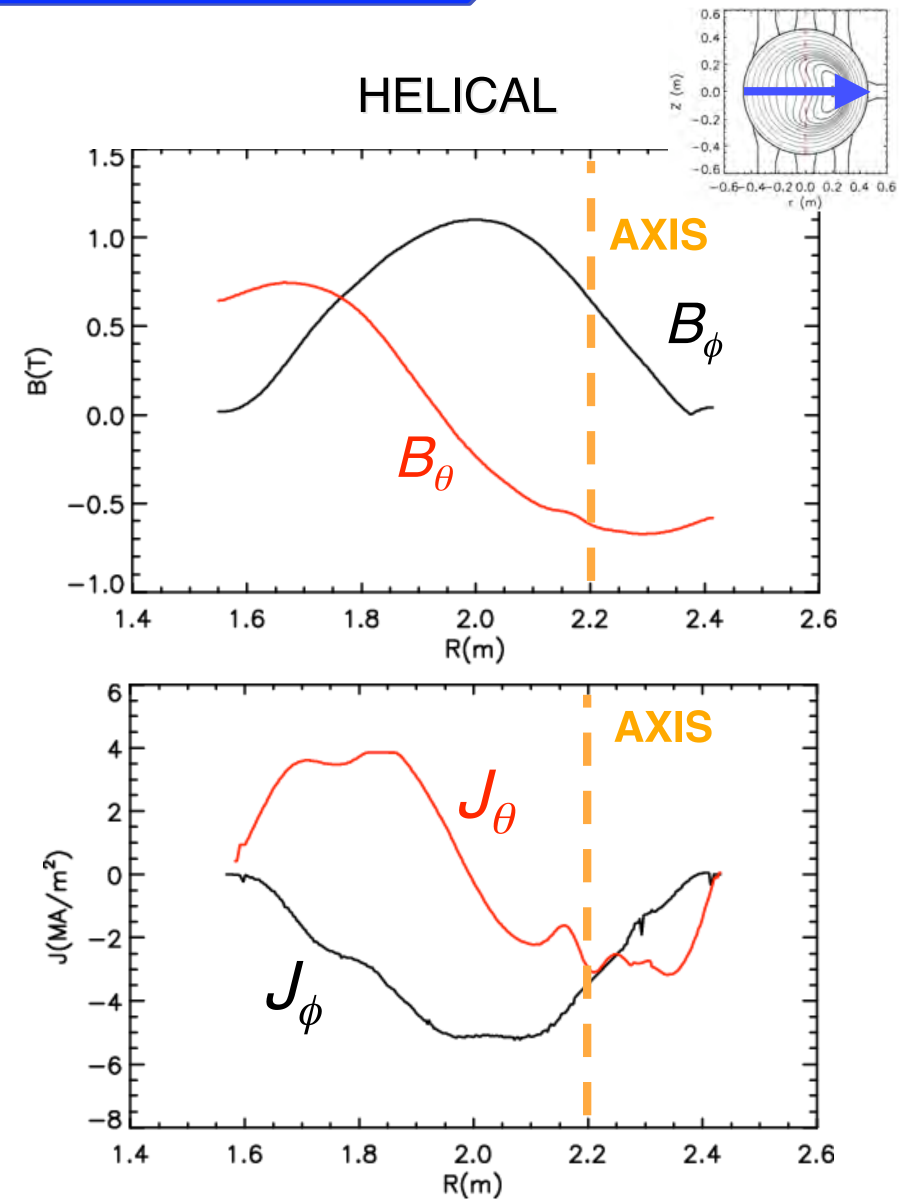
Flux surfaces



The flux surfaces obtained both in axisymmetric and helical configurations provide a good benchmark with present experimental observations.

Magnetic field and current density profiles





Magnetic field profiles asymmetries

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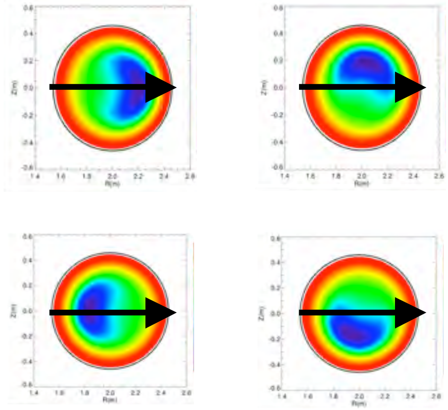
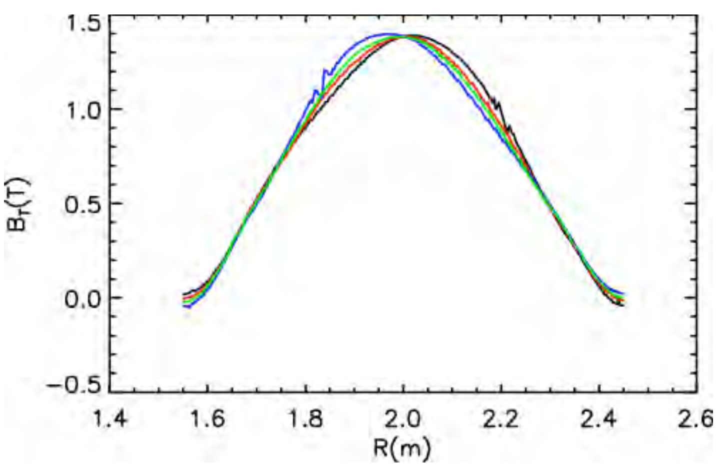
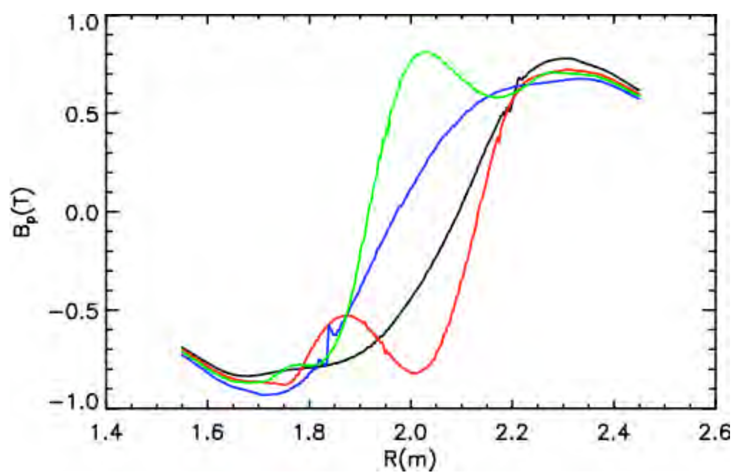
$\theta_{op}=0$ ■ $\theta_{op}=\pi/2$ ■

$\theta_{op}=\pi$ ■ $\theta_{op}=3\pi/2$ ■



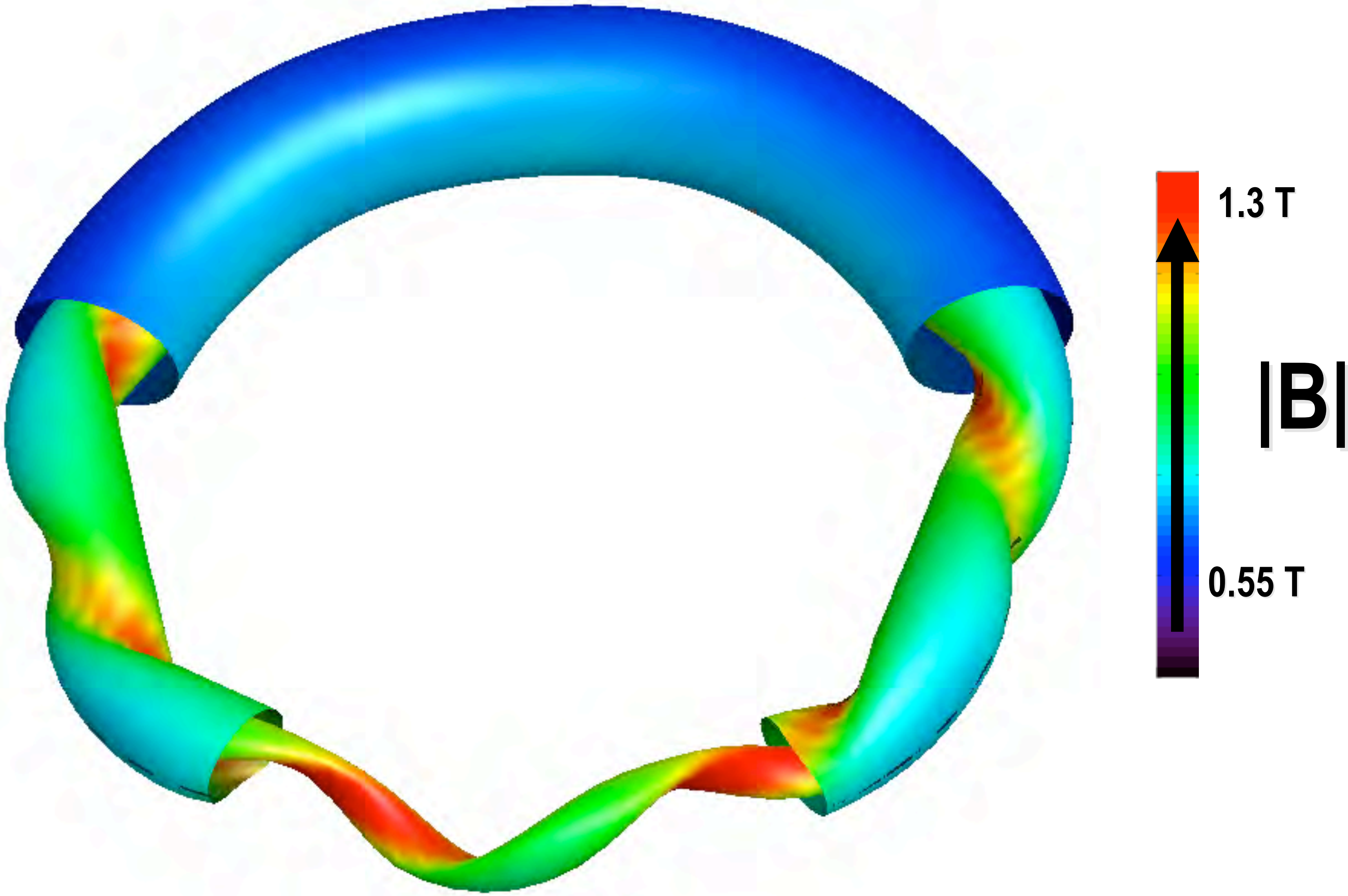
With respect to the axisymmetric configuration B_T has a small deviation while B_P has a large deviation.



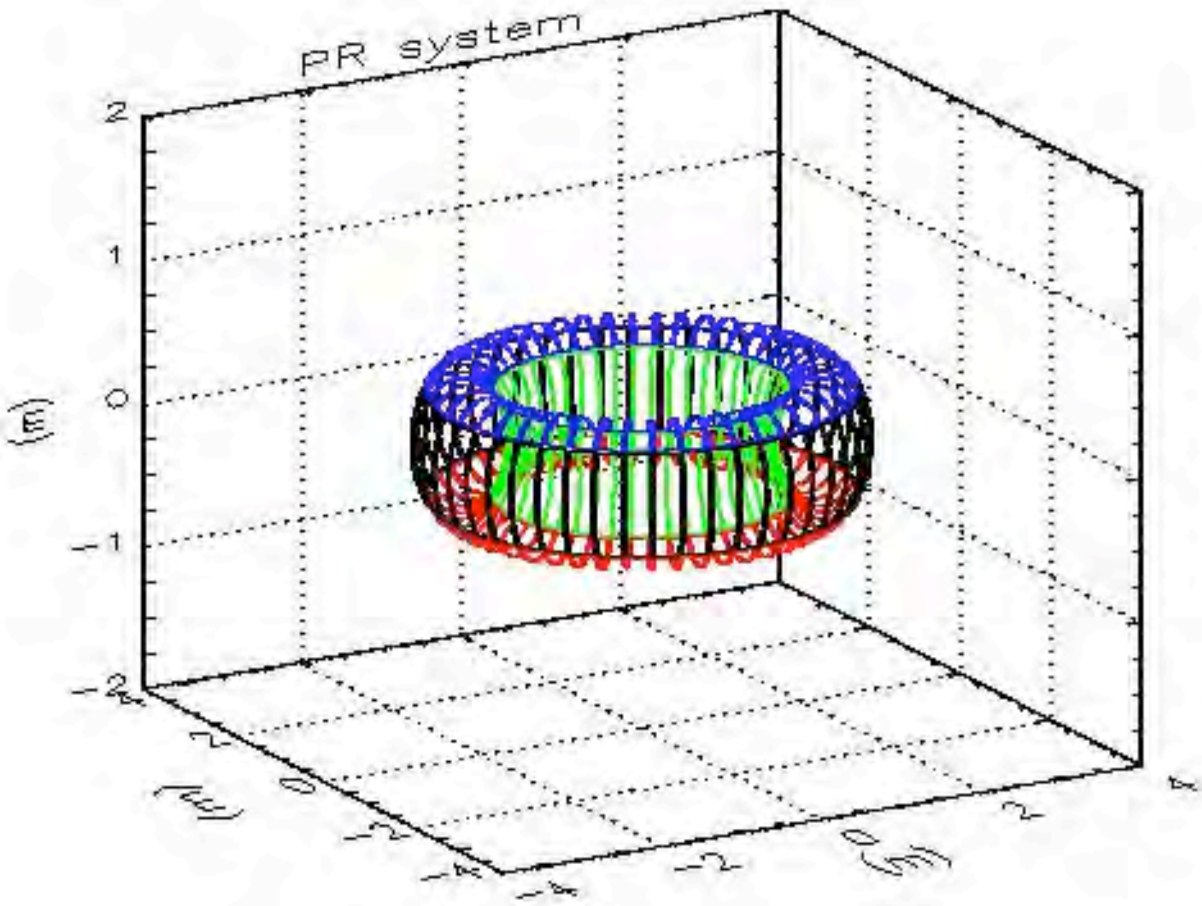


For more detailes see the Poster by Marco Gobbin on Wednesday (P03-06).

Flux surfaces and field strength



VMEC free boundary



VMEC in free boundary mode to asses the issue of using RFX-mod active boundary control system for controlling the helical equilibrium as suggested by recent studies and papers (for examples A.H. Boozer and N. Pomphrey, Phys. Plasmas **16** (2009) 022507).

Conclusions

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- In RFX-mod spontaneous helical equilibria with an axisymmetric boundary show improved performances both in terms of energy and particle confinement.
- Equilibrium reconstruction requires a 3D analysis. Two aproaches were adopted: a perturbative approach in toroidal geometry (NCT) and a full 3D approach (VMEC modified for the RFP).
- Reconstructed equilibria allow a correct interpretation of experimental data and a more complete description of helical states.
- VMEC proves to be a powerful tool and allows the use of a suite of codes:
  - Equilibrium with ***pertubations*** [SIESTA].
  - ***Stability***: current and pressure [COBRA] driven modes.
  - ***Transport***: DKES and ASTRA [G. Pereversev *et al.*, Max Planck Institut für Plasmaphysik, Rep. IPP 5/98 Garching, February 2002]).
- Collaborations are ongoing and being started on these topics.

RFX-mod team

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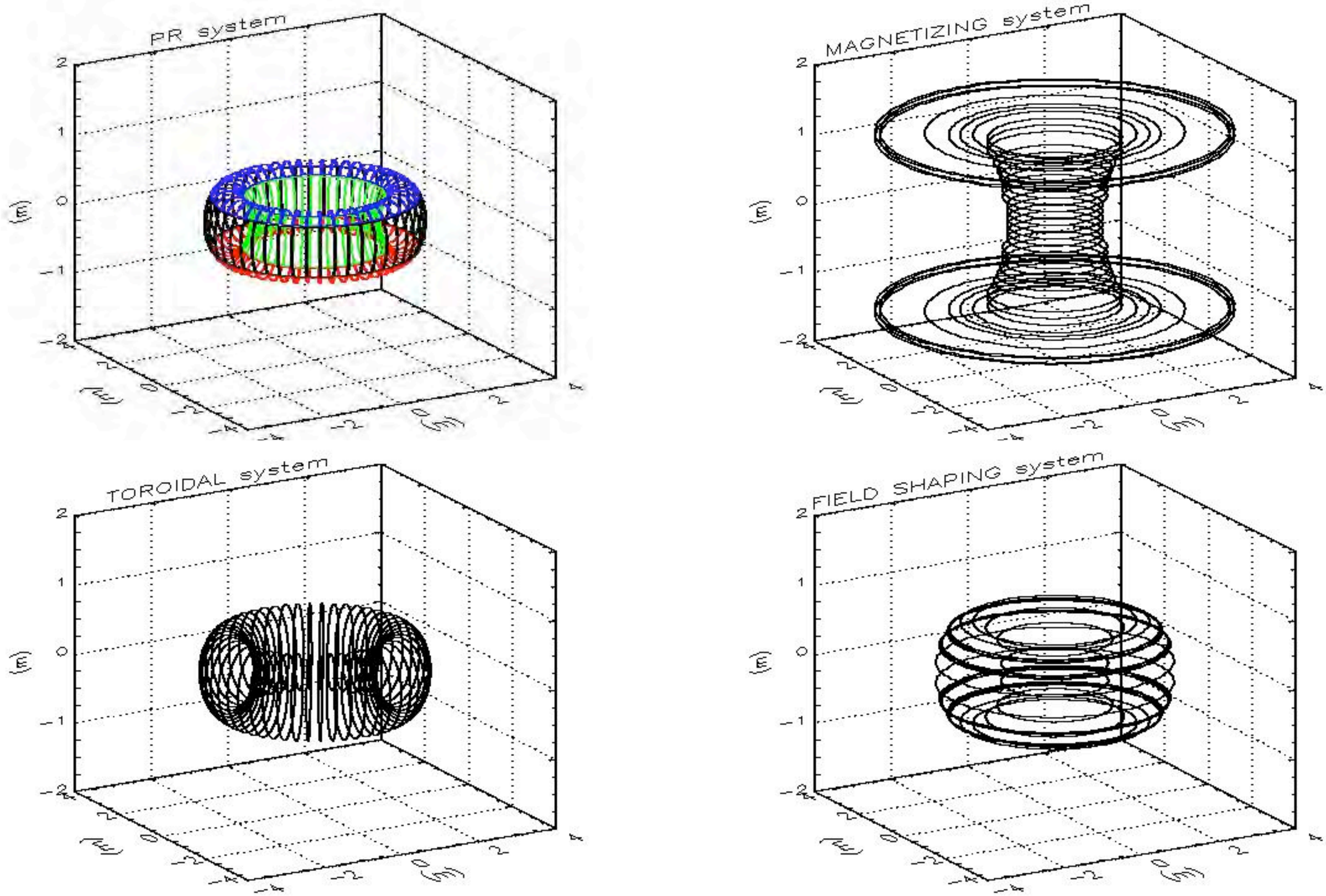
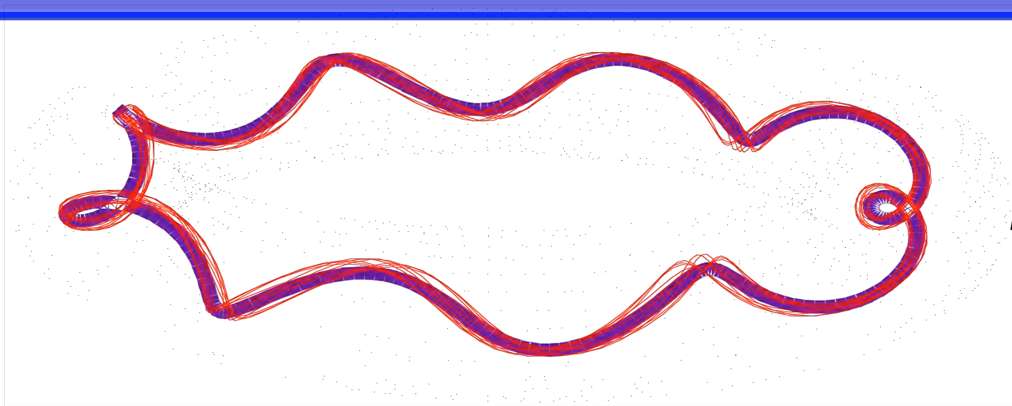
RFX-mod team

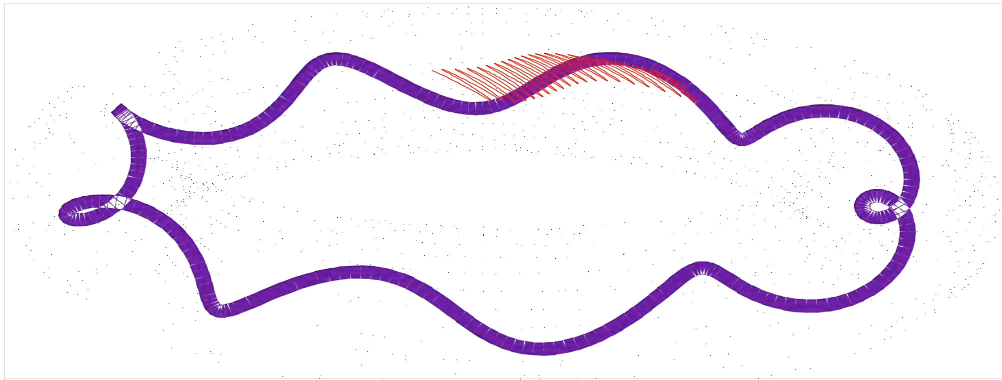
VMEC free boundary



Trapped particles with ORBIT



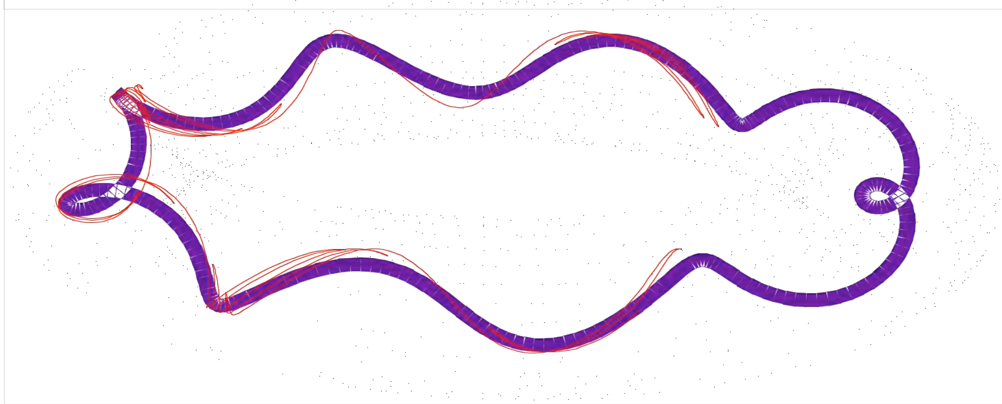
Passing Ion



Poloidal Trapping

Banana width: ***0.2 cm***

(800 eV)

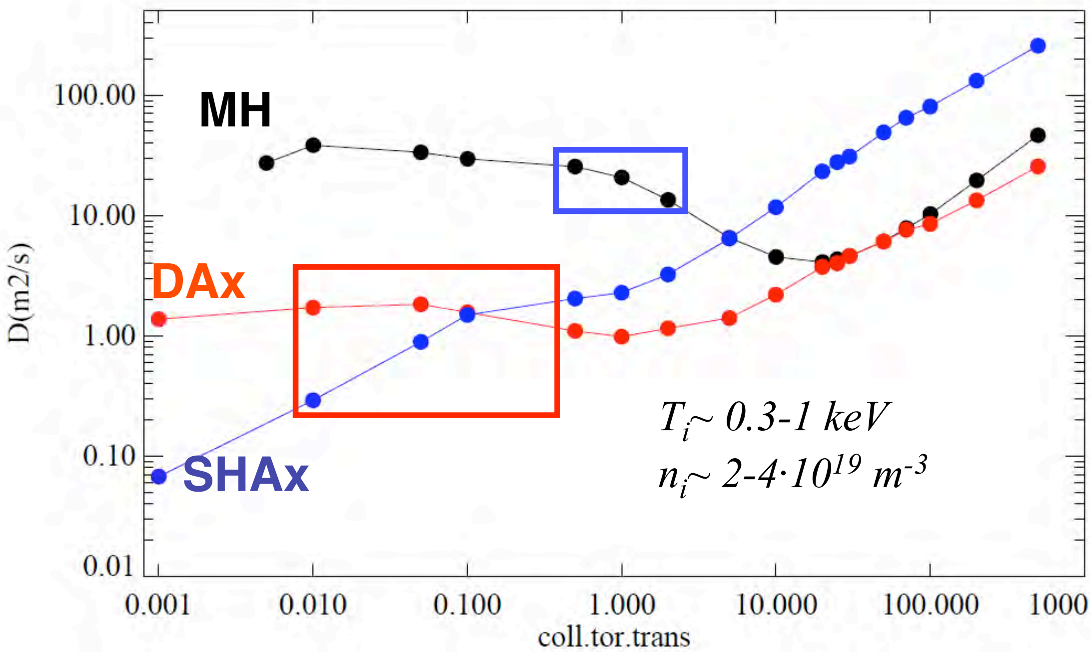


Helical Trapping

Banana width: ***0.5 – 5 cm***

(300 – 1200 eV)

Ion diffusion coefficient with ORBIT



$D_{i,MH} \sim 10\text{-}20\ m^2/s$

$D_{i,DAX} \sim 1\text{-}3\ m^2/s$

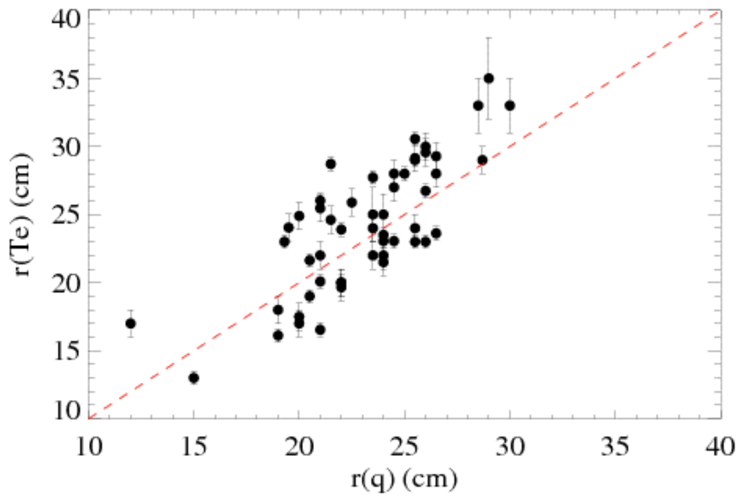
$D_{i,SHAX} \sim 0.3\text{-}1\ m^2/s$

$D_{e,SHAX} \sim 0.3\text{-}1\ D_{i,SHAX}$

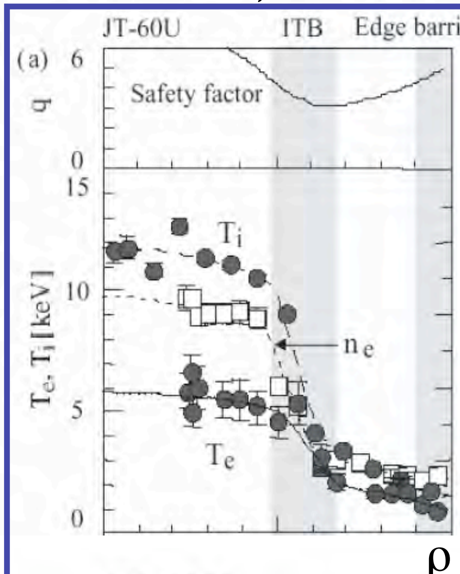
SHAx: the main contribution comes from ***trapped particles*** (poloidally + helically).
MH: the main contribution comes from ***chaotic transport***.

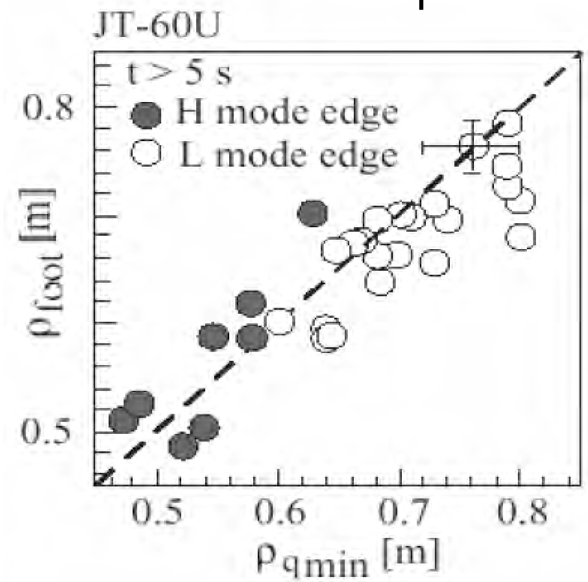
In **helical configurations** the ***total fraction*** of trapped particles may increase up to **~40%**, to be compared with a fraction of **~30%** in the **axisymmetric** ones.

$D_{pas} / D_{trap} \sim 0.01$ at $T_e = T_i = 800$ eV



from Connor et al, Nucl. Fus. 2004





RFP:

electron transport barriers linked to a **maximum of q**

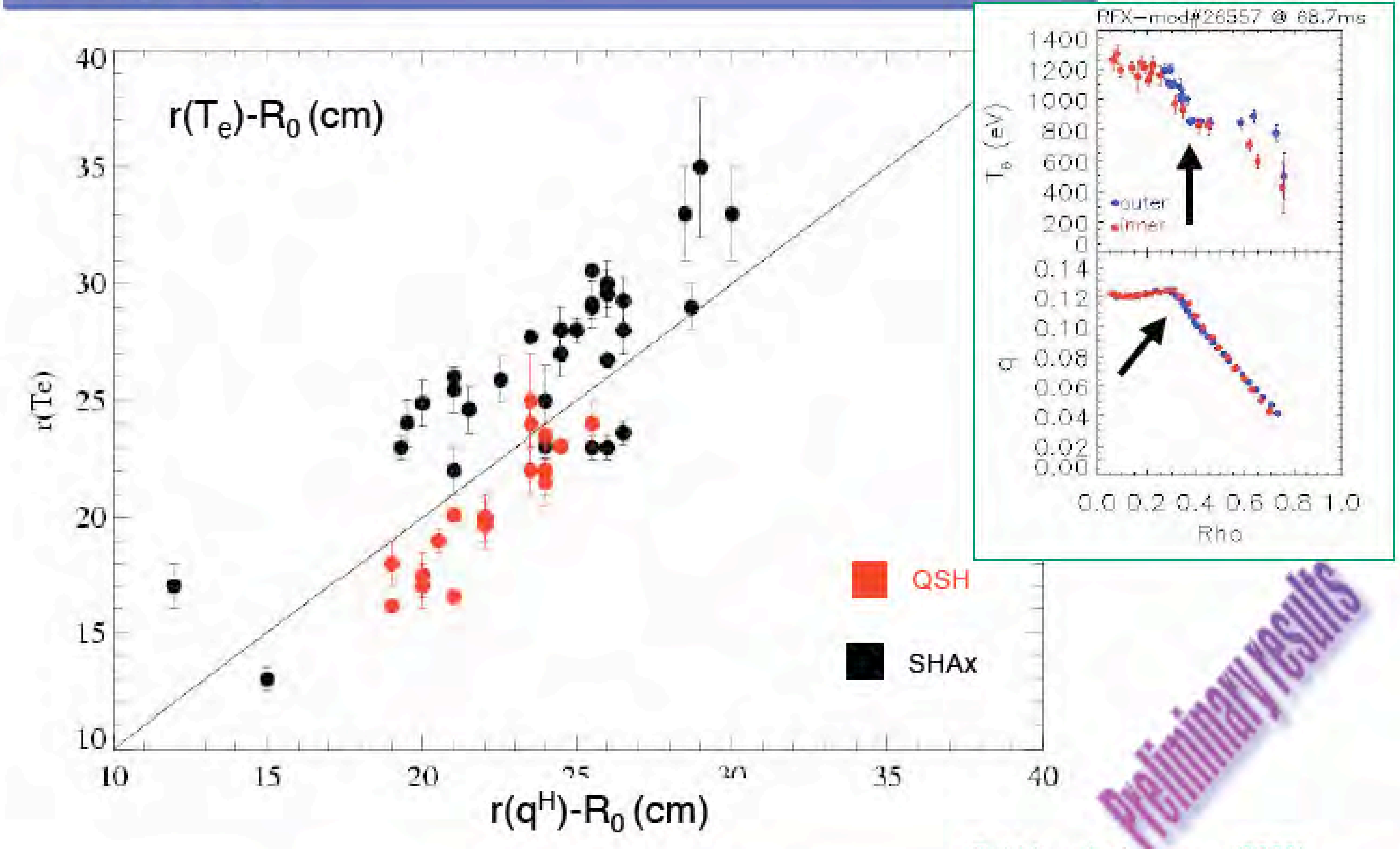
barrier location at qmax position

Tokamak:

electron transport barriers triggered by a **minimum of q**

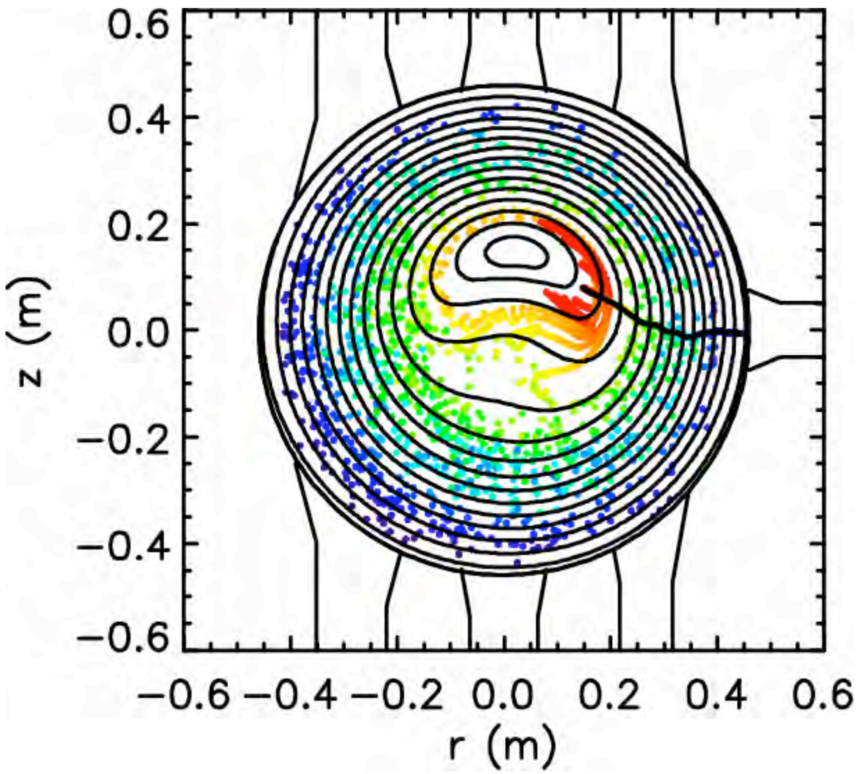
barrier location at qmin position

The foot of the transport barrier coincides with the change of slope in q^H



Gobbin, private comm. (2009)

ITBs correspond to weak chaos



ITBs are correlated to regions of reduced magnetic chaos.

Barriers in RFX helical states can be described in terms of ALMOST INVARIANT FLUX SURFACES.

Across the larger islands the temperature flattens, and across the cantori (broken KAM surfaces) and small islands temperature gradients are supported.

S.R. Hudson and J. Breslau, PRL **100,** 095001 (2008)