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

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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 $B_\phi$ sensors

$R=2m$, $a=0.46m$
Self-organized helical equilibria

- 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

\[ m=1, n=-7 \]
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]
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]
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

W/O and WITH external 3D fields added
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 $\sim 15\%$
- Performance may improve with a helical divertor

![Graphs showing secondary m=1 modes, m=0 modes, and $\tau_E$ with varying $b_{1-7}/B$.](image-url)
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A dynamo electric field is required to sustain an Ohmic RFP equilibrium:

\[ E_{\text{loop}} + \mathbf{v} \times \mathbf{b} = \eta j \]

In a single helicity equilibrium the dynamo can be driven by a laminar helical flow, \( \mathbf{v} \) [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

![Graph showing m=1, n=-7](image)

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

The local 1/7 $B_r = b_{r1,7} \cos(\theta_d - 7\phi_d + \Phi_{1,7})$ correlates with the m=1 flow.

spectroscopy lines of sight
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
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).
• ITB forms where $q$ and the flow shear ($10^4$-$10^5$ s$^{-1}$) are maximum, with strong similarity with tokamak and stellarator results.
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[M. Gobbin et al., submitted to PRL]
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Simulations with the GS2 gyrokinetic code predict micro-tearing modes to be unstable in the ITB region with $\gamma \sim 5 \times 10^4 \text{s}^{-1}$.

The measured shear flow $10^4-10^5 \text{s}^{-1}$ could be sufficient or marginal for stabilization.

[Predebon I. et al. 2010 PRL 105 195001]
In nonlinear MHD simulations of single helicity equilibria, the flow shear peaks where \( q \) is maximum, i.e. where ITBs form.

[flux surface averages]

- **Safety factor**
- **Shear flow**

**radius/a**

**helical flux label**
Ambipolar electric fields

- 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.

![Graphs showing T_e (eV), V_{pol} (km/s), and V_{tor} (km/s)]
Possible links with tokamaks and stellarators

- 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
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Nonlinear MHD simulations with external 3D 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

![Graphs showing 1/$7 b_r/B$ (%) vs radius/a, q profile, and shear flow (a.u.) vs helical flux label.](image_url)
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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Conclusions and future work

- 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
portion of flattop with helical state

\[ b_{\phi}^{m=1,n=7} / B \text{ at the edge} \]

Lundquist number

m=1/n=7

“secondary” modes

magnetic chaos

0.5 plasma current (MA) 1.5

portion of flattop with helical state

Lundquist number
$b_{\phi}^{m=1,n=7}/B$ at the edge

Poincaré plots of magnetic field lines including the equilibrium and the 1/7 helicity (no “secondary” modes)
MAGNETIC ISLAND  
\[ b_\phi^{1.7}/B = 2\% \]

SINGLE-HELICAL-AXIS  
\[ b_\phi^{1.7}/B = 5\% \]

- \[ R/L_{T_e} \sim 20-30 \]
- \[ \chi_e \sim 5-10 m^2 s^{-1} \]