The electrostatic response to edge islands induced by Resonant Magnetic Perturbations

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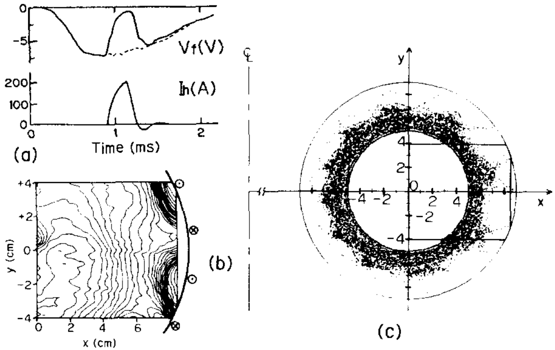
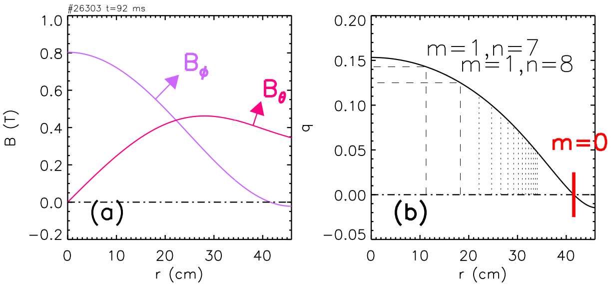
Measurements of convective cells around islands



- Example from [Takamura 1987]: measurements of floating potential V_f during application of RMP (a), poloidal map of V_f (b), and comparison with a Poincaré plot (c);
- In TEXT simple diffusion was not capable of describing density profiles during RMP application: strong convective flux was necessary [Evans 1987].

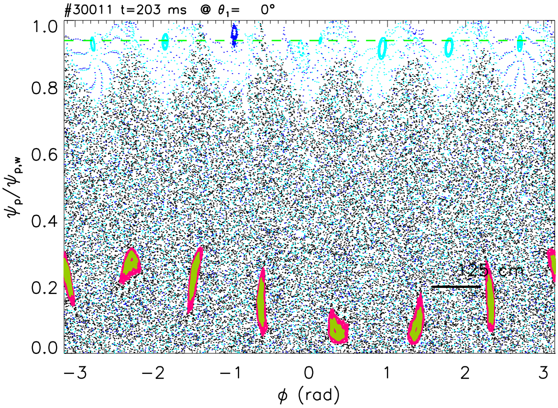
Equilibrium RFX - Padova



(a) **Toroidal** and **Poloidal** $\vec{B}$ field

(b) Field helicity q, with first two resonances, q = 1/7 and q = 1/8, plus chain of islands $q = 0$, all n's

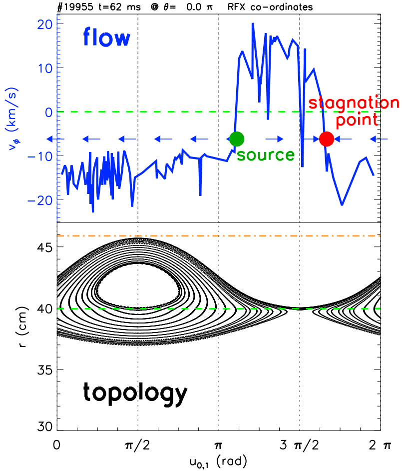
Magnetic topology RFX - Padova



Reversed field pinch $\rightarrow$ stable spectrum of saturated tearing modes (TM)
Conserved islands in the core (dominant $q = 1/7$, "single helicity" [Escande 2000]) and in the edge (dominant $q = 0/1$).
TM amplitudes and phases are known, slowly rotate $\omega \sim 10 \div 50$ Hz

Measurements in the RFP stochastic edge

The edge magnetic topology influences plasma flow [Vianello 2013]



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

- Gas-puff imaging (GPI) toroidal flow @ $r = 0.98a$
- Toroidal flow $E^r \approx v_\phi B$ in the RFP
- The convective cell has the same symmetry as the $m/n = 0/1$ 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]

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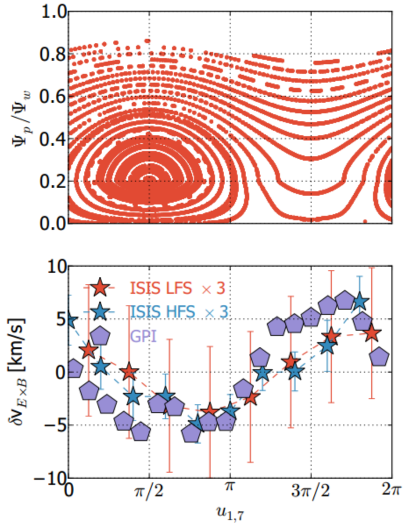
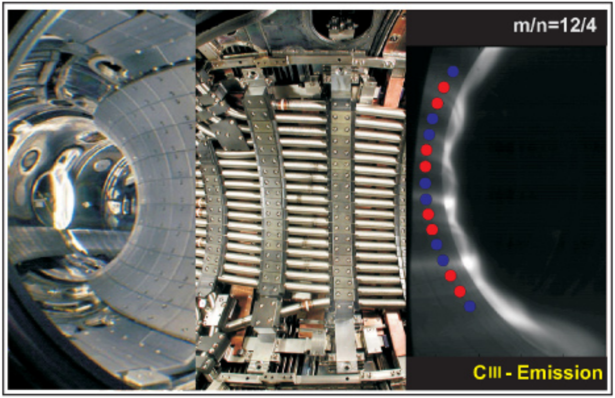


$$u_{1,7} = \theta - 7\zeta + \omega_{1,7} t$$

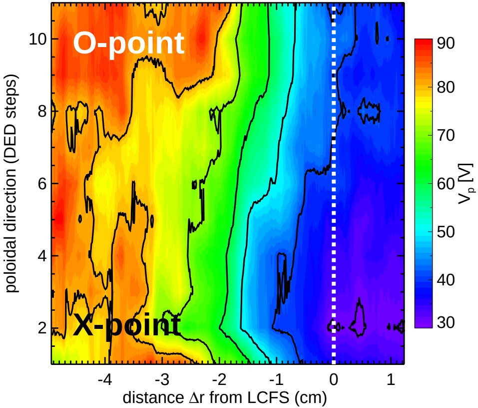
- Gas-puff imaging (GPI) toroidal flow @ $r = 0.98a$
- . . . plus measurements with the internal system ISIS @ $r = a$
- The convective cell has the same symmetry as the $m/n = 1/7$ mode resonating well inside the plasma [Vianello 2013]

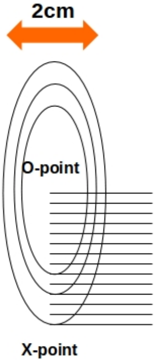
RMP at TEXTOR

TEXTOR was a circular tokamak with limiter in Jülich, Germany (shut down in December 2013). It was capable of producing a stochastic edge via the "Dynamic Ergodic Divertor" (DED), with main resonance at the $q = 3$ surface [Schmitz 2008]



Ripple of E^r in TEXTOR





- Measurements of plasma potential inside a $m/n = 4/1$ island;
- Excess of V_p towards the island O-point (OP) and decrease (potential well) towards the X-point (XP) [Ciaccio 2015]

Summary of results on measurements

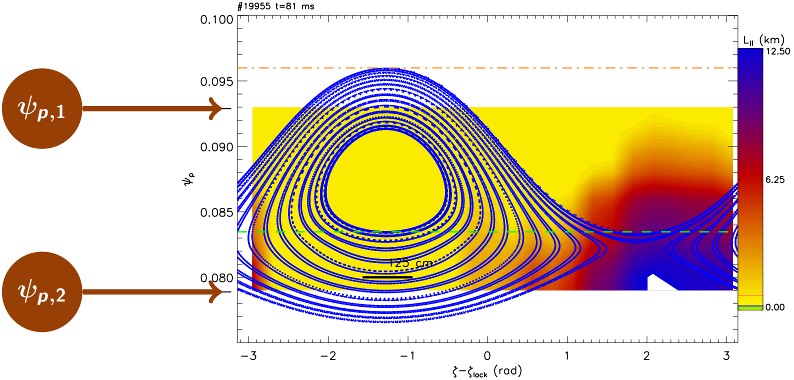
- Magnetic islands spontaneously resonating in the RFX, or induced in the TEXTOR tokamak, are associated with macroscopic fluctuations of the flow (up to ≈ 20 km/s) and related E^r field (order $2 \div 15$ kV/m)
- The symmetry is the same as the generating island (1/7 low density, and 0/1 at high density in the RFX; 4/1 in TEXTOR)
- 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)
- Change in E^r seen also in DIII-D [Mordijck 2014], but poloidal dependence not investigated in detail yet

Test-particle simulations with ORBIT

- 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 for tearing modes (constraint=magnetic fluctuations measured in the experiment)
- TEXTOR: input=analytic form for the radial (resonant) perturbation induced by the DED, based on current levels in the coils [Abdullaev 2014]
- Collisions are implemented as pitch-angle and energy scattering between particles, using the Boozer-Kuo approach [Boozer 1981]

Simulations - Connection lengths (RFX)

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

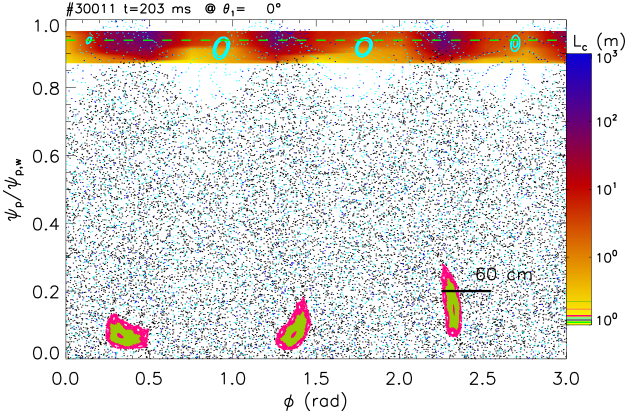


$L_{||}(\psi_p, \theta, \zeta) \simeq v_{th}\tau_{trav}$, τ_{trav} electron travel time between deposit $\psi_{p,1}$ and recovery surface $\psi_{p,2}$.

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 (RFX)

Poincaré and L_c with full spectrum

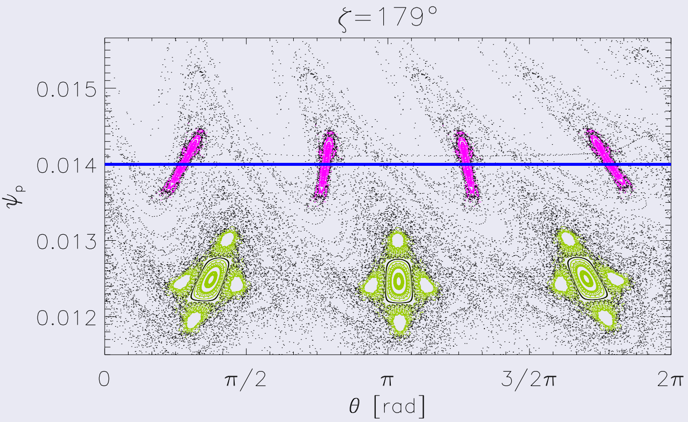


BUT in the case of the 1/7 mode, the electron connection length is shorter at the XP, and longer at the OP

Still open issue: dependence on helicity?

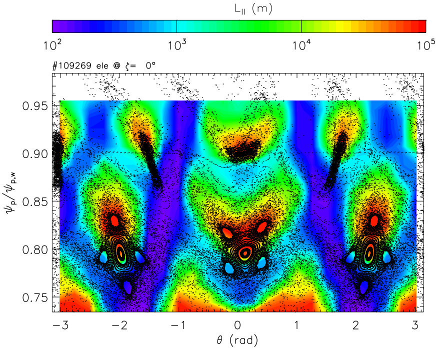
Topology of stochastic edge in TEXTOR

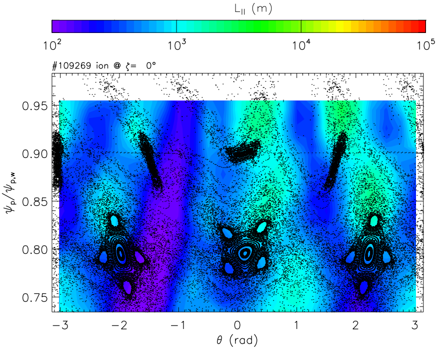
Poincaré plot with RMP



"Base mode" is the 3/1, while the "secondary islands" are 4/1 resonating at $q = 4$ (horizontal line) [Schmitz 2008]

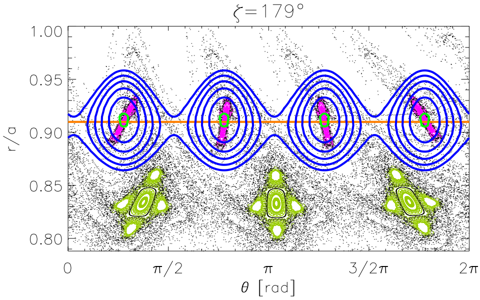
Simulations - Connection lengths - TEXTOR





- LEFT=electrons, RIGHT=ions $\longrightarrow$ ion $L_{||}$ more uniform along θ
- **ions =larger drifts**
- $L_{||}$ has the same symmetry as the RMP helicity (4/1 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

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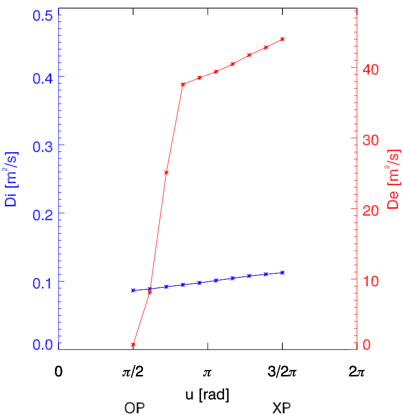

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- D_i almost neoclassical, small change along u; $D_e \gg D_i$ everywhere
- $D_e \gg D_i$ at the XP, $D_e \approx D_i$ at the OP $\rightarrow E^r \sim 0$ at the OP [Ida 2001]

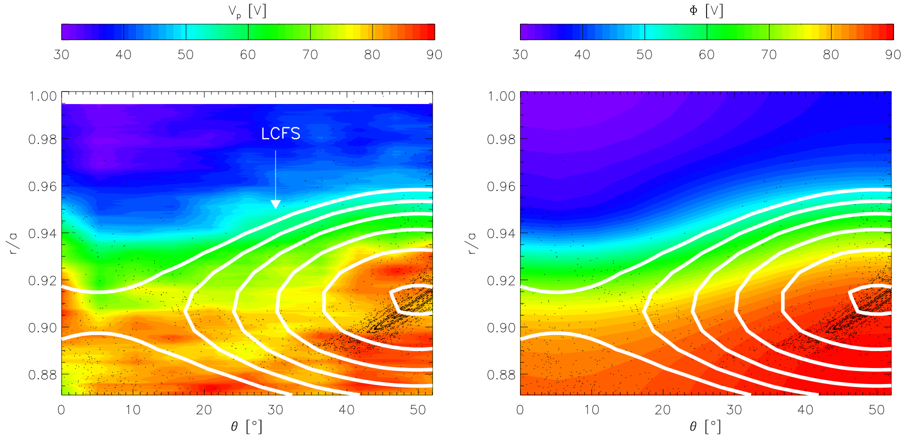
Model of ambipolar potential

- Up to now, electrons and ions are evolved indipendently one to the other
- Require ambipolarity: $\Gamma_e = \Gamma_i$ at some flux surface (e.g., the LCFS)
- Insert a model of potential $\Phi(\psi_p, \theta, \zeta)$ into ORBIT guiding-center equations

$$\Phi(\psi_p, \theta, \zeta) = \Phi_0 \left[f_1(\psi_p) + \frac{1}{2}(f_2(\psi_p) - f_1(\psi_p)) \sin(-m\theta + n\zeta + \tilde{\phi}) \right], \quad (1)$$

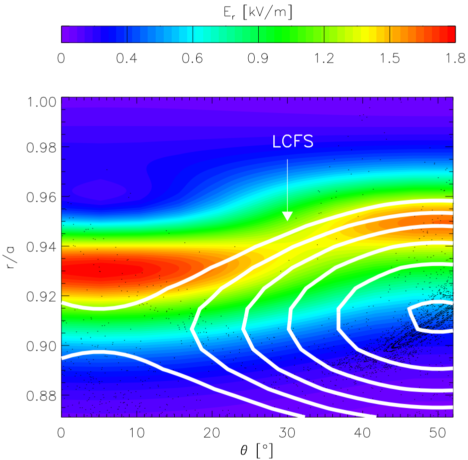
- angular dependence $\rightarrow$ the helical angle
- radial dependence is not simply *const*. $\times\ \psi_p$, but contains the radial functions f_1, f_2 which are deduced from the experiment (it is the only ansatz in the model)
- free parameters = amplitude Φ_0 and phase $\tilde{\phi}$

Map of plasma potential: measurements, model



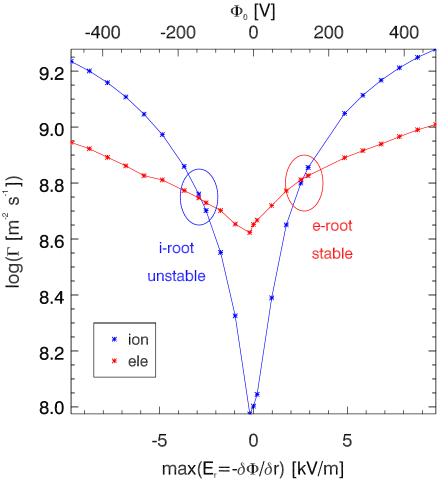
- LEFT=measurements, remapped on helical flux surfaces
- RIGHT= model, phase $\tilde{\phi} = const.$ (fixed RMP)

Radial electric field in TEXTOR



Consequence: strong radial electric field $E^r > 0$ (well known in RMP measurements). As anticipated, $E^r \approx 0$ in the OP, $E^r \gg 0$ in the XP Modulation of E^r along the helical angle u (*convective cell*)

Ambipolar roots w/ RMP



- It is possible to vary the amplitude Φ_0 and check the ambipolar solution $\Gamma_e = \Gamma_i$
- Same tool used in the stellarator community to determine the electron- and ion-roots [Hastings 1985]
- With RMPs, both ion- and electron-dominated transport regimes can exist [Ciaccio 2015]
- With the experimental T_e and T_i the analogous "electron" root is favored

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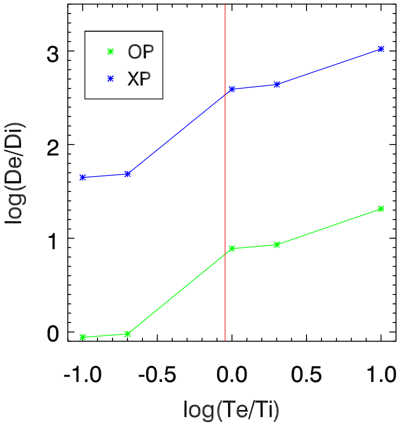

- In stellarators, it is possible to jump from the ion- to the electron-root by using ECRH [Hastings 1985]
- Is it feasible in a tokamak with RMP?
- Sensitivity scan: in the OP the system flips to the ion root ($D_e/D_i < 1$) for $T_e/T_i \lesssim 0.5$

Summary of results - RFX, TEXTOR

fixed p.	RFX 0/1				RFX 1/7		
	L_c	D_e/D_i	E^r	n_e, T_e	L_c	δE^r	n_e, T_e
OP	min	$\gg 1$	< 0	min/max	max	< 0	max
XP	max	≈ 1	> 0	max/min	min	> 0	min

fixed p.	TEXTOR 4/1			
	L_c	D_e/D_i	E^r	n_e, T_e
OP	max	≈ 1	≈ 0	max
XP	min	$\gg 1$	> 0	min

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