Outline & Background
Experimental data
Test-particle simulations

Edge ambipolar potential in toroidal fusion plasmas

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Plasma surface is not smooth

**Tokamak: DIII-D**
[Moyer 2012]

**RFP: RFX-mod**
[Vianello 2013]

**Stellarator: LHD**
[Feng 2011]
The edge magnetic topology influences plasma flow [Vianello 2013]

- Gas-puff imaging (GPI) toroidal flow @ $r = 0.98a$
- Two null points of flow define a convective cell
- The convective cell has the same symmetry as the $(m=0; n=1)$ mode resonating at $q = 0$
- In particular, the center of the cell corresponds to the X-point of the island
- Density accumulation & MARFE at $n/n_G \approx 0.8$ [Puiatti 2009]

$$u_{m,n} = m\theta - n\zeta + \omega_{m,n} t = -\zeta + \omega_{0,1} t$$
Experimental data: The (0,1) topology in RFX

- Measured values of $E^r \approx v_\phi B$ mapped onto an edge flux-surface calculated with VMEC/V3FIT [Terranova 2013]
Experimental data: The (1,7) topology in RFX

- $E'$ measured with the array of internal sensors (ISIS) [Serianni 2003] mapped onto a helical flux-surface calculated with VMEC/V3FIT
Magnetic islands spontaneously resonating in the RFP are associated with macroscopic fluctuations of the flow (up to $\approx 20$ km/s).

The symmetry is the same as the generating island ($1/7$ low density, and $0/1$ at high density in the RFX).

The values of $E^r$ are not constant on a flux-surface $\rightarrow$ this suggests that the electrostatic potential $\Phi \neq \Phi(\psi)$.

In the RFP, and in the $0/1$ case, the fluctuations in the flow are also associated to macroscopic changes in transport properties (stagnation point and MARFE).

Inductive correction is small: helical case,

$$E^r_{ind} = -\langle B \rangle \omega r / m \approx -70 V/m \ll 10kV/m \ [\text{Scarin 2013}]$$
Test-particle simulations

- We use the guiding-center code ORBIT [White 1984] to analyze the magnetic field topology and the motion of (monoenergetic) electrons and ions embedded in the magnetic field.
- ORBIT is in Boozer co-ordinates ($\psi_p, \theta, \zeta$).
- RFX: input = the eigenfunctions [Zanca 2004] obtained by solving the Newcomb’s equations (constraint = magnetic fluctuations measured in the experiment).
- TEXTOR: input = analytic form for the radial perturbation induced by the DED, based on current levels in the coils [Finken 2005].
- Collisions are implemented as pitch-angle and energy scattering between particles, using the Boozer-Kuo approach [Boozer 1981].
- The standard ORBIT perfectly absorbing wall has been modified [Spizzo 2012] to take into account recycling $R = 1$. 
Simulations - Connection lengths (RFX)

Poincaré with 0/1 mode only, $L_\parallel$ with full spectrum

$\psi_{p,1}$

$\psi_{p,2}$

$L_\parallel(\psi_p, \theta, \zeta) \simeq \nu_{th} \tau_{trav}$ [Scarin 2011], $\tau_{trav}$ electron travel time between deposit $\psi_{p,1}$ and recovery surface $\psi_{p,2}$.
Electrons spend on average more time near the XP, and less time near the OP (classical pendulum - period $T_{XP} \to \infty$)
Simulations - Connection lengths (TEXTOR with RMP)

- LEFT = electrons, RIGHT = ions $\longrightarrow$ ion $L_\parallel$ more uniform along $\theta$
- ions $\Rightarrow$ larger drifts
- $L_\parallel$ has the same symmetry as the RMP helicity (3/1 in this case)
Simulations - $D_e$, $D_i$ (TEXTOR with RMP)

- **Evaluate steady state distributions** $n(\psi)$ by fixing source and sink
  
  [Spizzo&White 2009]

- Choose small (helical) domain, reinsert lost particles at the center with uniform pitch

- Find $D$ from flux of particles leaving the domain and the density gradient.

- $D_i$ almost neoclassical, small change along $u$; $D_e \gg D_i$ everywhere

- ... but $D_e$ depends also strongly on $u$: 1 order of magnitude difference between OP and XP
The ambipolar mechanism

Standard picture with RMP chaos: $D_e \gg D_i$ and density pump-out.

→ Too simplified! A strong potential builds up to balance $\Gamma_e = \Gamma_i$

- the potential arises to balance the fluxes that are modulated along $u$, so it has the same symmetry as the original $m/n$ mode
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**Analytic form of the potential-radius**

- Old RFX data: the edge $E_r$ changes sign [Puiatti 2001] along $\phi$, coherently with $\nu_\phi$
- start from experiment to define

\[
E_\psi_p = E_a + \frac{1}{2} E_{r,w} \left[ \tanh \left( \frac{\psi_p - \psi_{p,rv}}{\sigma_{\psi_p}} \right) + 1 \right]
\]

where $\psi_{p,rv}$ is the reversal surface, $\psi_{p,rv} - \sigma_{\psi_p} = 0.077$, $\sim 38$ cm, $E_a = -1.5$ kV/m, $E_{r,w}$ free parameter
Angular dependence derived from GPI data (see slide 4):

$$A(\zeta) = 2e^{-\frac{(\zeta-\zeta_0)^2}{2\sigma^2}} - 1 \quad (2)$$

such that

$$\Phi(\psi_p, \zeta) = -E_a\psi_p + V(\psi_p) \times A(\zeta) \quad (3)$$

and $E_{\psi_p} = -V'(\psi_p) + E_a$

In the plot, $\zeta_0 \sim 100^\circ$ is only a guess
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In the plot, \( \zeta_0 \sim 100^\circ \) is only a guess.
Convective cell in the edge

As a consequence of $\frac{\partial \Phi}{\partial \zeta} \neq 0$, a convective cell forms near the edge.

Motion across the potential $\vec{v} \cdot \nabla \Phi = 0$ (on the equipotential surfaces)

$\rightarrow$ conserves kinetic energy and drives the density limit phenomena ($\nabla \cdot (n \vec{v}) \neq 0$)
Determine the potential amplitude

Vary the free parameter $E_{r,w}$ until electrons are trapped (no perturbations)

Linear dependence with energy,

$E_{r,w} = -\frac{T_e}{eL_{\text{well}}}$

$L_{\text{well}} \sim 6.6 \text{ cm} \left( L_{\text{well}} = 2\sigma_{\psi_p} \right)$

Experimental evaluation from GPI

$E_r = \frac{T_i}{Ze} \frac{\nabla P_i}{P_i} + v_\phi B_\theta$

$\simeq 0.15E_r + v_\phi B_\theta \quad (4)$

Field is likely to be ambipolar
Determine the potential phase

✓ Let $6 \times 10^4$ particles diffuse between

$\psi_{p,1} = 0.093$  
($\sim 44.6$ cm) and

$\psi_{p,2} = 0.079$  ($\sim 39$ cm)

✓ Each run is performed by varying the free parameter $\zeta_0$

✓ look at the fluxes $\Gamma_e$ and $\Gamma_i$ at $\psi_{p,2}$ (each point = one run)

✓ Ambipolarity is reached at $u = \pi/2$, and not $u = 3/2\pi$ as measured
The Orbit results on the phases suggest that there could be a collisional effect (the ambipolar field results from a particle trapping and detrapping in an electrostatic potential).

Energy-exchanging collisions are necessary.

In the meantime, in April 2013 we performed an experimental scan on collisions.

The 1/7 configuration (helical-QSH) is obtained only at low density, \( n/n_G \approx 0.2 \).

It is possible, using the feedback system of RFX, to get a low-collision, MH state at \( n/n_G \sim 0.2 \), to compare with the 0/1, high density case.
The phase of the potential is such that the well (maximum $E^r$) is always at $u \approx 3/2\pi$ (XP of the island)
Magnetic islands in the edge plasma generate an ambipolar potential with their symmetry, as deduced from measurements of $E^r$ and flow.

Test particle simulations in the RFX 0/1 case can reproduce this potential:

- Amplitude = determined by electron energy
- In simulations (RFX), the phase is such that the potential well (maximum $E^r$) corresponds to the OP of the island, and not the XP as in measurements
- In TEXTOR the measured potential well corresponds to the electron depletion region (XP in that case), as in ORBIT

Role of collisions and electron energy is an open issue.
Future: introduction of energy-exchanging collisions in Orbit simulations can allow for

- simulating energetic tails (e.g. ECRH): since the ’80s the electrostatic $E^r$ was seen to depend on ECRH [Hsu 1984];
- trying to understand the collisional dependence of RMP application.
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The Reversed-Feld pinch (RFP) shows a bifurcation from a chaotic regime to helical equilibrium [Lorenzini 2009, Cappello 2011].

Chaotic regime = MH = dominated by the $m=0; n=1$ island
Helical regime = QSH = dominated by the $m=1; n=7$ island
Motion across on the equipotential surfaces

\[ \vec{v} \cdot \nabla \Phi = 0 \]  

(5)

Together with \( \frac{\partial \Phi}{\partial \theta} = 0 \), Eq. (5) allows for using the same formalism as the flux coordinates:

\[ \vec{v} = \nabla \Phi \times \nabla \theta = \frac{\partial \Phi}{\partial \psi_p} \nabla \psi_p \times \nabla \theta - \frac{\partial \Phi}{\partial \zeta} \nabla \zeta \times \nabla \theta \]  

(6)

Since, in general, \( \nabla \cdot (\nabla A \times \nabla B) = 0 \), Eq. (6) implies \( \nabla \cdot \vec{v} = 0 \)
Energy dependent collisions

- Being the main mechanism a trapping/detrapping in an **electrostatic** potential, monoenergetic assumption is too strict;
- Relaxation to a Maxwellian: single particle (ion), initial $E = 400$ eV, ion background $T_i = 230$ eV, 50 collisional times (analogue to Fig.4 in [Boozer 1981])
- Maxwellian = straight line in the plot

we take into account collisions between all of the 3-species (ion, electrons and main impurity- C$^{4+}$)