Edge ambipolar potential in toroidal fusion plasmas

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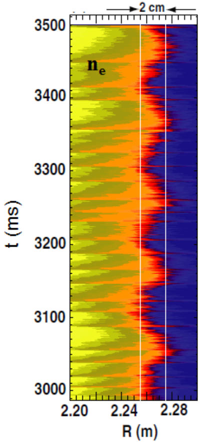
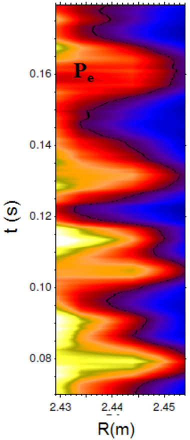
Plasma surface is not smooth

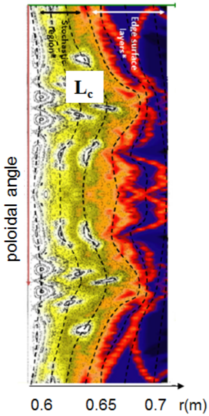
Tokamak: DIII-D
[Moyer 2012]



RFP: RFX-mod
[Vianello 2013]

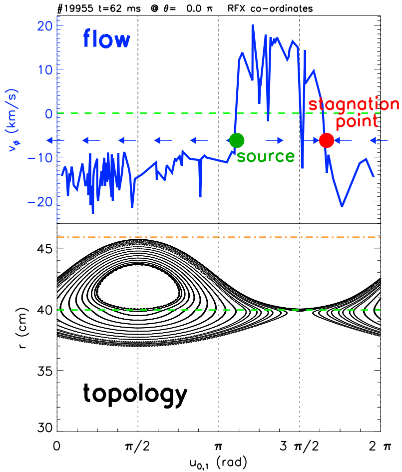


Stellarator: LHD
[Feng 2011]



Stochastic edge in RFP

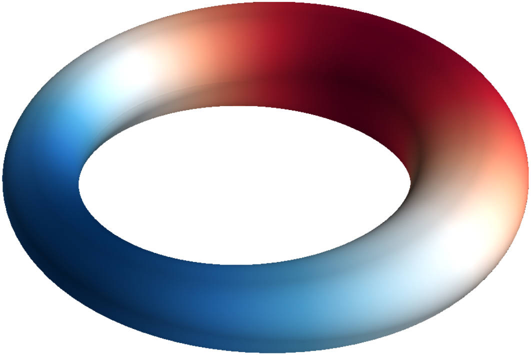
The edge magnetic topology influences plasma flow [Vianello 2013]



- 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]

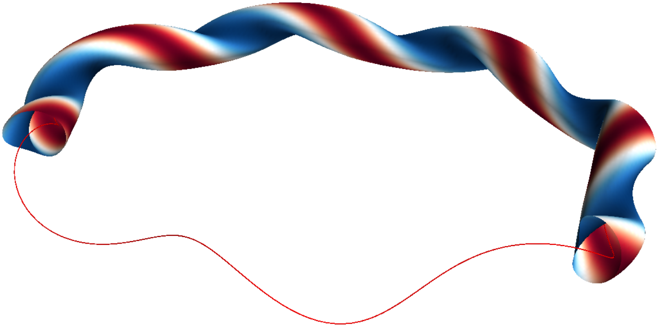
$$u_{m,n} = m\theta - n\zeta + \omega_{m,n} t = -\zeta + \omega_{0,1} t$$

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^r measured with the array of internal sensors (ISIS) [Serianni 2003] mapped onto a helical flux-surface calculated with VMEC/V3FIT

Summary of results on the stochastic edge

- Magnetic islands spontaneously resonating in the RFP are associated with macroscopic fluctuations of the flow (up to ≈ 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 → 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, $E^r_{ind} = -\langle B \rangle \omega r/m \approx -70V/m \ll 10kV/m$ [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 (ψ_p, θ, ζ)
- 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** $R = 1$

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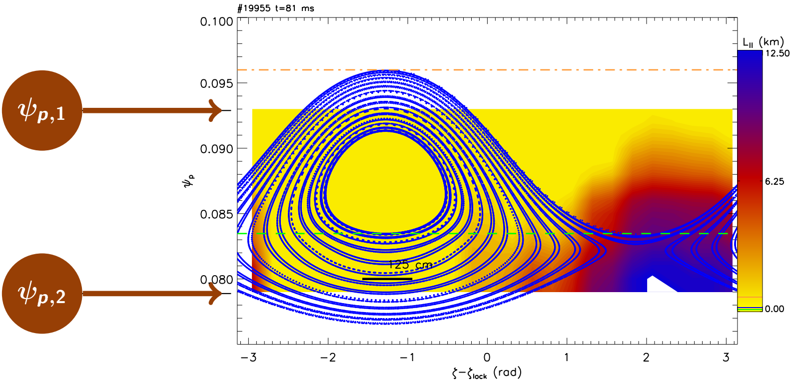
Simulations - Connection lengths (RFX)

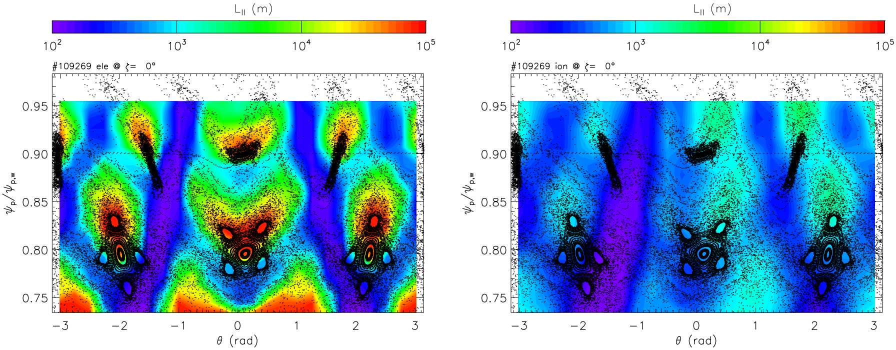
Poincaré with $0/1$ *mode only,* $L_{||}$ *with full spectrum*



$L_{||}(\psi_p, \theta, \zeta) \simeq v_{th}\tau_{trav}$ [Scarin 2011], τ_{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 $L_{||}$ more uniform along θ
- **ions =larger drifts**
- $L_{||}$ has the same symmetry as the RMP helicity (3/1 in this case)

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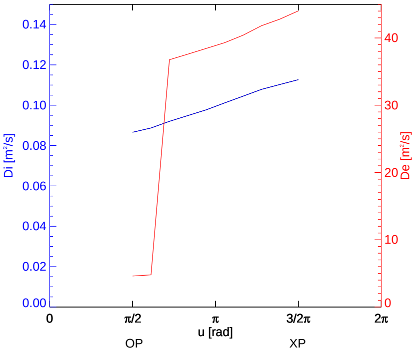
Simulations - D_e, D_i (TEXTOR with RMP)



- **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.
$\rightarrow$ 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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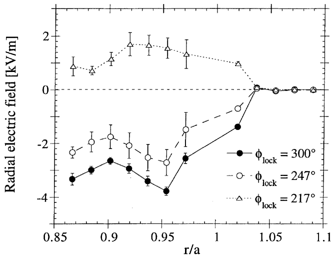
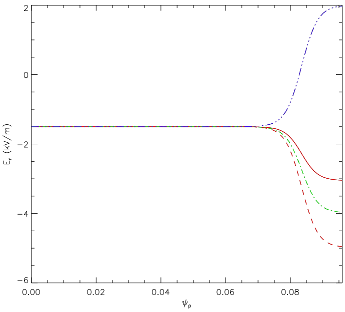
Analytic form of the potential-radius





- Old RFX data: the edge E_r changes sign [Puiatti 2001] along ϕ, coherently with v_ϕ
- start from experiment to define

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

where $\psi_{p,rv}$ is the reversal surface, $\psi_{p,rv} - \sigma_{\psi_p} = 0.077$, ~ 38 cm, $E_a = -1.5$ kV/m, $E_{r,w}$ free parameter

Analytic form of the potential-angle

Angular dependence derived from GPI data (see slide 4):

$$\mathcal{A}(\zeta) = 2e^{-(\zeta-\zeta_0)^2/2\sigma_\zeta^2} - 1 \quad (2)$$

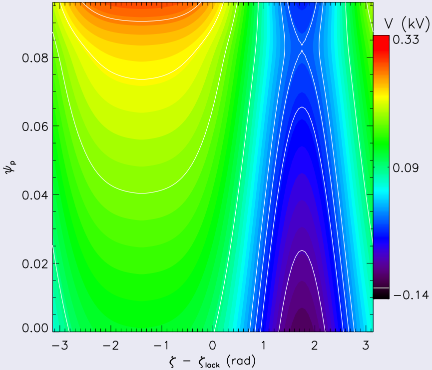
such that

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

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

In the plot, $\zeta_0 \sim 100°$ is only a guess

Potential $\Phi(\psi_p, \zeta)$



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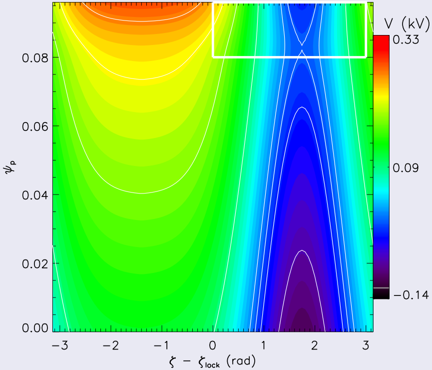


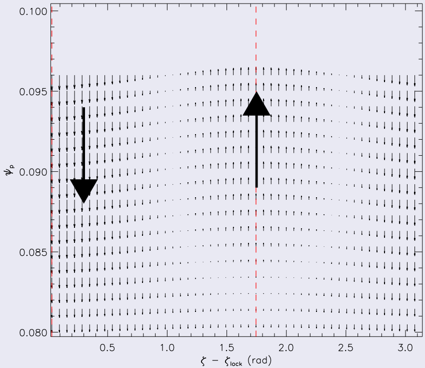
Convective cell in the edge

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 ($\nabla \cdot (n\vec{v}) \neq 0$)

Field E^{ψ_p}, E^{ζ}



Determine the potential amplitude

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

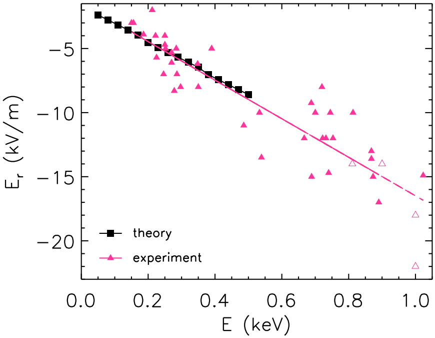
Linear dependence with energy, $E_{r,w} = -T_e/eL_{well}$

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

Experimental evaluation from GPI

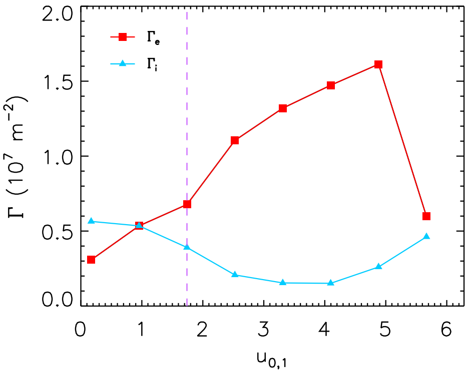
$$E_r = \frac{T_i}{Ze}\frac{\nabla P_i}{P_i} + v_\phi B_\theta \simeq 0.15 E_r + v_\phi B_\theta \quad (4)$$

Field is likely to be ambipolar



Determine the potential phase

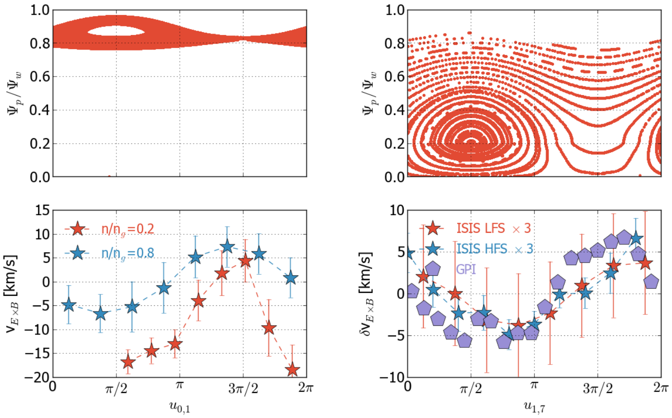
- ✓ Let 6×10^4 particles diffuse between $\psi_{p,1} = 0.093$ (~ 44.6 cm) and $\psi_{p,2} = 0.079$ (~ 39 cm)
- ✓ Each run is performed by varying the free parameter ζ_0
- ✓ look at the fluxes Γ_e and Γ_i at $\psi_{p,2}$ (**each point=one run**)
- ✓ Ambipolarity is reached at $u \simeq \pi/2$, **and not** $u = 3/2\pi$ as measured



Collisional scan

- 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

Collisional scan-experiment



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)

Conclusions and Perspectives

- 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

Conclusions and Perspectives

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- 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.

References I

- M.E.Puiatti, *et al.* 2009 *Phys. Plasmas* **16** 012505
  http://dx.doi.org/10.1063/1.3063060
- H. Stoschus, O. Schmitz, H. Frerichs, *et al.* 2012 *Nucl. Fusion* **52** 083002
  http://stacks.iop.org/0029-5515/52/i=8/a=083002
- Y. Feng *et al.* 2011 *Plasma Phys. Control. Fusion* **53** 024009
  http://stacks.iop.org/0741-3335/53/i=2/a=024009
- R. A. Moyer, *et al.* 2012 *Nucl. Fusion* **52** 123019
  http://dx.doi.org/10.1088/0029-5515/52/12/123019
- N.Vianello *et al.* 2013 *Nucl. Fusion* **53** 073025
  http://dx.doi.org/10.1088/0029-5515/53/7/073025
- D.Terranova *et al.* 2013 *Nucl. Fusion* **53** 113014
  http://dx.doi.org/10.1088/0029-5515/53/11/113014
- G.Serianni *et al.* 2003 *Rev. Sci. Instruments* **74** 1558–1562
  http://dx.doi.org/10.1063/1.1538358

References II

P.Scarin *et al.* 2013 *J. Nucl. Materials* **438** S550–S553
http://dx.doi.org/10.1016/j.jnucmat.2013.01.114

R. B. White and M. S. Chance 1984 *Physics of Fluids* **27** 2455-2467
http://link.aip.org/link/?PFL/27/2455/1

P. Zanca and D. Terranova 2004 *Plasma Phys. Control. Fusion* **46** 1115
http://dx.doi.org/10.1088/0741-3335/46/7/011

Finken K.H. *et al.* 2005 *The Structure of Magnetic Field in the TEXTOR-DED: Schriften des Forschungszentrums Jülich*, Band 45

Allen H. Boozer and Gioietta Kuo-Petravic 1981 *Physics of Fluids* **24** 851–859
http://link.aip.org/link/?PFL/24/851/1

G. Spizzo *et al.* 2012 *Nucl. Fusion* **52** 054015
http://stacks.iop.org/0029-5515/52/i=5/a=054015

P.Scarin, *et al.* 2011 *Nucl. Fusion* **51** 073002
http://stacks.iop.org/0029-5515/51/i=7/a=073002

References III

G.Spizzo and R.B.White 2009 *Plasma Phys. Control. Fusion* **51** 124026
http://dx.doi.org/10.1088/0741-3335/51/12/124026

M.E. Puiatti, *et al.* 2001 *J. Nucl. Materials* **290–293** 696
http://dx.doi.org/10.1016/S0022-3115(00)00529-8

J.Y.Hsu, V.S.Chan, R.W.Harvey, *et al.* 1984 *Phys. Rev. Lett.* **53** 564
http://dx.doi.org/10.1103/PhysRevLett.53.564

R. Lorenzini *et al.* 2009 *Nature Phys.* **5** 570-574
http://www.nature.com/doifinder/10.1038/nphys1308

S. Cappello *et al.* 2011 *Nucl. Fusion* **51** 103012
http://stacks.iop.org/0029-5515/51/i=10/a=103012

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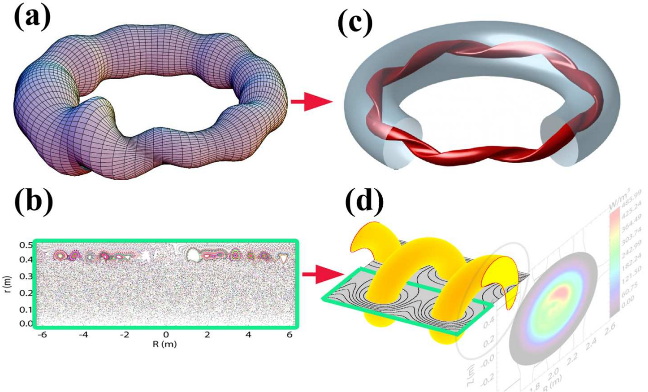
Spare slides

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



Spare slides-II

Motion across on the equipotential surfaces

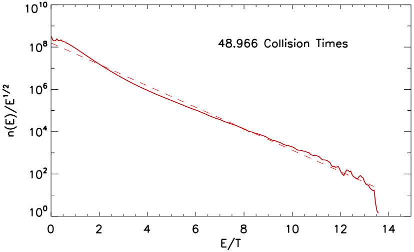
$$\vec{v} \cdot \nabla \Phi = 0 \tag{5}$$

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

$$\begin{aligned} \vec{v} =& \nabla \Phi \times \nabla \theta \\ =& \frac{\partial \Phi}{\partial \psi_p} \nabla \psi_p \times \nabla \theta - \frac{\partial \Phi}{\partial \zeta} \nabla \zeta \times \nabla \theta \end{aligned} \tag{6}$$

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

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+})