Edge topology and flows in the reversed-field pinch

G.Spizzo

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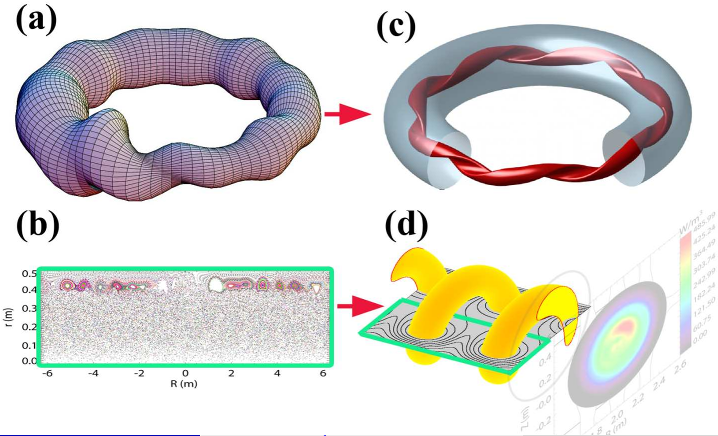
Background

The Reversed-field pinch (RFP) shows a bifurcation from a chaotic regime to *helical equilibrium*, Escande, et al., PRL **85**, 3169 (2000); Lorenzini et al., Nat. Phys. 2009

In the RFP the access to the helical state, and generally speaking, the performance, is influenced by the edge plasma

The RFP is ohmic, circular without divertor → simple boundary



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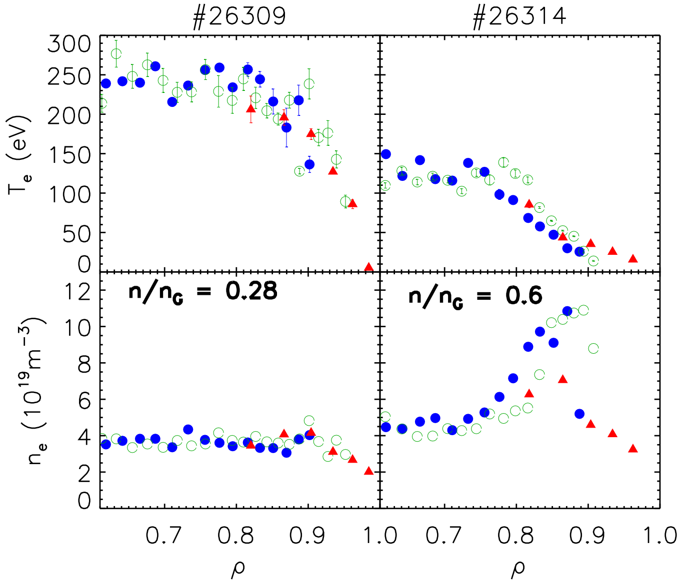
3. In this talk we concentrate on the density limit, which in its extreme situation is a paradigm of edge transport
4. The topology and associated transport is studied with a Hamiltonian guiding-center code (ORBIT)

Density limit: a paradigm for edge transport



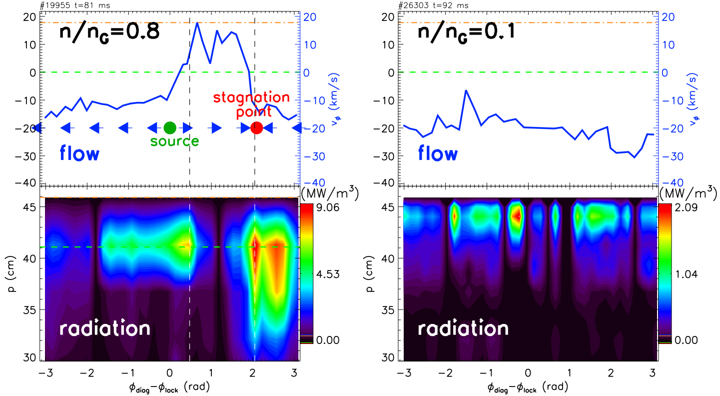
High density and edge: radial profiles

Increasing n/n_G:

1. temperature decreases
2. density increases in the edge

A.Alfier *et al.* PPCF **52**, 035004 (2010)

G.Spizzo *et al.* PPCF **52**, 095011 (2010)



GPI: P. Scarin *et al. Proc. 18th PSI Conference, Toledo, Spain* (2008), J. Nucl. Mater. **390-391** (2009) 444 (4pp).

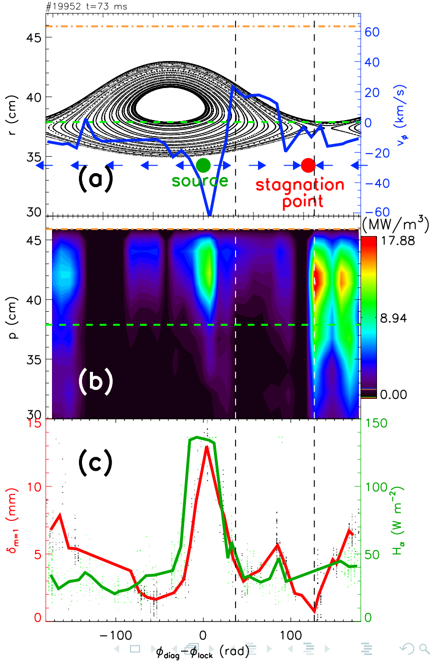
Toroidal patterns

- density accumulation = total radiation and OIV-OVI line emissions are localized toroidally; total radiation is poloidally symmetric ($m = 0$)
- max radiation corresponds to a stagnation point for plasma flow

- ✓ Edge magnetic topology in MH is dominated by $m = 0, n = 1$and $(1, all)$ modes
- ✓ source of particles: plasma-wall interaction of the **O-points of (1,all)**
- ✓ Start with a single (0,1) mode in the Poincaré plot: particle accumulation = **X-point of (0,1)**
- ✓ Accumulation due to the flow reversal

M.E.Puiatti *et al.* NF **49**, 045012 (2009)

M.E.Puiatti *et al.* PoP **16**, 012505 (2009)



Now add all the modes

(a) the X-point of the $m = 0, 1$ island is no more visible

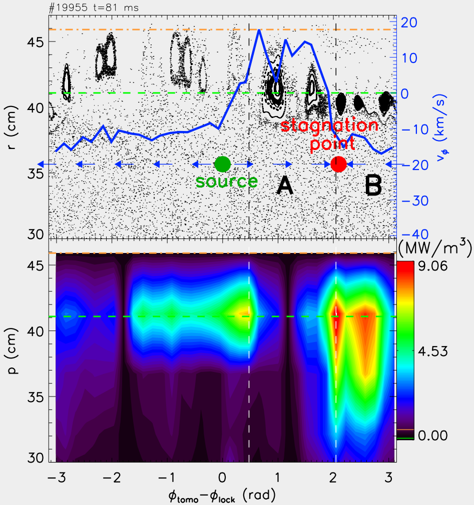
(b) Near the "old" X-point, a chain of small, conserved islands is present (indicated by letter **B**)

$\longrightarrow$ **X points possess structural stability**

Lieberman & Lichtenberg, p.35 (1992)

(c) Analogy with MARFE, provided Tokamak $\hat{\theta} \rightarrow$ RFP $\hat{\phi}$

Toroidal patterns, $n/n_G = 0.8$



Test-particle simulations

- We use the guiding-center code ORBIT [1] to analyze the magnetic field topology and the motion of (monoenergetic) electrons and ions embedded in the magnetic field (no potential)

[1] R. B. White and M. S. Chance, Phys. Fluids **27**, 2455-2467 (October 1984).
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- The standard ORBIT perfectly absorbing wall has been modified to take into account **recycling** $R = 1$ [4]

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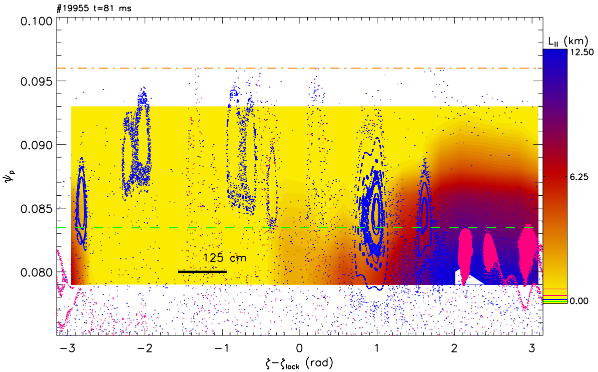
Connection lengths



Parallel electron connection length to the wall can be defined as $L_{\|}(\psi_p,\theta,\zeta) \simeq v_{th}\tau_{trav}$ [P.Scarin, N.Vianello, *et al.*, to appear in NF (2011)]

τ_{trav} electron travel time between the initial $(\psi_{p,0},\theta_0,\zeta_0)$ and final position $(\psi_{p,1},\theta_1,\zeta_1)$.

Initial and final conditions are $(0.093, random, \zeta_0)$ and $(\psi_{p,1}, random, random)$

$L_{\|} \sim$ 12 km near the (0,1) X-point, $\sim$ 50 m near the O-point.

Diffusion plots

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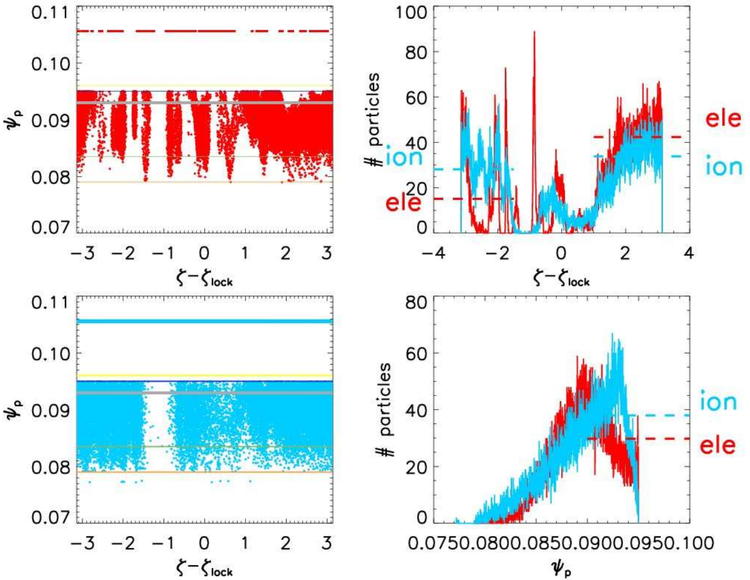
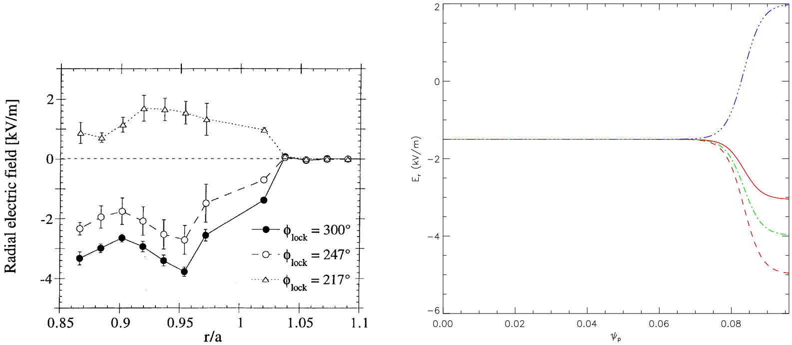
- particles are monoenergetic
- collect particles at $\psi_p = 0.079$ (~ 39 cm)
- analyze distributions as a function of radius, $N(\psi_p)$ and toroidal angle $N(\zeta)$

Particle diffusion, no potential (ORBIT simulations)



The potential needed for ambipolarity



- Old RFX data: the edge E_r changes sign [5] along ϕ, coherently with v_ϕ
- start from experiment to define

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

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

[5] Puiatti et al., J. Nucl. Mater. **290-293**, 696 (2001)

Angular dependence derived from recent data (GPI):

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

such that

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

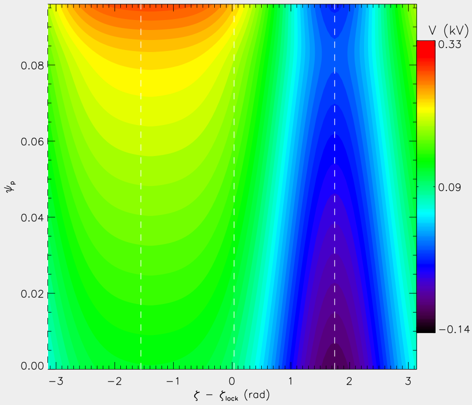
and $E^{\psi_p} = -V'(\psi_p) + E_a$

Moreover, assume $\frac{\partial \Phi}{\partial \theta} = 0$

Toroidal width $\sigma_\zeta \sim 50°$, free parameters are $E_{r,w}$ and ζ_0

Initial guess: potential well near the (0,1) X-point, $\zeta_0 \sim 100°$

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



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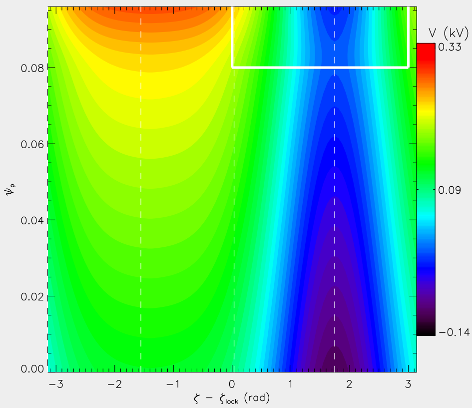


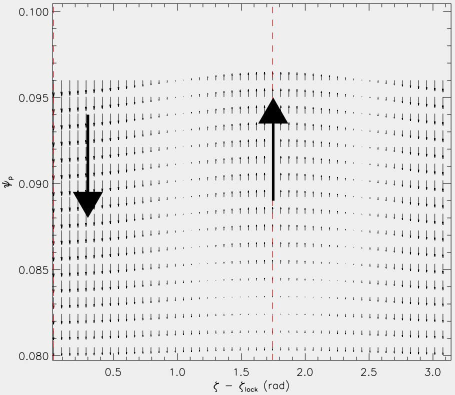
Convective cell in the edge

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

Motion across the potential $v \cdot \nabla \Phi = 0$ (on the equipotential surfaces) conserves kinetic energy

$\rightarrow$ but is likely to be a precursor of the density limit phenomena in RFX-mod

Field E^{ψ_p}, E^{ζ}



Determine the $E_{r,w}$ parameter

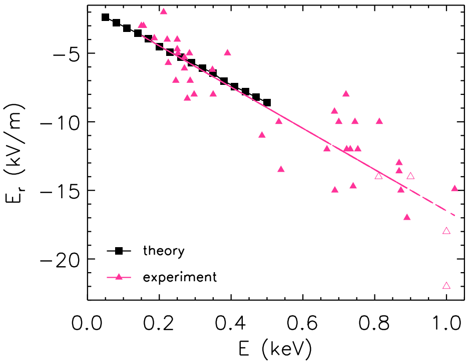
Vary the free parameter $E_{r,w}$ until electrons are trapped (no perturbations)

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

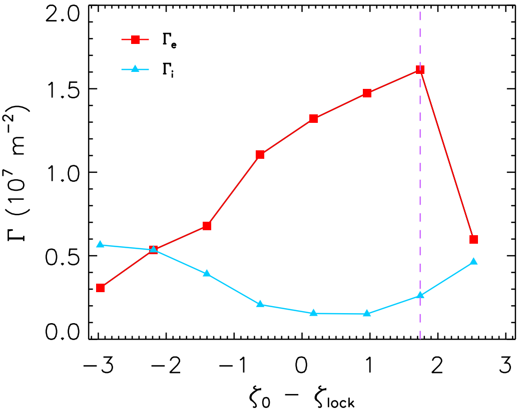
$$E_r = \frac{T_i}{Ze}\,\frac{\nabla P_i}{P_i} + v_\phi B_\theta \simeq 0.15 E_r + v_\phi B_\theta \qquad (4)$$



Field is likely to be ambipolar

Diffusion plots, with potential

- ✓ Repeat exercise of diffusion plots, 6×10^4 particles
- ✓ Each run is performed by varying the free parameter ζ_0
- ✓ look at the fluxes Γ_e and Γ_i at $\psi_p = 0.079$ (**each point=one run**)
- ✓ Ambipolarity is reached at $\zeta_0^a \sim -120°$, shifted toroidally of $\sim \pi$ with respect to the (0,1) X-point



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- Numerical simulations with ORBIT show that a proper analytic form of the potential can balance the different radial diffusion of electrons and ions subject to magnetic field and collisions with a background
- The origin of this phenomenon lies in the fact that electrons accumulate near X-points of $m = 0$ islands resonating at the $q = 0$ surface

Work in progress (modeling)

- so far, collisions do not enter too much in the mechanism governing the density limit $\rightarrow$ pitch angle scattering does not influence too much particle losses, see G.Spizzo *et al.* PPCF **52**, 095011 (2010)

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- similar mechanism at work in the QSH edge with a helical potential? Hints in P.Scarin, N.Vianello, M.Agostini *et al.*, to appear in NF (2011) and P.Piovesan *et al.*, to appear in PPCF (2011)

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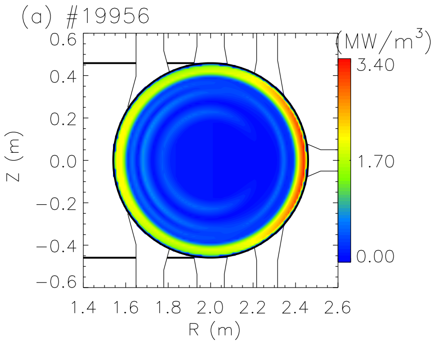
- feedback on $m = 0$ modes

Thank you for your attention!

Spare slides



(a): Radiation at the **O-points of (1,all)**
(b): Radiation at the **X-point of (0,1)** (poloidally symmetric)

M.E.Puiatti *et al.* NF **49**, 045012 (2009)

(a) v_ϕ from GPI

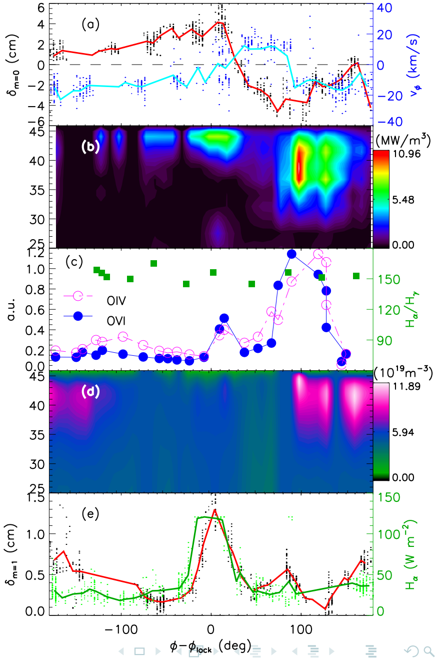
(b) map of total radiation, $\epsilon(r, \phi)$

(c) OIV, OVI impurities H_α/H_γ ratio

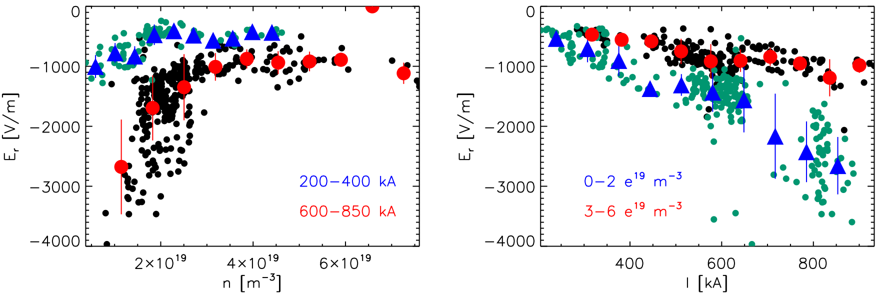
(d) density map $n_e(r, \phi)$ (interferometer)

(e) H_α along ϕ

M.E.Puiatti *et al.* NF **49**, 045012 (2009)



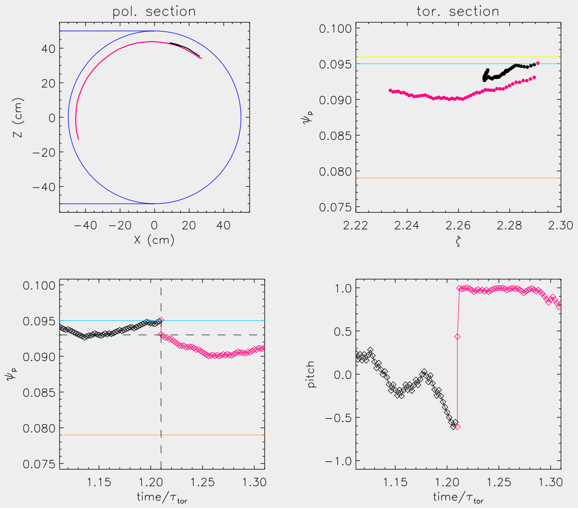
Experimental E_r vs current, density



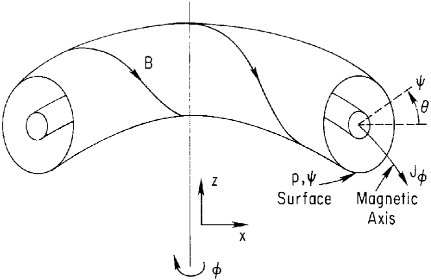
Dependence of the experimental E_r as a function of

- current
- density

Recycling wall



- when particles reach the wall, they are bounced back and reinserted back by a gyroradius
- particle pitch $= v_{\parallel}/v$ is re-initialized randomly.



Covariant B (toroidal flux ψ, poloidal flux ψ_p)

$$\vec{B} = \delta\nabla\psi + I\nabla\theta + g\nabla\zeta \tag{5}$$

Contravariant B

$$\vec{B} = \nabla\psi \times \nabla\theta + \nabla\zeta \times \nabla\psi_p$$
$$\text{with} \quad \frac{\mathrm{d}\psi}{\mathrm{d}\psi_p} = q(\psi_p) \tag{6}$$

Hamiltonian

$$\rho_\parallel = v_\parallel / B$$
$$H = \rho_\parallel^2 B^2/2 + \mu B + \Phi \tag{7}$$

Guiding center equations of motion

$$
\begin{aligned}
\dot{\zeta} &= \frac{\rho_\parallel B^2}{D}(q + \rho_\parallel I') - (\mu + \rho_\parallel^2 B)\frac{I}{D}\frac{\partial B}{\partial \psi_p} - \frac{I}{D}\frac{\partial \Phi}{\partial \psi_p} \\
\dot{\theta} &= \frac{\rho_\parallel B^2}{D}(1 - \rho_\parallel g') + (\mu + \rho_\parallel^2 B)\frac{g}{D}\frac{\partial B}{\partial \psi_p} + \frac{g}{D}\frac{\partial \Phi}{\partial \psi_p} \\
\dot{\psi}_p &= -\frac{g}{D}(\mu + \rho_\parallel^2 B)\frac{\partial B}{\partial \theta} + \frac{I}{D}(\mu + \rho_\parallel^2 B)\frac{\partial B}{\partial \zeta} + \frac{I}{D}\frac{\partial \Phi}{\partial \zeta} - \frac{g}{D}\frac{\partial \Phi}{\partial \theta} \\
\dot{\rho}_\parallel &= -\frac{(1 - \rho_\parallel g')(\mu + \rho_\parallel^2 B)}{D}\frac{\partial B}{\partial \theta} - \frac{(1 - \rho_\parallel g')}{D}\frac{\partial \Phi}{\partial \theta} \\
&\quad - \frac{q + \rho_\parallel I'}{D}\frac{\partial \Phi}{\partial \zeta} - \frac{(q + \rho_\parallel I')(\mu + \rho_\parallel^2 B)}{D}\frac{\partial B}{\partial \zeta}
\end{aligned}
\tag{8}
$$

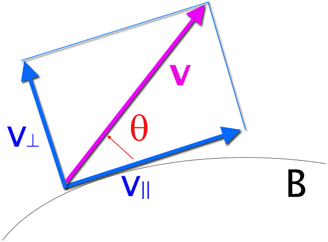
Pitch angle scattering

Coulomb collisions modify the direction of particle velocity: this has to be translated in the frame of reference of the guiding centre, in terms of the particle pitch $\lambda = v_{\|}/v$ and collision frequency ν

$$\lambda(t + \mathrm{d}t) = \lambda \cdot (1 - \nu \mathrm{d}t) \pm \sqrt{(1 - \lambda^2)\, \nu \mathrm{d}t} \tag{9}$$

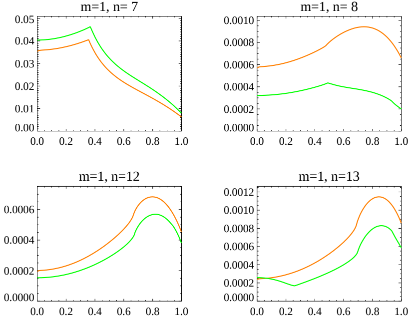
A. H. Boozer and G. Kuo-Petravic, Phys. Fluids **24** (1981) 851

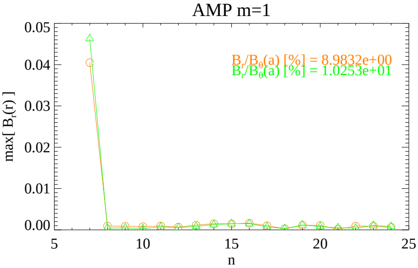
- The collision operator realizes a continuous transition between trapped and untrapped particles.
- The trapping-untrapping threshold depends on equilibrium fields and particle energy.



- The pitch is defined as $\cos\theta = v_{\|}/v$

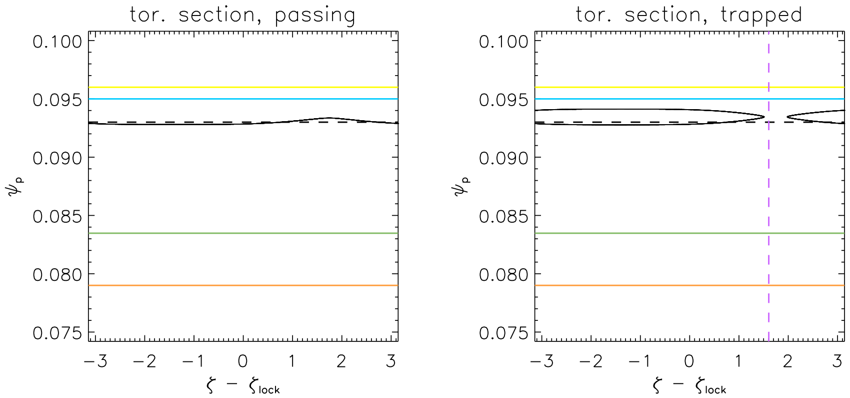
Perturbations



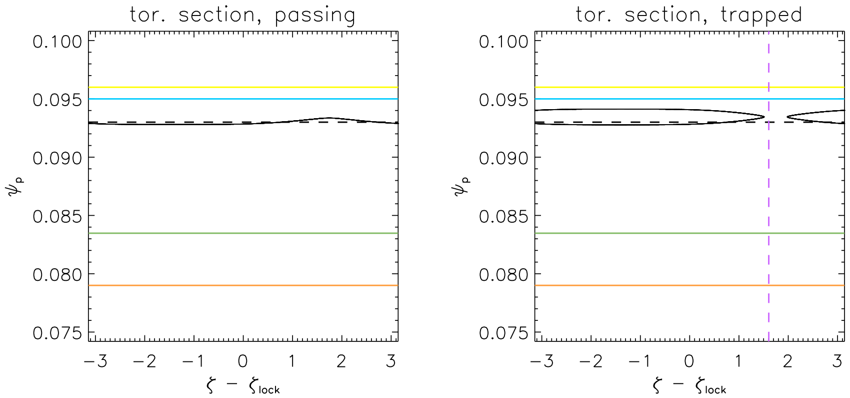


- Perturbations are obtained by solving Newcomb's equations in toroidal geometry [6]
- Input to ORBIT, in order to fulfil the hamiltonian form $H = H_0 + \alpha H_1$ is the scalar function $\alpha(r)$, chosen to satisfy $\delta B_r = (\nabla \times \alpha B)_r$
- Note that the $m = 1$, $n = 7$ eigenfunction decreases radially from the resonance ($r/a \approx 0.35$) to the wall ($r/a = 1$).

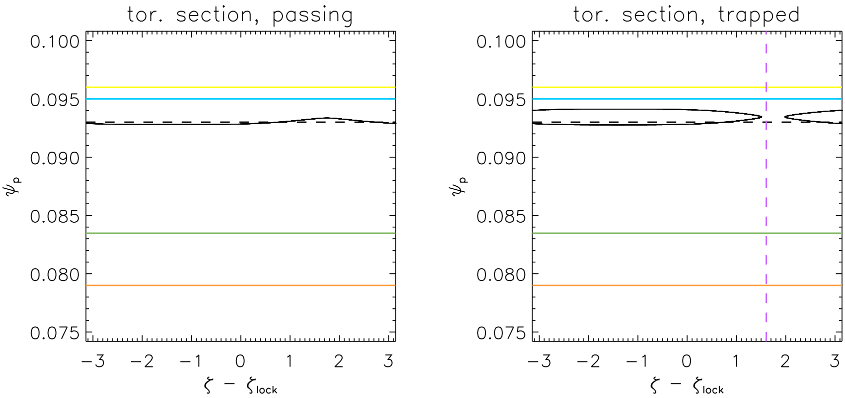
[6] P. Zanca and D. Terranova, Plasma Phys. Controlled Fusion **46**, 1115 (2004).



- Single particle motion (electron) with potential, no perturbations



- Single particle motion (electron) with potential, no perturbations
- Creation of a new whole population of trapped particles, opposing parallel streaming of electrons to/from the edge



- Single particle motion (electron) with potential, no perturbations
- Creation of a new whole population of trapped particles, opposing parallel streaming of electrons to/from the edge
- Necessary condition $\rightarrow T_e \leq e\Phi_{hill}$