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3D magnetic fields and plasma flow in helical RFX-mod equilibria

Paolo Piovesan

in collaboration with D. Bonfiglio, F. Bonomo, M. Gobbin, L. Marrelli, P. Martin, E. Martines, B. Momo, L. Piron, I. Predebon, A. Soppelsa, P. Zanca, B. Zaniol, and the RFX-mod team / Consorzio RFX, Padova, Italy

15th Workshop on MHD Stability Control

Madison, WI, USA, November 15th-17th, 2010

Reversed Field eXperiment / RFX-mod

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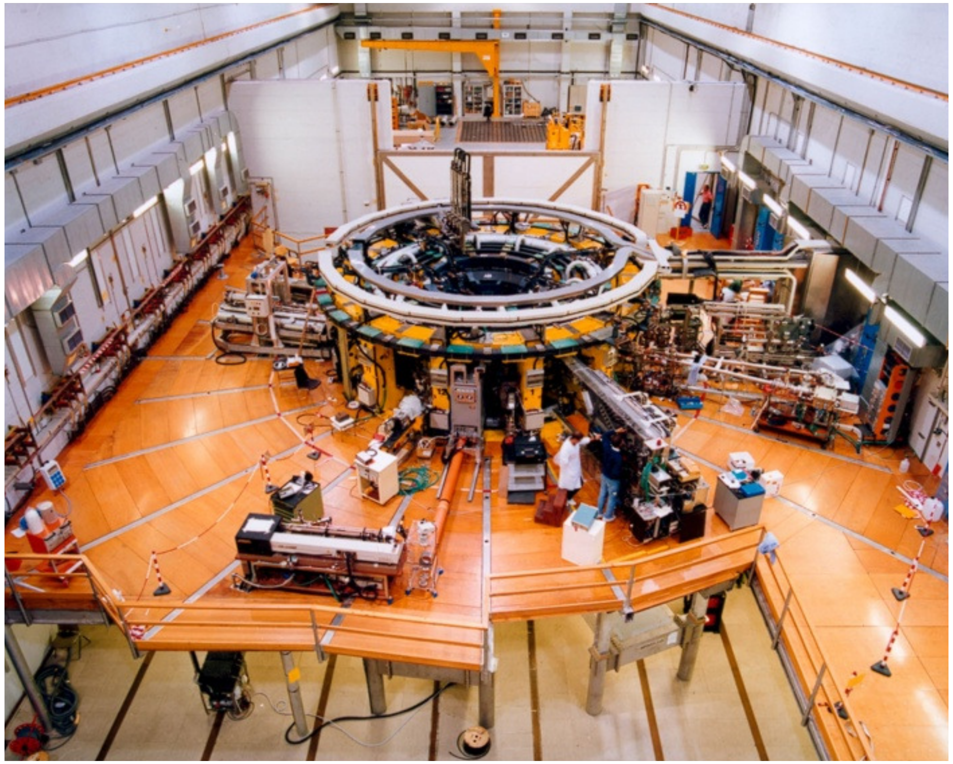
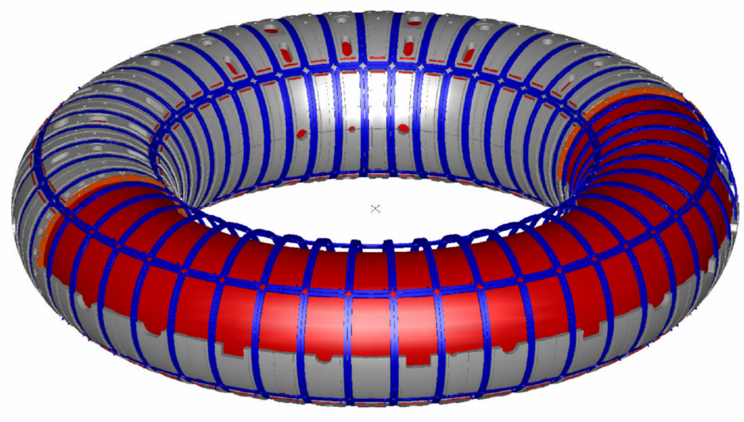
- RFX-mod has the unique capability to reach high plasma currents up to 2MA in a RFP
- with the most sophisticated magnetic feedback system ever realized in a fusion device





192 active coils independently controlled and 192 respective B_r and B_ϕ sensors

R=2m, a=0.46m

Self-organized helical equilibria

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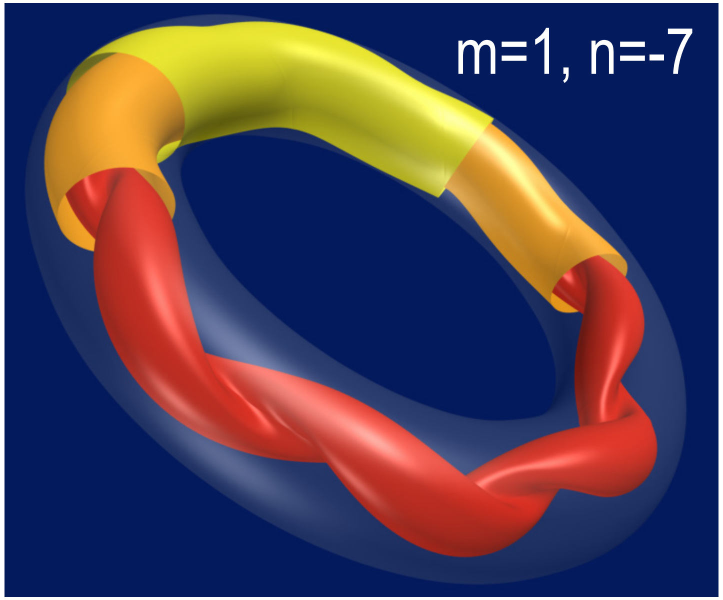
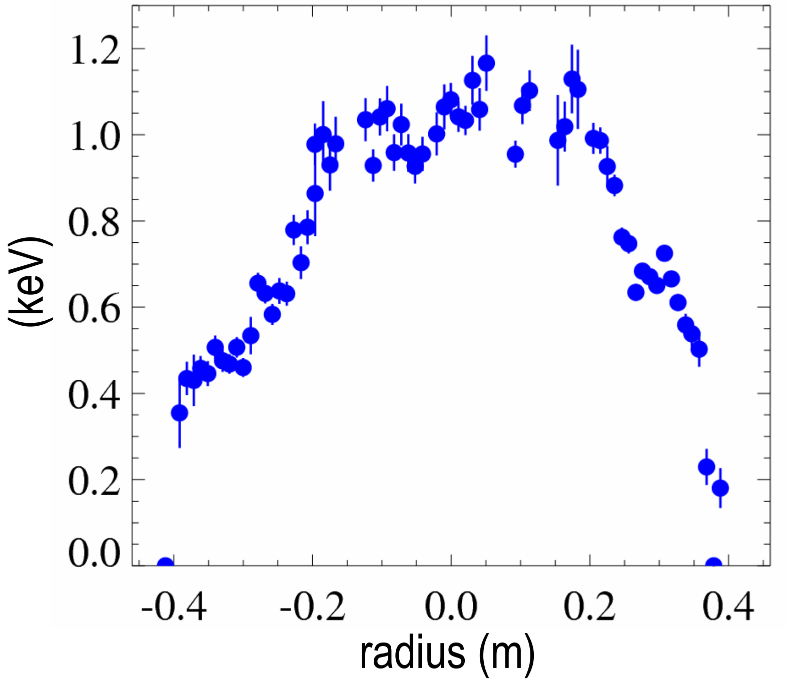
- At high plasma current a helical equilibrium with an electron internal transport barrier spontaneously forms [Lorenzini R. *et al.* 2009 *Nature Phys.* **5** 570]

Flux surfaces from constant-p_e contours

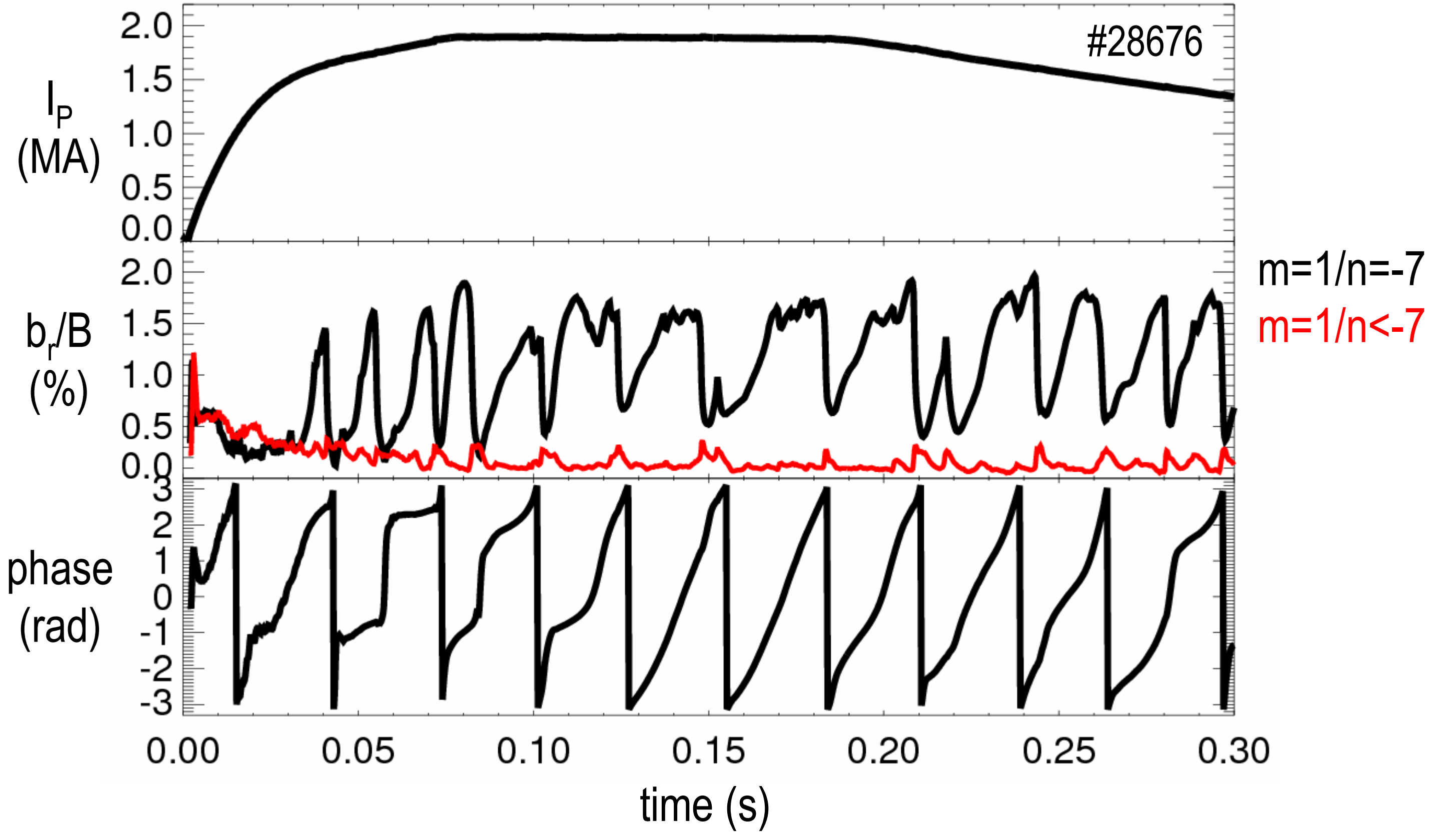


Electron temperature ITB



Pros and cons of self-organization

- Helical equilibria result from a self-organization process, during which a m=1/n=-7 resistive kink-tearing mode nonlinearly saturates at large amplitude
- But such self-organized states can be transiently perturbed by relaxation events



Outline

- Helical RFP equilibria can be controlled by external 3D magnetic fields
- Helical flow and possible effects on ITB
- 3D magnetic fields as a knob to change the flow profile
- Conclusions and future work

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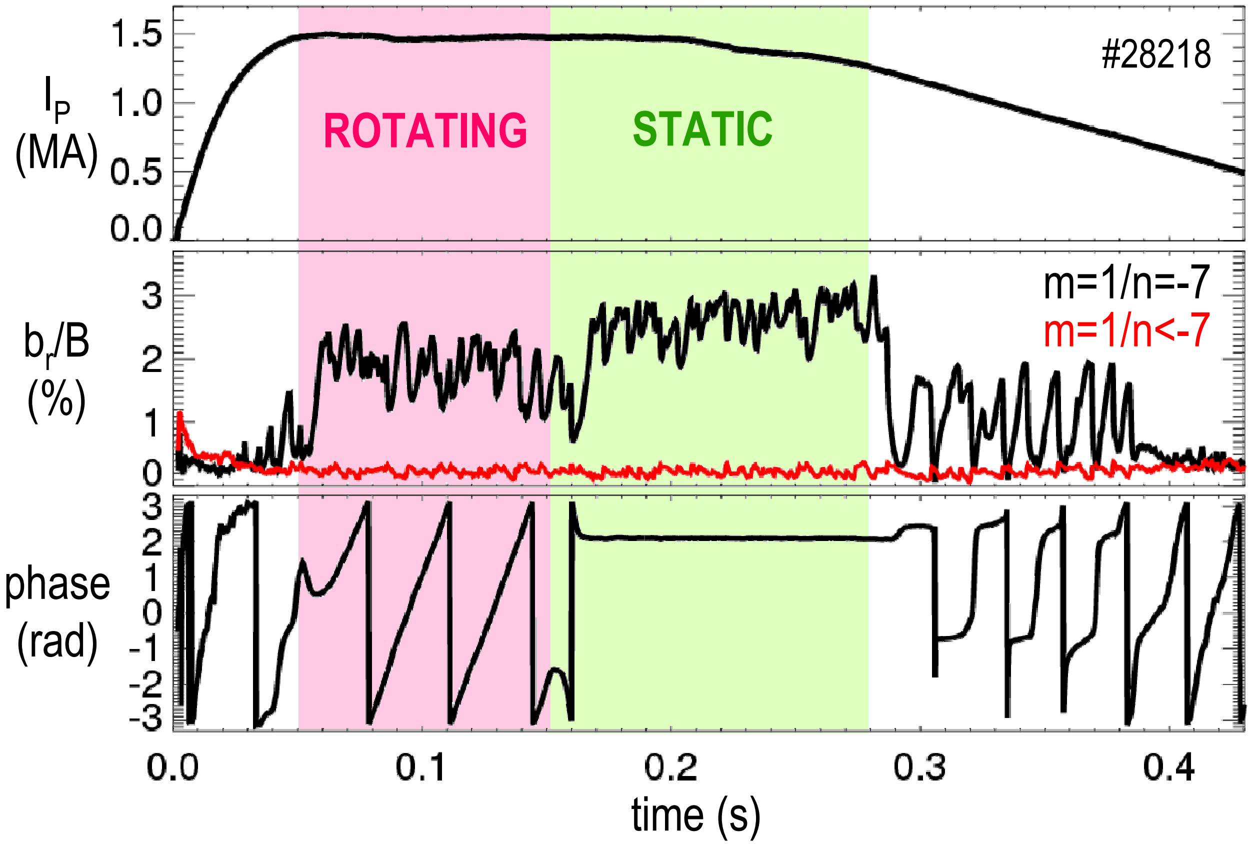
Helical RFP controlled by external 3D fields

- An almost stationary helical equilibrium can be sustained by imposing a finite m=1/n=-7 $B_r(a)$ at the edge through magnetic feedback
- Important for helical divertor operation [E. Martines *et al.* 2010 *NF* **50** 035014]



Helical RFP controlled by external 3D fields

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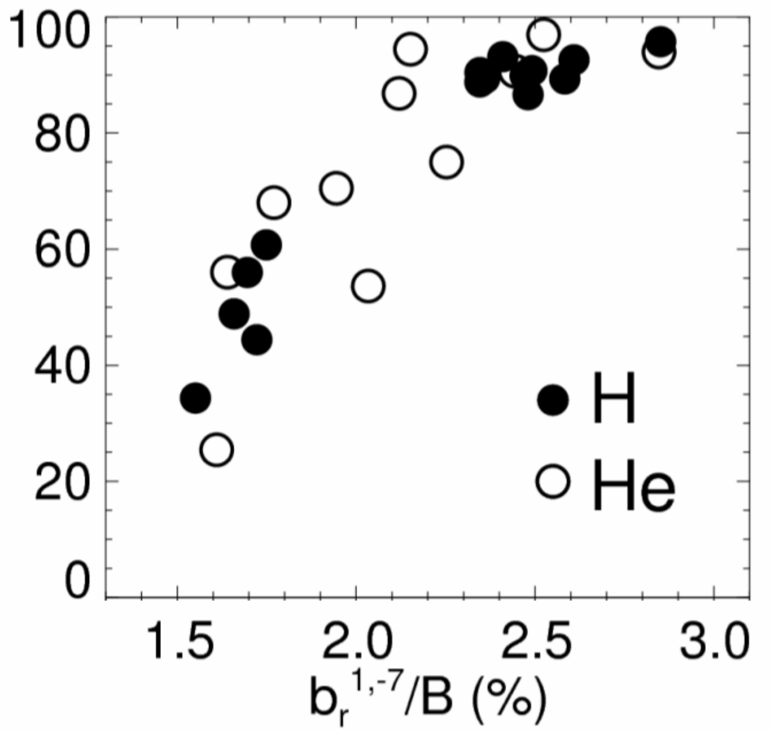
- The helical RFP becomes more and more stationary as the external 3D field increases
- A finite B_r near the edge was shown analytically to be a necessary condition for the existence of helical Ohmic RFP equilibria [Escande D.F. *et al.*, APS 2009]

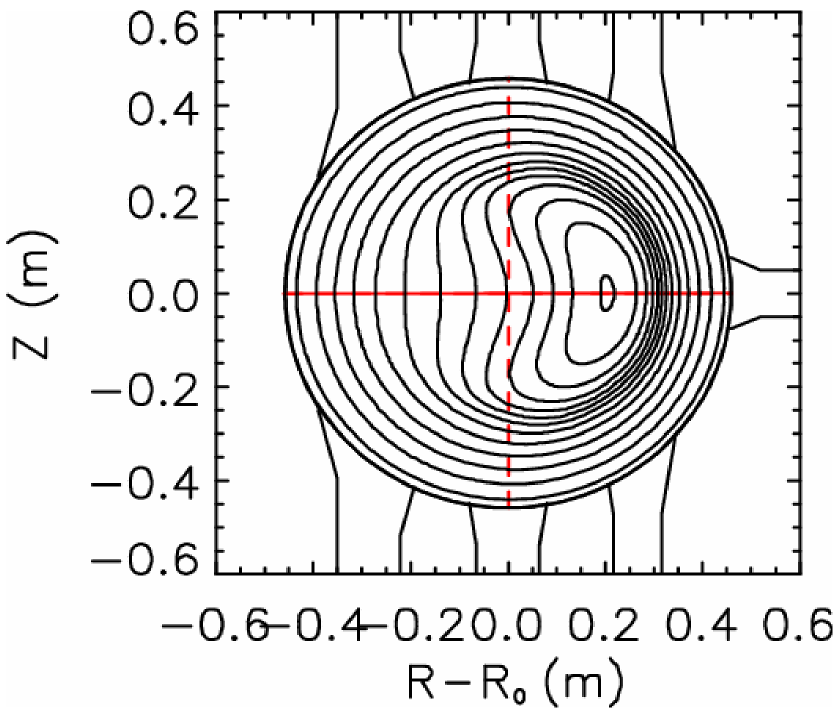
Helical state duration / flattop duration (%)



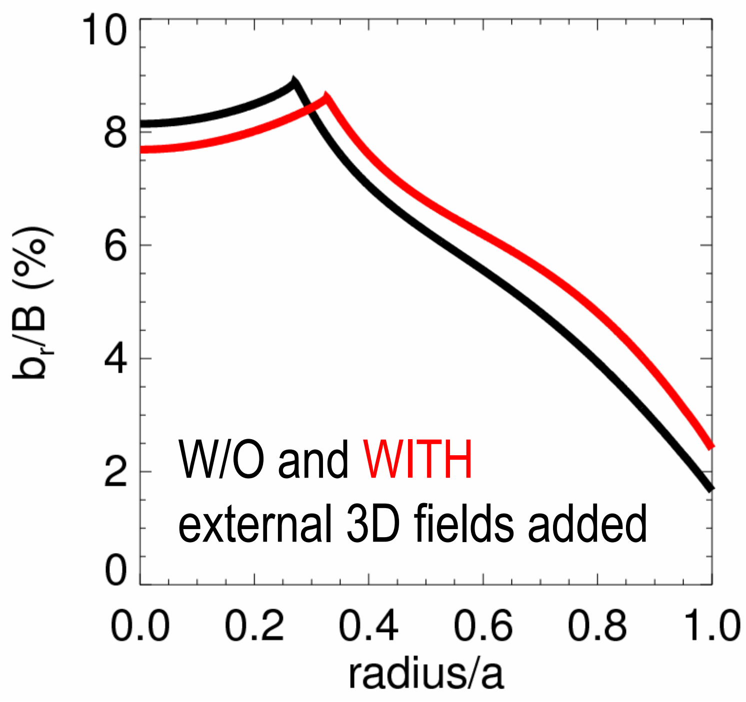
Weak external control required

- The helical deformation is mostly provided by internal currents
- The configuration is almost axi-symmetric at the edge
- Only weak external control is needed to sustain such equilibria

VMEC 3D equilibrium

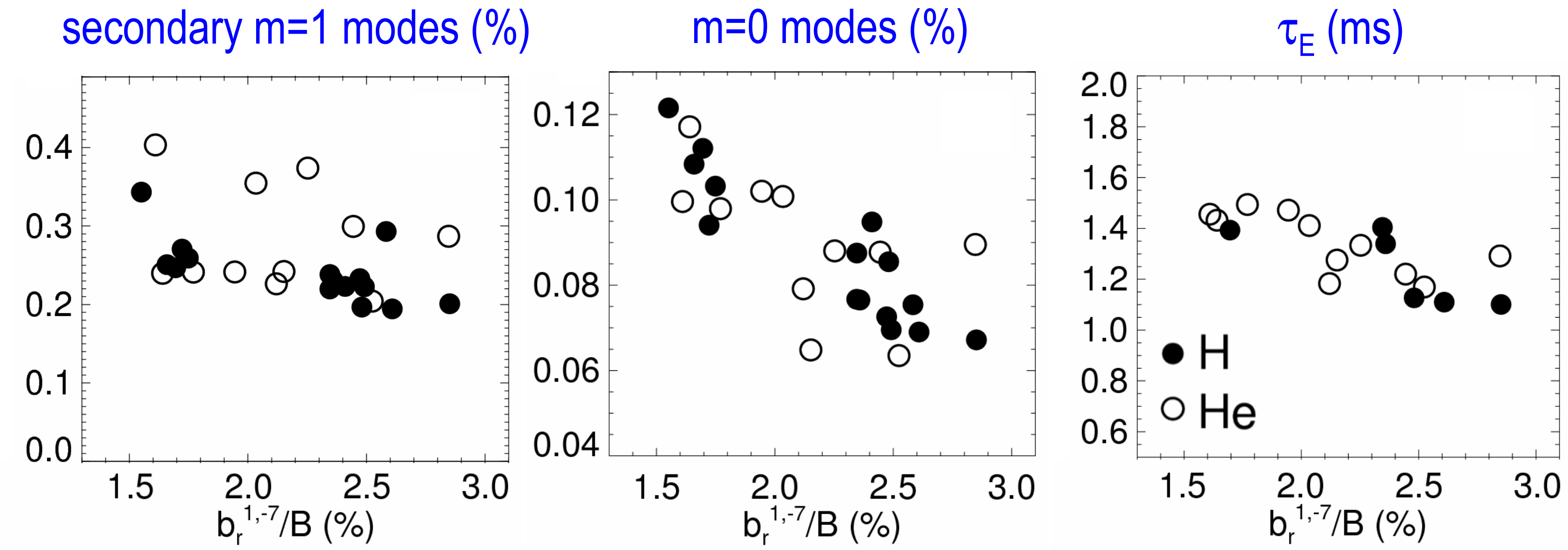


m=1/n=-7 eigenfunction



How external 3D fields affect performance

- Magnetic field stochasticity due to secondary modes decreases
- But the finite $B_r(a)$ increases the PWI and the confinement is slightly degraded ~15%
- Performance may improve with a helical divertor



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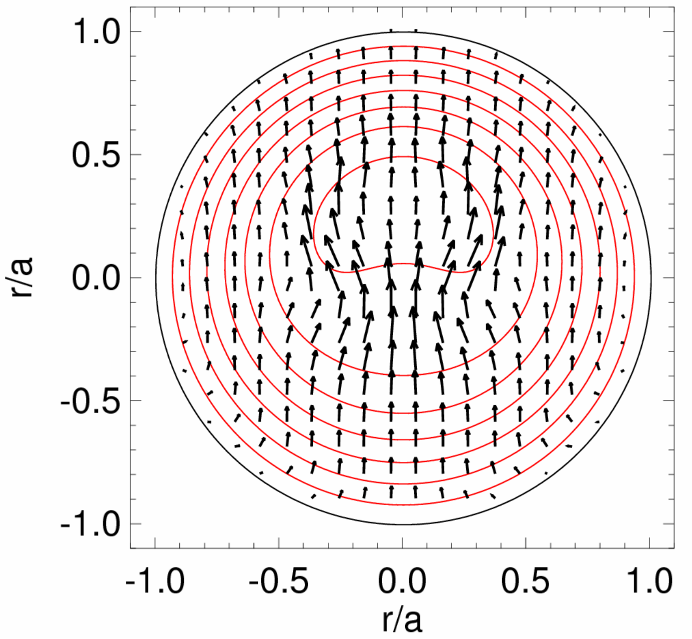
Role of 3D flows in a RFP

- A dynamo electric field is required to sustain an Ohmic RFP equilibrium:

$$\mathbf{E}_{loop} + \mathbf{v}^{1,-7} \times \mathbf{b}^{1,-7} = \eta \mathbf{j}$$

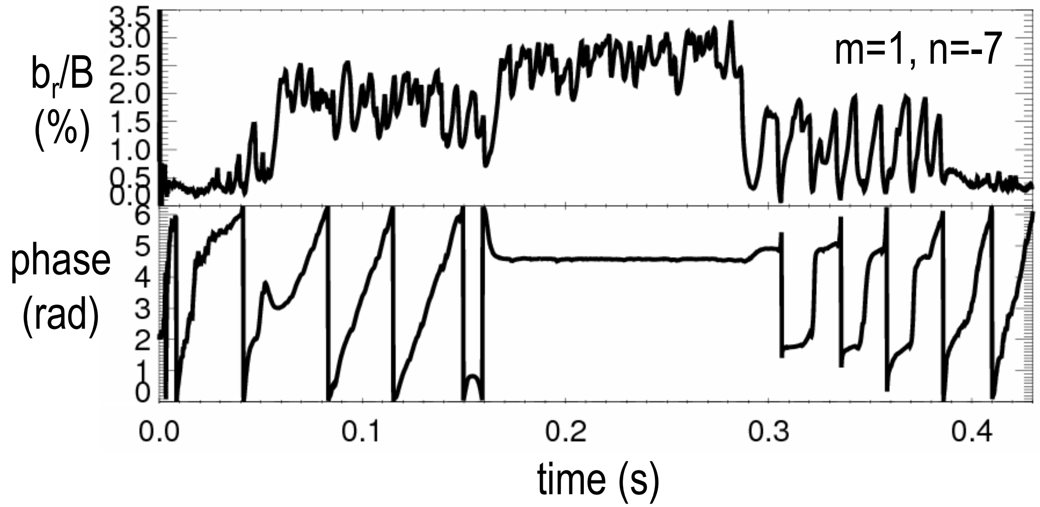
- In a single helicity equilibrium the dynamo can be driven by a laminar helical flow, $\mathbf{v}^{1,-7}$ [Bonfiglio D. *et al.* 2006 *PoP* **13** 056102]
- A global laminar flow may have beneficial effects on confinement

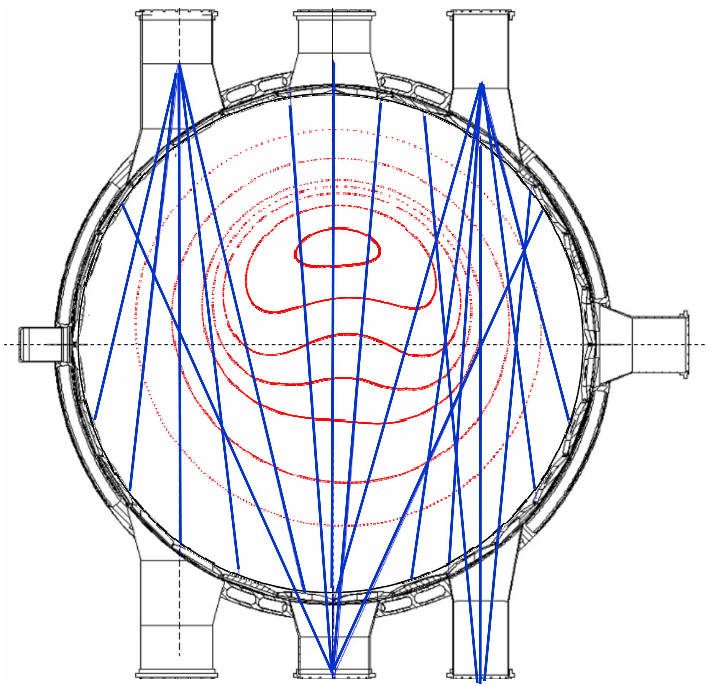


m=1 flow from a nonlinear MHD simulation of a helical equilibrium

Flow measurements in helical equilibria

- Multi-chord passive Doppler spectroscopy of CV and BV ions was used to determine the m=1 helical flow pattern





spectroscopy
lines of sight

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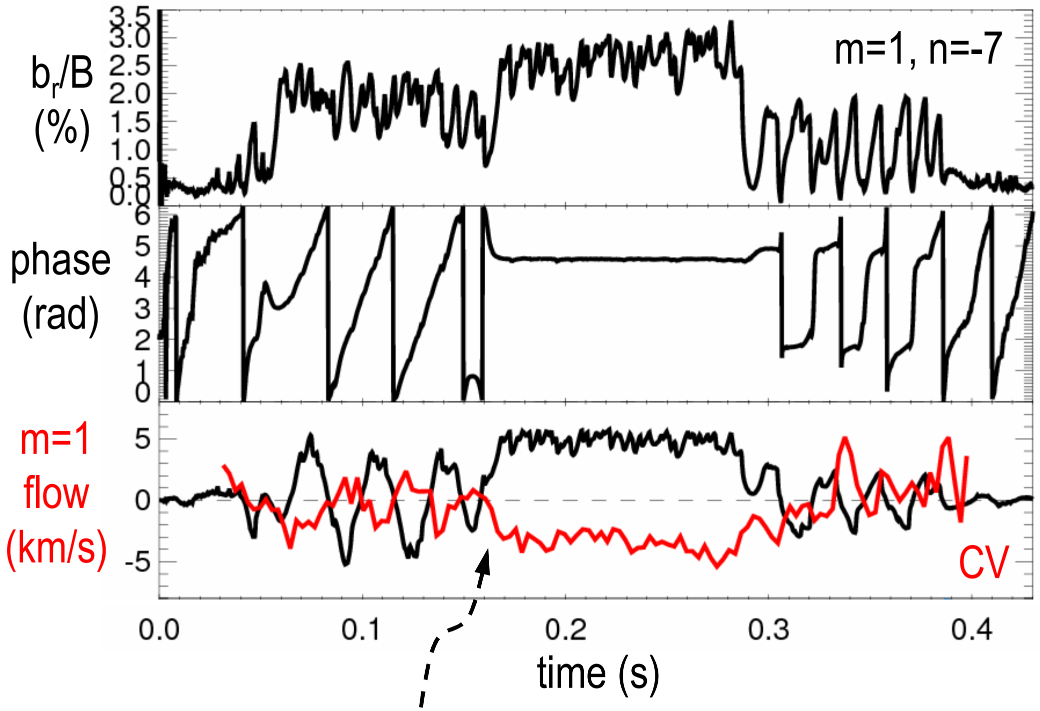

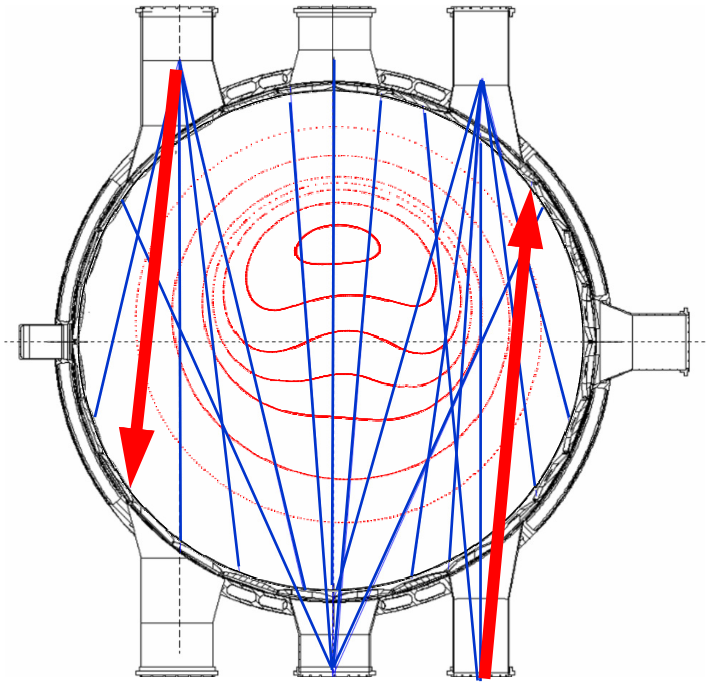

spectroscopy lines of sight

The local 1/-7 $B_r = b_r^{1,-7} \cos(\theta_d - 7\phi_d + \Phi^{1,-7})$ correlates with the m=1 flow

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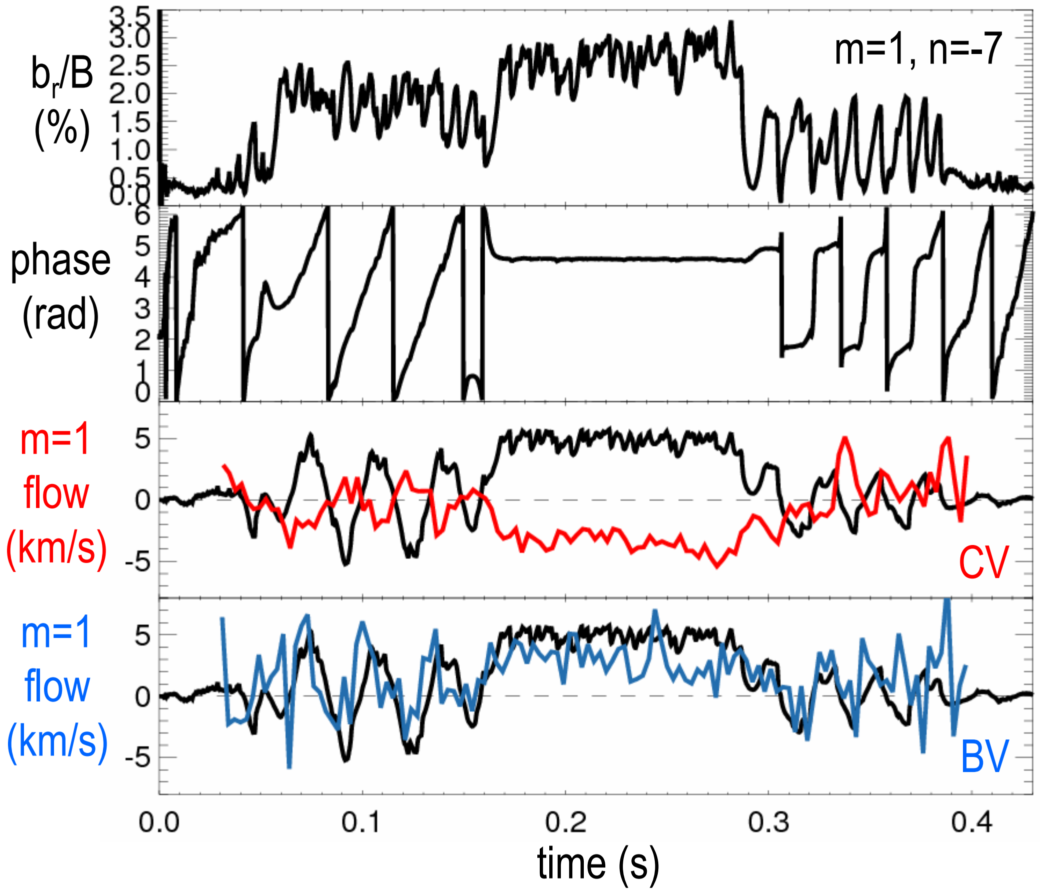
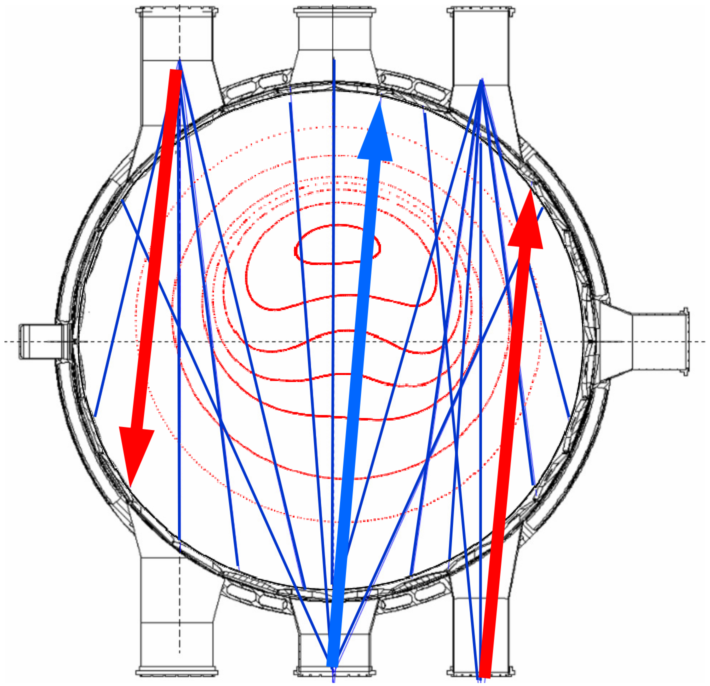
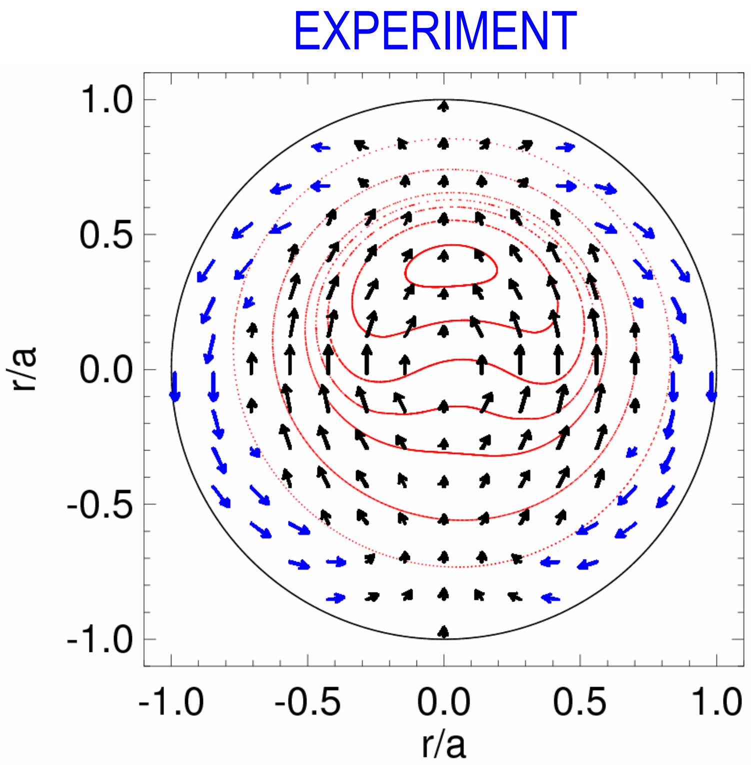




spectroscopy lines of sight

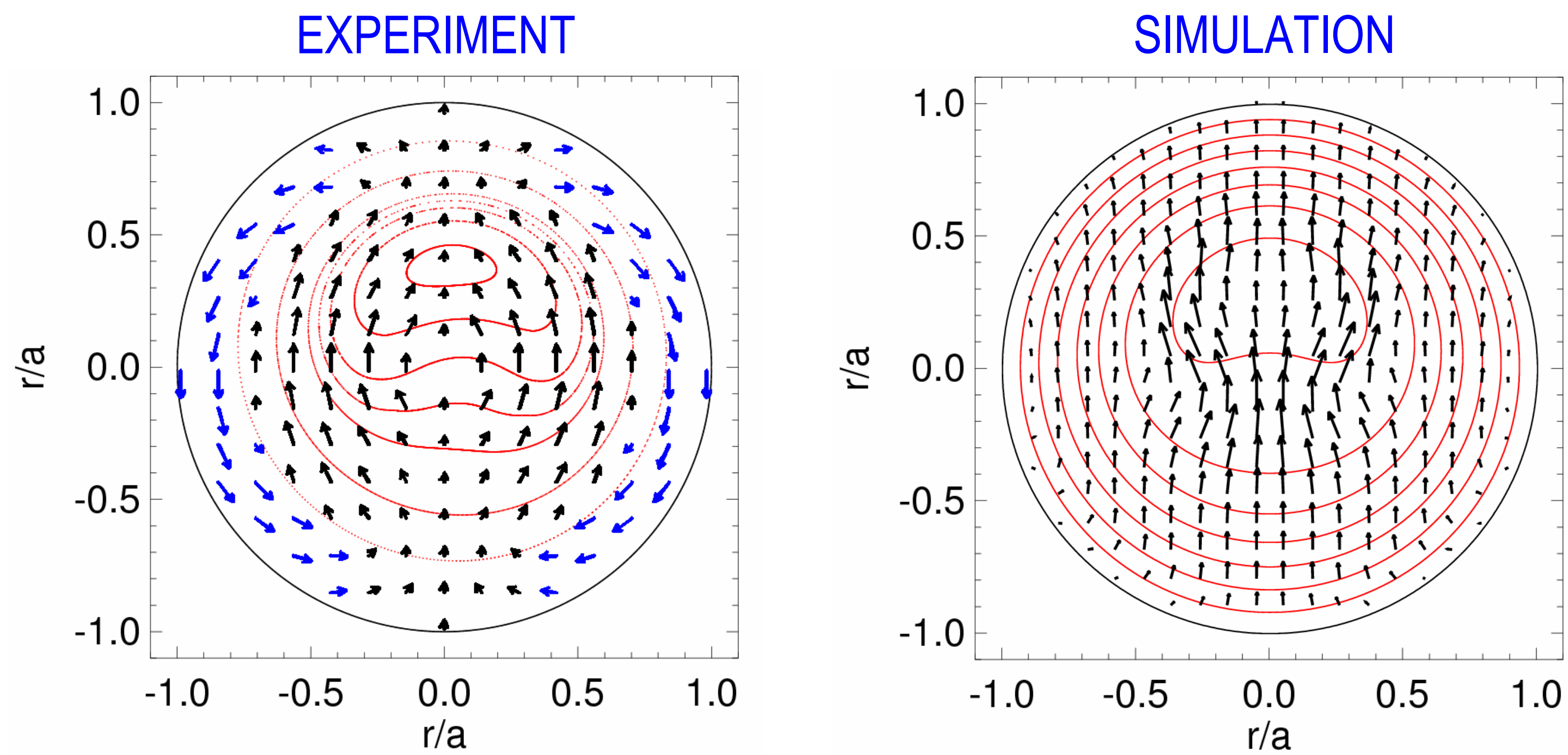
A global helical flow forms

- The m=1/n=-7 flow pattern was reconstructed on a poloidal cross-section by fitting all lines of sight. Compatible with probe measurements at the edge



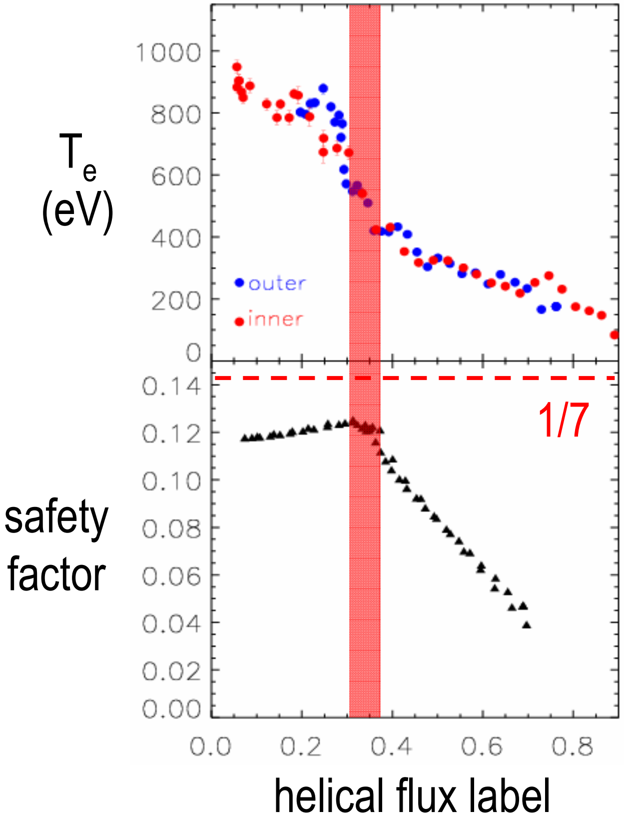
A global helical flow forms

- The m=1/n=-7 flow pattern was reconstructed on a poloidal cross-section by fitting all lines of sight. Compatible with probe measurements at the edge
- The m=1 flow pattern resembles that from nonlinear MHD simulations of single helicity equilibria (SpeCyl code)



Role of magnetic & flow shear on ITB formation

- ITB forms where q and the flow shear (10^4-$10^5 s^{-1}$) are maximum, with strong similarity with tokamak and stellarator results



[M. Gobbin *et al.*, submitted to PRL]

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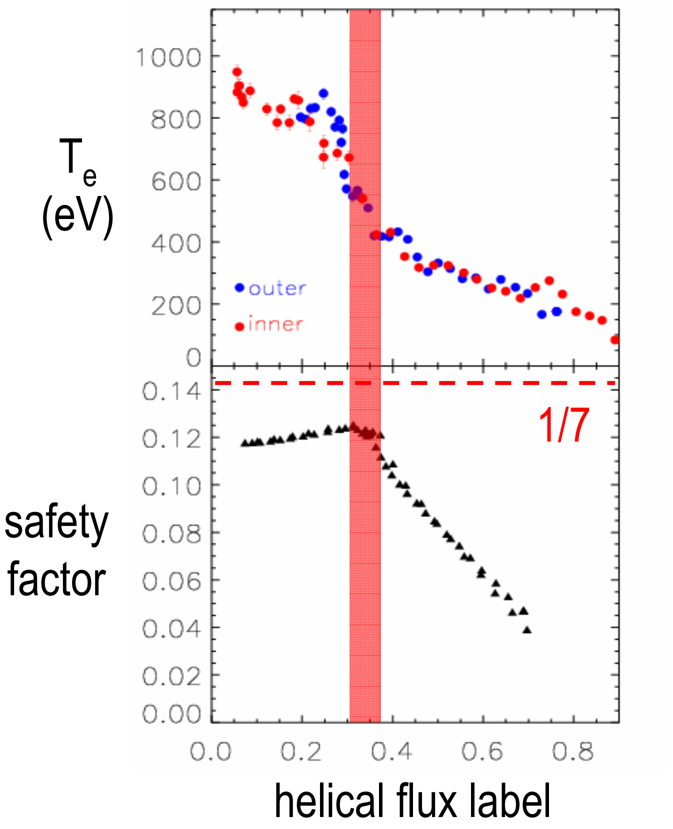

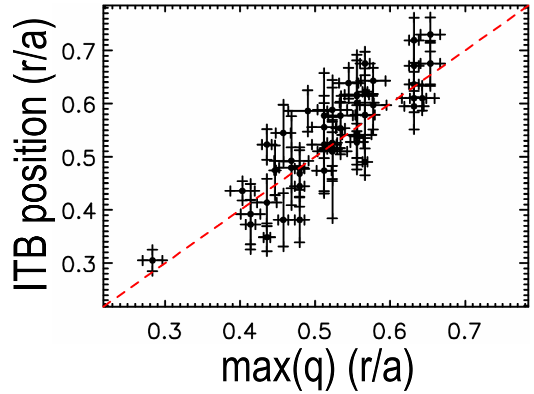

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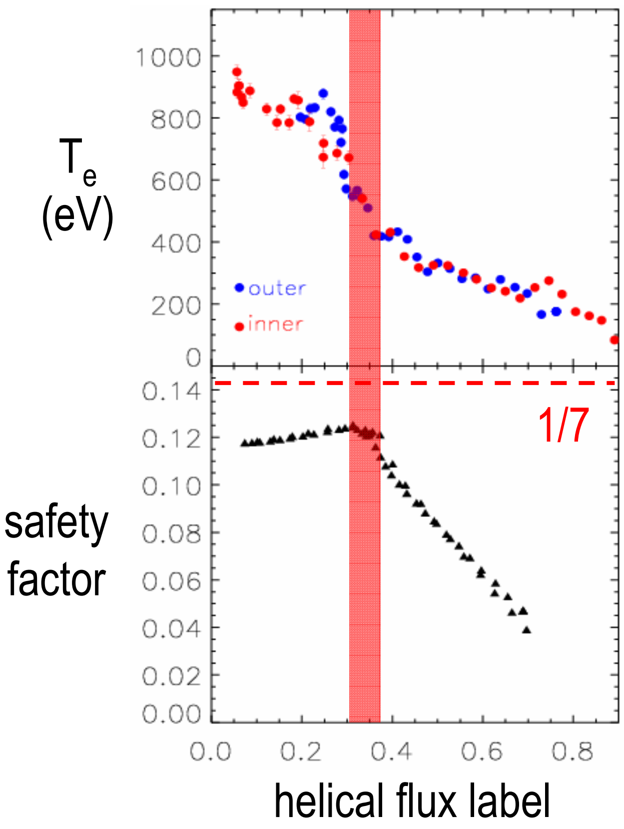

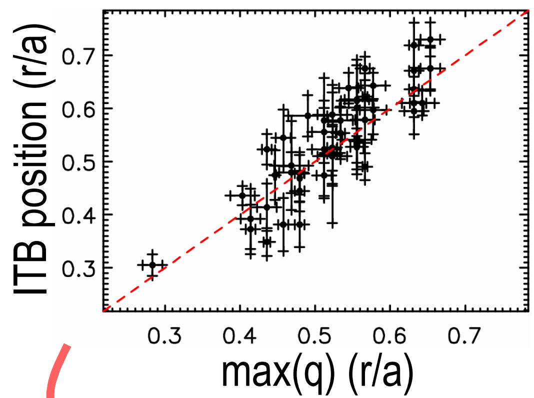

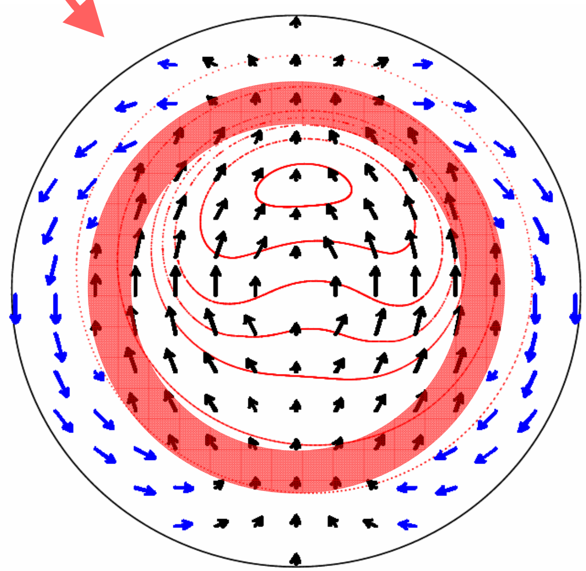

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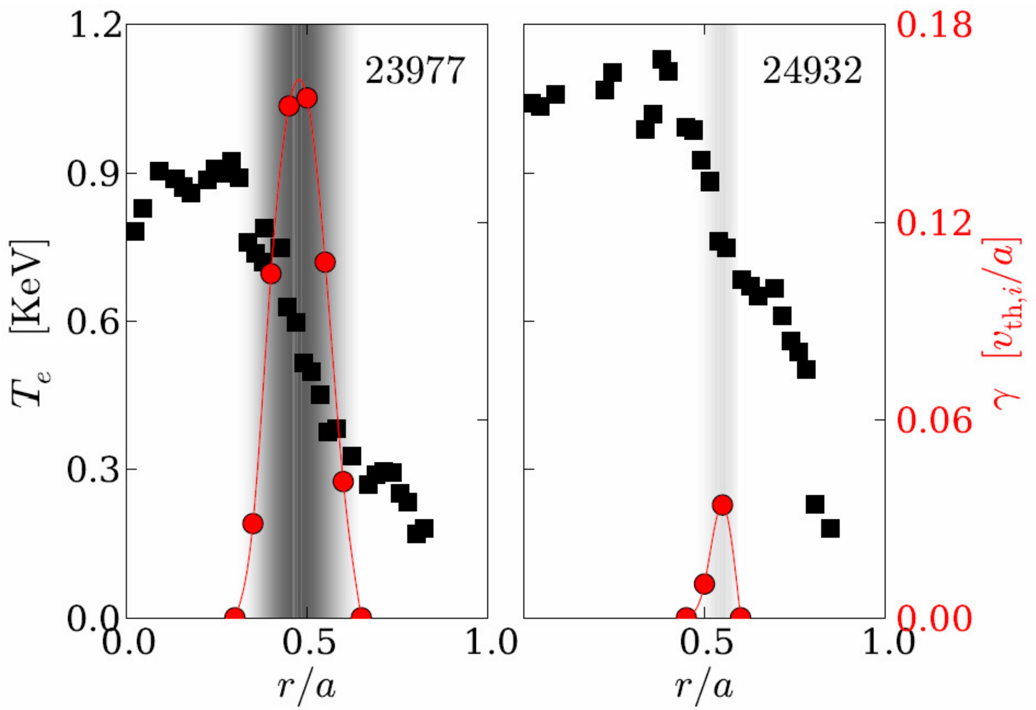
Shear flow and micro-turbulence

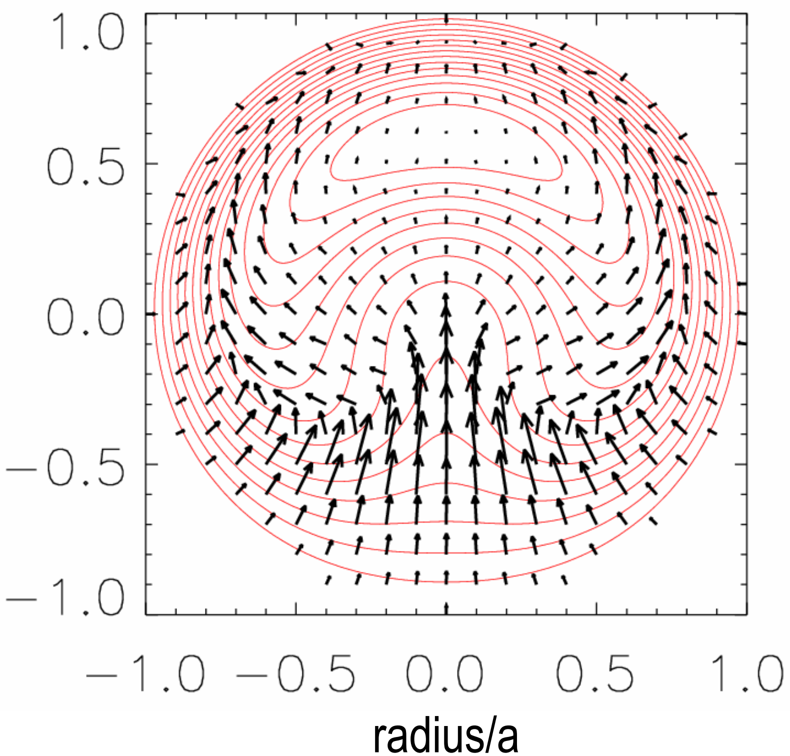
- Simulations with the GS2 gyrokinetic code predict micro-tearing modes to be unstable in the ITB region with $\gamma \sim 5\times10^4 s^{-1}$
- The measured shear flow 10^4-$10^5 s^{-1}$ could be sufficient or marginal for stabilization



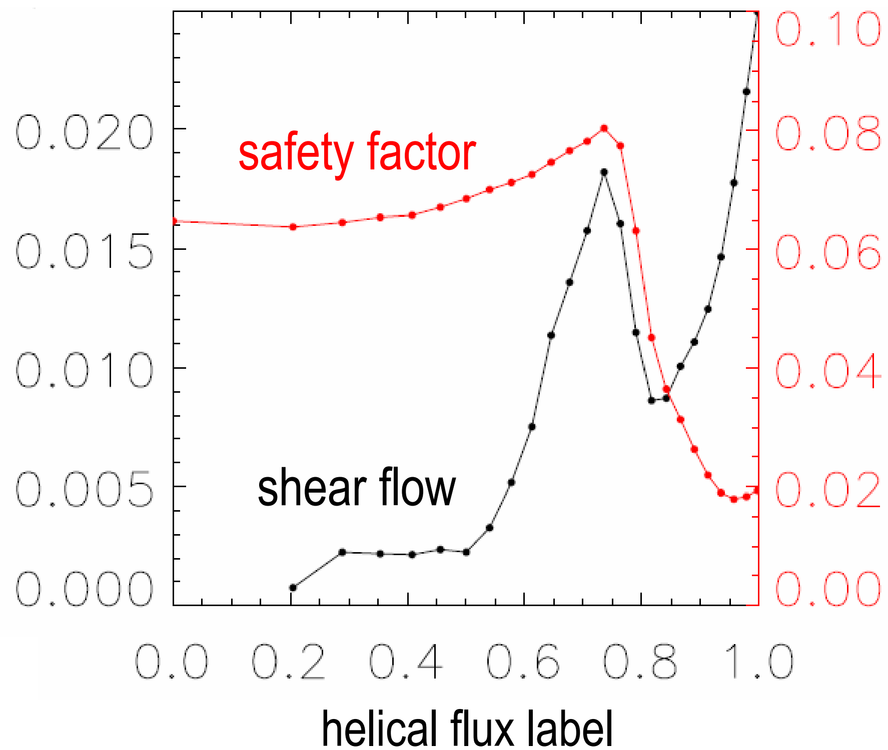
[Predebon I. *et al.* 2010 *PRL* **105** 195001]

Magnetic & flow shear in MHD simulations

- In nonlinear MHD simulations of single helicity equilibria, the flow shear peaks where q is maximum, i.e. where ITBs form



[flux surface averages]



Ambipolar electric fields

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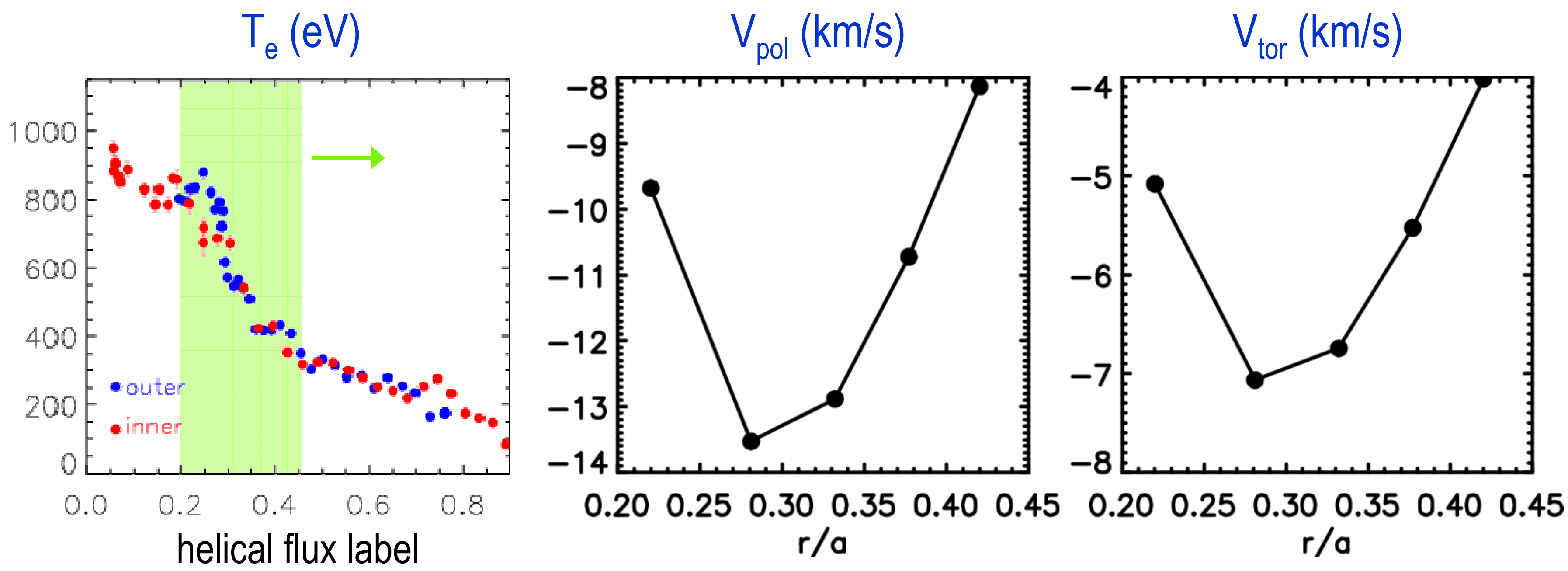
- Ambipolar electric fields and associated flows, originating from neoclassical transport and/or residual magnetic chaos, may be important
- Such effects are being investigated with DKES+PENTA and ORBIT
  [M. Gobbin's invited talk APS 2010]
- Sheared flows similar to the experimental ones or even larger predicted near the ITB



Possible links with tokamaks and stellarators

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- ITB forms near q maximum or integer q surfaces
  - rarefaction of rational surfaces
    [Yu F. Baranov *et al.* 2004 *PPCF* **46** 1181]
- Sheared flows around magnetic islands
  - reduce transport in the LHD stellarator
    [Ida K. *et al.* 2002 *PRL* **88** 015002] →
  - proposed as an ITB trigger in tokamaks
    [Dong J.Q. *et al.* 2007 *PoP* **14** 114501]
- Ambipolar electric fields and associated flows
  - core electron root confinement in stellarators
    [Yokoyama M. *et al.* 2007 *NF* **47** 1213]
  - NTV from non-resonant perturbations drives toroidal flow in tokamaks
    [Garofalo A.M. *et al.* 2008 *PRL* **101** 195005]

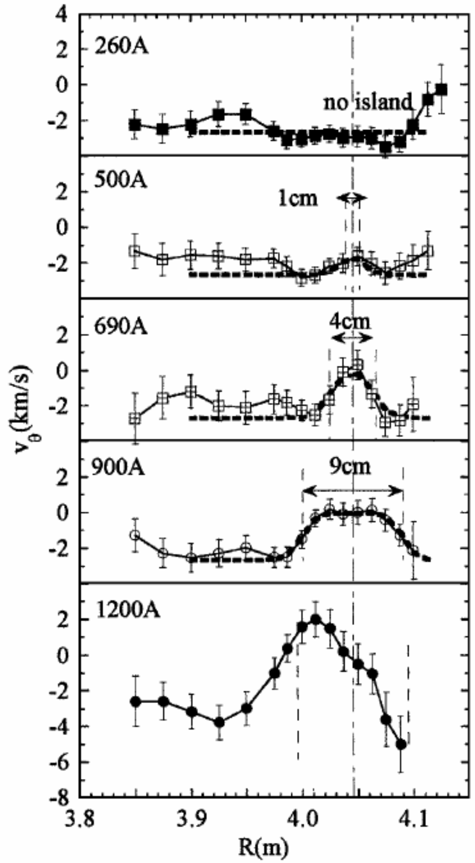

FIG. 2. Radial profiles of poloidal rotation velocity, for various currents of $n/m = 1/1$ external perturbation coils, in the plasma with $B = 1.5$ T and $R_{ax} = 3.5$ m. The last closed surfaces are at $R = 3.28$ m and $R = 4.10$ m at the cross section vertically elongated. The major radius for the center of island, R_i, is indicated with a line as a reference. The dashed lines are fitted profiles of poloidal velocity to the measured values.

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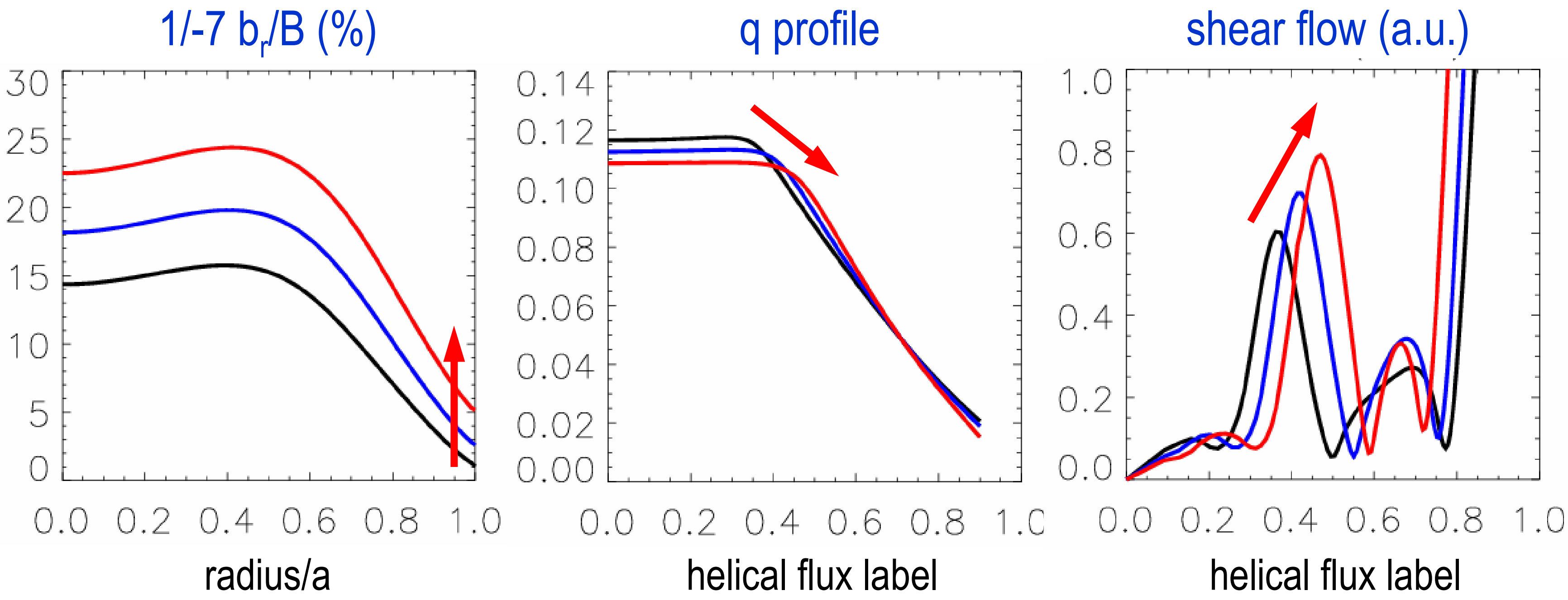
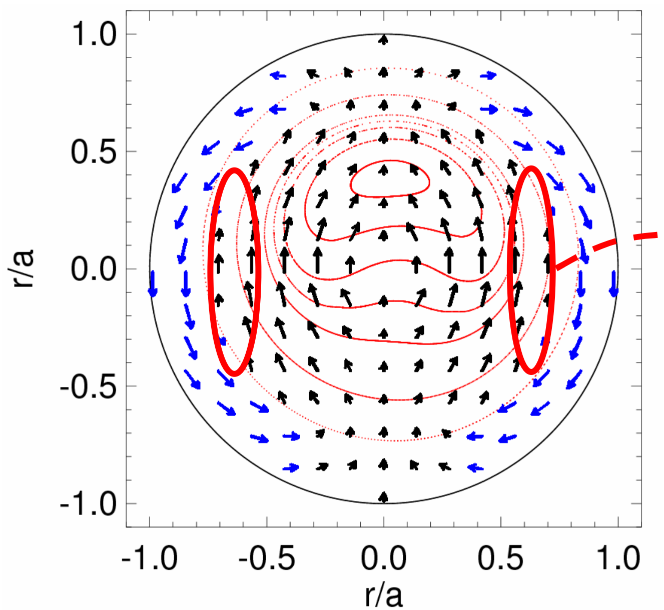
Nonlinear MHD simulations with external 3D fields

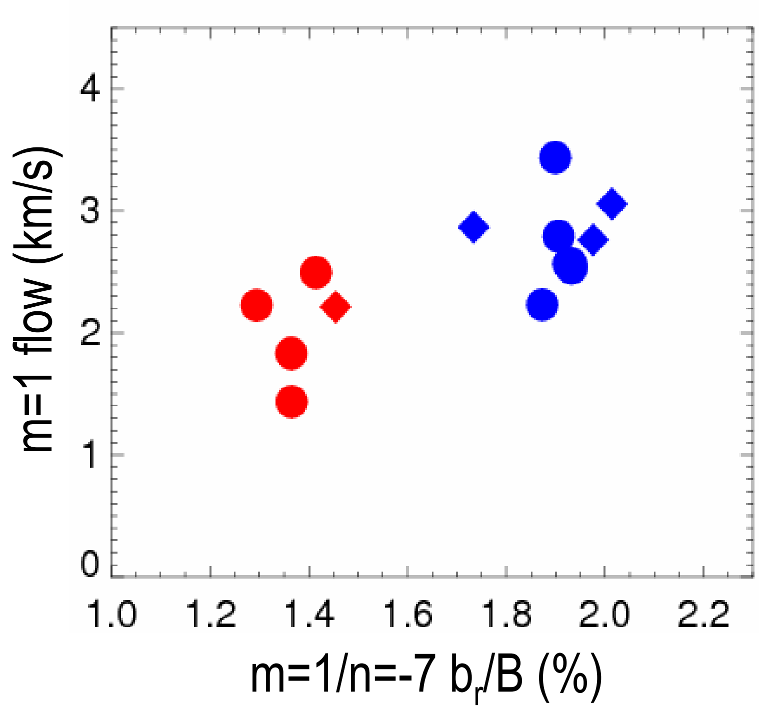
- Nonlinear MHD simulations with external 3D magnetic fields have been performed
- Both the shear flow peak and the q maximum move outward as $b_r(a)$ is increased
- External 3D magnetic fields may be used to improve ITBs



External 3D fields affect the flow profile

- External 3D magnetic fields modify the flow profile also in experiment
- A 50% increase of the m=1 flow inside the ITB is observed
- Possible beneficial effects on ITB, dynamo, and error field screening, to be tested in near future experiments





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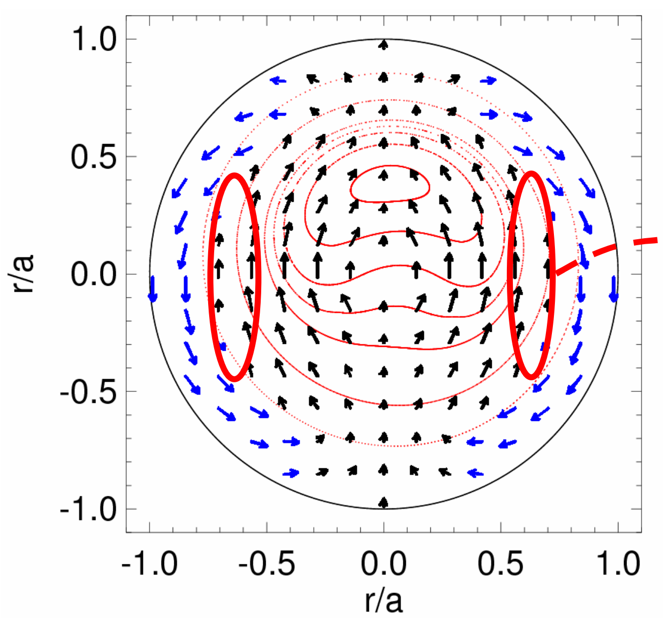

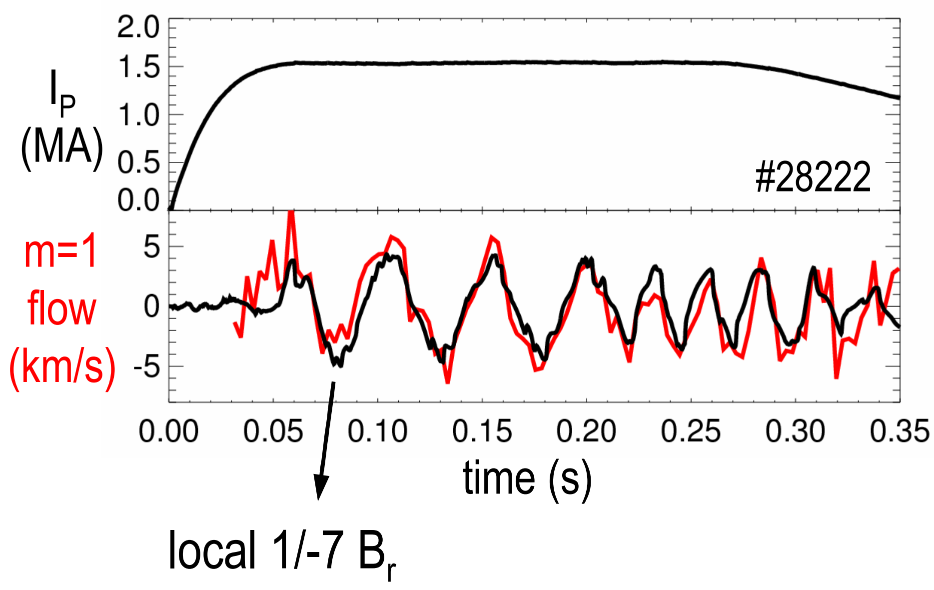

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Conclusions and future work

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- External 3D magnetic fields allow to sustain and control helical RFP equilibria
- A global helical flow forms, which has probably an effect on ITB formation
- 3D magnetic fields can be used to modify the flow profile
- … and possibly to optimize ITBs in near future experiments
- Role of ambipolar electric fields being investigated with ORBIT and DKES+PENTA
- Combining in some way MHD and ambipolar effects in a single simulation is a challenging work, but it could be important to understand and optimize this scenario

Spare slides

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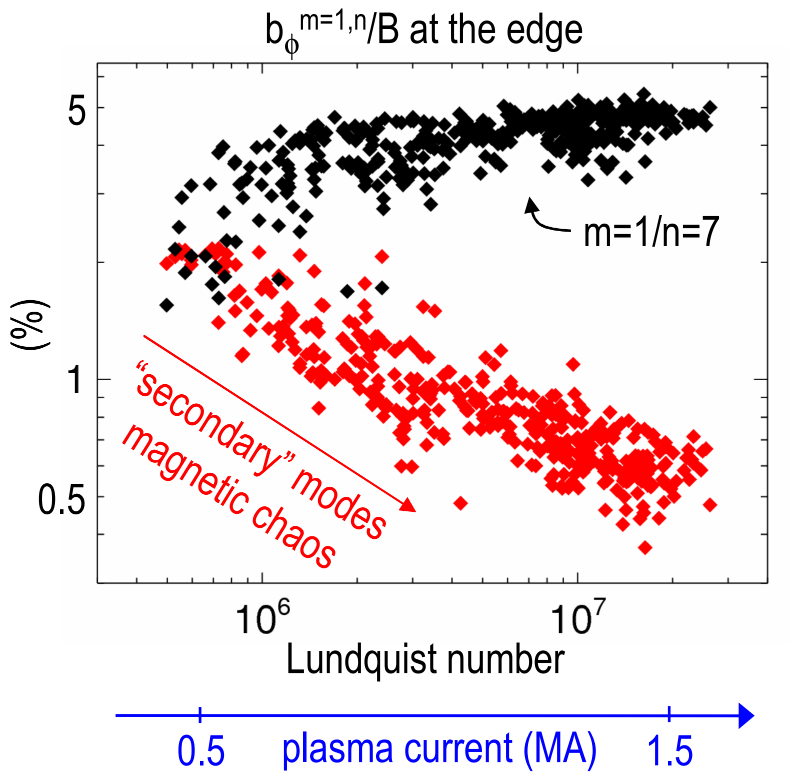
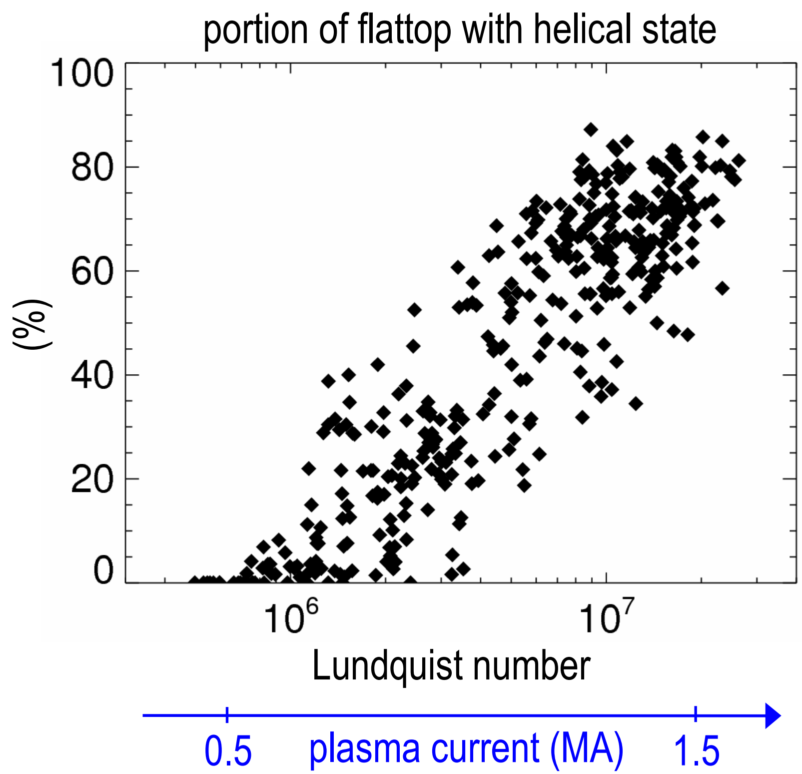
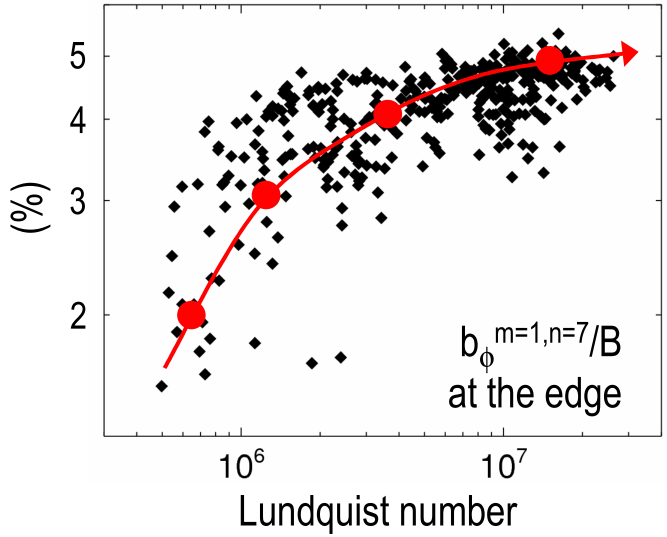
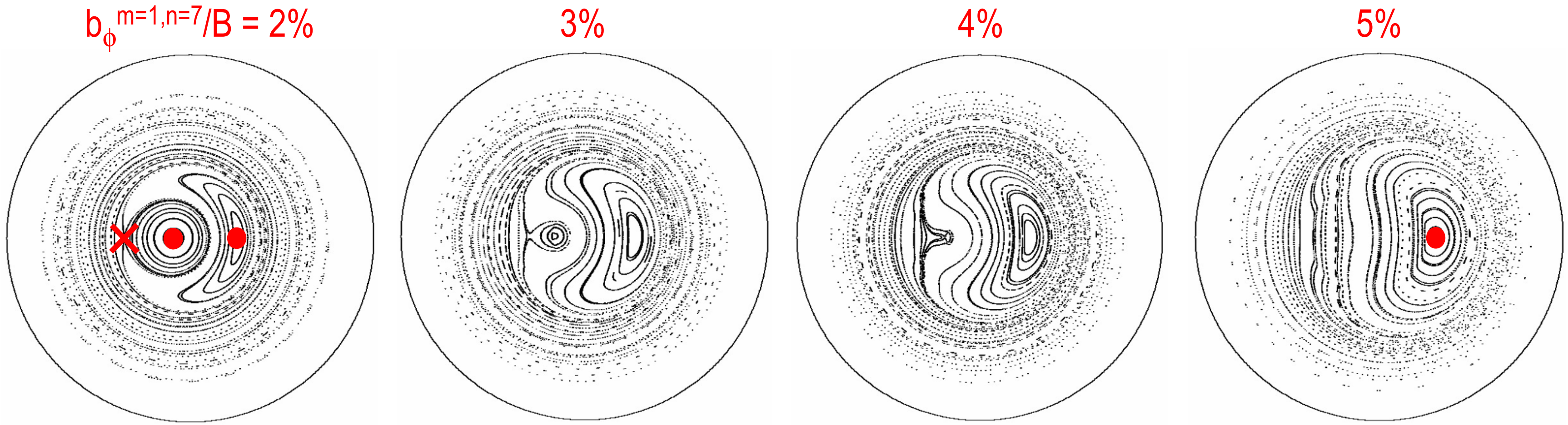




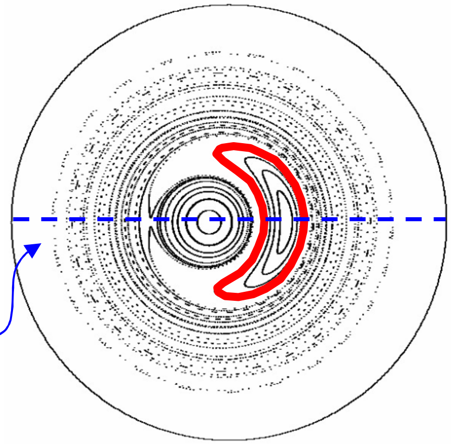




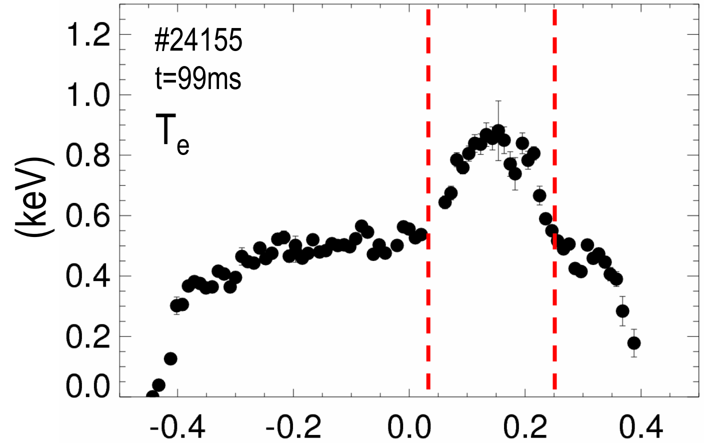
Poincaré plots of magnetic field lines including the equilibrium and the 1/7 helicity (no “secondary” modes)

MAGNETIC ISLAND

$b_{\phi}^{1,7}/B = 2\%$



Thomson scattering line of sight



SINGLE-HELICAL-AXIS

$b_{\phi}^{1,7}/B = 5\%$

$R/L_{Te} \sim 20\text{-}30$

$\chi_e \sim 5\text{-}10 m^2 s^{-1}$