LETTER TO THE EDITOR

Helical modulation of the electrostatic potential due to magnetic islands in toroidal plasma confinement devices

G. Ciaccio[1], O. Schmitz[2], S. S. Abdullaev[3], H. Frerichs[2], G. Spizzo[1], and R. B. White[4]

[1] Consorzio RFX (CNR, ENEA, INFN, Università di Padova, Acciaierie Venete SpA), Corso Stati Uniti 4 - 35127 Padova (Italy)

[2] Department of Engineering Physics, University of Wisconsin - Madison, 1500 Engineering Drive, Madison, WI 53706

[3] Institut für Energieforschung-Plasmaphysik, Association EURATOM-FZJ, Jülich, Germany

[4] Plasma Physics Laboratory, Princeton University, P.O.Box 451, Princeton, New Jersey 08543

E-mail: giovanni.ciaccio@igi.cnr.it

Abstract.

The electrostatic response of a tokamak edge plasma to magnetic island with 4/1 poloidal/toroidal mode numbers is analyzed in direct comparison of measurements with the Hamiltonian guiding center code ORBIT. We find a strong correlation between the magnetic field topology in ion and electron velocity space and the poloidal modulation of the plasma potential measured. The ion and electron drifts yield a predominantly electron driven radial diffusion when approaching the island X-point while ion diffusivities are generally an order of magnitude smaller. This results in build up of a strong radial electric field structure pointing outward from the island O-point. An excellent agreement between measured and modeled plasma potential has been found. This shows for the first time in a tokamak edge plasma that a magnetic island can act as convective cell because of the particular drifts of electrons and ions in the 3D magnetic topology. An analytical model for the radial particle diffusion is derived and it is shown that both, an ion and an electron diffusion dominated transport regime can exist which are known as ion and electron root solutions in stellarators. This finding and comparison to reversed field pinches shows that the role of magnetic islands as convective cells and hence as major radial particle transport drivers is generic to 3D plasma boundary layers of toroidal magnetic confinement devices.

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Plasma flows along magnetic field lines under conditions of spontaneous self-organization are a generic question in space and terrestrial plasma physics [1, 2]. In magnetically confined high temperature plasmas explored for future fusion energy production, such directed plasma flows are responsible for transport in the plasma edge. By this, the magnetic field topology in the plasma edge and the resulting transport characterizes the interface of the plasma to the surrounding neutral gas. One form of such self-organized 3D magnetic structures are magnetic islands. They are present in all types of toroidal confinement devices by reconnecting field lines into a 3D magnetic topology which resembles an island structure in the poloidal cut [3]. In reversed field pinches (RFP), they are generated spontaneously on magnetic field lines which close on a rational ratio of poloidal to toroidal turns into themselves. These field lines can be easily perturbed in a resonant way by magnetic field perturbations with the same mode structure as the rational surface of these field lines. In tokamaks, this form of resonant magnetic perturbation (RMP) is used to control plasma edge transport and stability [4, 5]. In stellarators, these islands are inherent in the stationary 3D equilibrium because of the higher resonant mode components of the magnetic field setup. In the edge of all configurations, it has been observed that magnetic islands modulate the plasma pressure profile [8, 7, 6, 9], and influence the sign of the plasma flow, v, and the related radial electric field, E^r [12, 9, 11, 10]. The actual relation of these magnetic structures to plasma confinement and transport is an important question for fusion plasma research in particular as it has been demonstrated that magnetic islands in the plasma edge have a profound impact on plasma performance and plasma stability. At the RFP RFX-mod, for instance, a direct connection between a convective cell pattern and the empirical density limit (Greenwald limit) has been established [13, 14]. Island formation with impact on the particle confinement is also discussed as a key mechanism for stabilization of high confinement edge plasmas in tokamaks [15]. Finally, low-order rational surfaces in the periphery of stellarators make them prone to island formation which in some devices is used deliberately as exhaust layer between plasma core and the material wall elements around the plasma [16].

The role of E^r for the Greenwald density limit [13] was explored at RFX-mod with the ansatz that E^r was arising from the electrostatic ambipolar potential imposed by a differential radial diffusion of electrons and ions in a chaotic magnetic topology. Since particle drift extent depends on Larmor radius, electrons stream along the field lines, while ions have larger mass and, hence, larger shift of the drift orbit from the flux surface. This results in an ambipolar field, with the same symmetry as the main magnetic island, to balance the drifts and ensure quasi-neutrality. On the basis of transport particle simulations performed through the guiding center (GC) Hamiltonian code ORBIT [17], a model of electrostatic potential was built up for the island resonating with poloidal/toroidal mode number $m/n = 0/1$ at the edge of RFX-mod [14], which reproduces the main features of E^r, such as amplitude and geometry along the toroidal angle φ.

In this Letter a comparative analysis is conducted for the first time for a tokamak with RMP fields applied. We study a circular shaped, high field side limited plasma at the TEXTOR tokamak [18], where a stochastic layer can be generated at the edge, by inducing RMPs through the Dynamic Ergodic Divertor (DED) [19]. The particle transport properties of the magnetic topology in the DED configuration $m/n = 12/4$ were analyzed using Poincaré plots and by calculating the parallel connection length, $L_\parallel$, for ions and electrons. The resulting $L_\parallel$ map showed a radial and poloidal modulation, being footprints of the magnetic topology [20]. Results with ORBIT are consistent with maps of connection length made with GOURDON [21]. In this letter, we present for the first time evidence that a magnetic island in the plasma edge of a tokamak can generate enhanced radial particle transport by acting as a convective cell in the plasma potential causing strong $E \times B$ flow and hence a radially outward directed net transport.

For this experiment the mode number resonant field $m/n = 3/1$ was used. The numerical interpretation was conducted using test particle transport simulations by means of the code ORBIT. We calculate the particle diffusion coefficients for electrons, D_e, and ions, D_i, and develop a model for the ambipolar potential, which describes the two-fluid, plasma response to the RMP. The modeled potential reproduces quite well measurements of plasma potential, performed with a Langmuir sweeping probe, inside of a $m/n = 4/1$ island which is formed close to the plasma edge. The results show that the development of an electrostatic potential is a general feature of magnetic islands resonating at the plasma edge: moreover, two possible ambipolar solutions are present, which resemble the "ion" and "electron-roots" typical of the E^r in stellarators [22]. A consequence is that modifying the T_e/T_i ratio can let the system flip from one solution to the other.

We consider a TEXTOR discharge with static RMP, in the $m/n = 3/1$ operational mode. In Fig. 1 we show the Poincaré plot of the magnetic field lines, superimposed to the helical 4/1 flux surfaces, $\psi_h^{(4,1)}$ [23], used for the computation domain and displayed as blue curves. We can recognize the characteristic magnetic topology of TEXTOR at the edge [21]: in the inner region the last main island chain composed by three conserved structures (green points), in the middle four *remnant islands* (purple points) and in the outermost region the *laminar flux tubes* embedded into the *ergodic fingers*. In order to evaluate the particle diffusion coefficients, D, we proceed as in

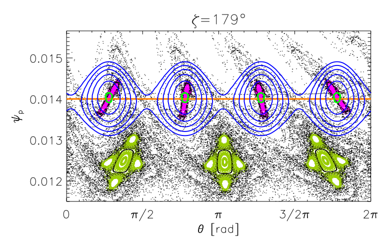

Figure 1: Poincaré plot of magnetic field lines, superimposed to the helical 4/1 flux surfaces, $\psi_h^{(4,1)}$ (blue curves). The x-axis is the poloidal angle while the y-axis is the poloidal flux.

Ref. [24]. We define a proper domain, Δ, centered at the $q = 4$ resonance, ($r \approx 36\ cm$), and bounded by the helical flux surface, ψ_h, highlighted in orange and light green in Fig. 1, respectively. ψ_h is chosen to fit as well as possible the borders of the 4/1 island since our interest is to evaluate the local radial transport in its fixed points, O and X (OP and XP in the remainder of the Letter). We deposit test particles, randomly distributed (poloidally and toroidally), at the center of Δ, and let them diffuse with temperature $T_e = 90$ eV and $T_i = 100$ eV under the action of magnetic chaos and thermal collisions with a background at density $n_e = 8.7 \times 10^{12}$ cm $^{-3}$, until they reach the border of Δ. Then, particles are redeposited at the center. By letting each particle perform at least ~ 30 cycles in and out Δ, we obtain steady-state local density distributions, with a measured flow of particles across ψ_h: the ratio between flux and density gradients gives the local transport rate [24]. The area of the domain is an *Archimedes' serpentine*, namely, a cyclic helical surface generated by the helical motion of a circle, whose area is $\mathcal{A} = 4\pi^2 b\sqrt{r_s^2 + R^2 q^2}$. In the formula, b is the radius of the circle normal to the helix, r_s is the resonance radius, and R the major radius.

The domain can be shifted from the OP towards the XP by varying the phase, ϕ, of $\psi_h^{(4,1)}$, i.e. $\phi = 0$ for the OP and $\phi = \pi$ for the XP. By performing a series of steps in ϕ, we evaluate the diffusion coefficients along a helical path from the OP to the XP, being $u_{4,1} = 4\theta - \zeta + \phi$ the helical angle [9], with θ and ζ the general poloidal and toroidal angle, respectively ($\zeta = \varphi - \nu(\psi_p, \theta)$, with ν required to fulfill the straight-field line condition in Boozer coordinates [25]). The result is shown in Fig. 2. D_i is rather constant along the path ($\approx 0.1\ m^2/s$), while D_e is larger, with typical values in a stochastic field [24] ($0.6 \div 40\ m^2/s$). More important, D_e is strongly modulated along u (larger at the XP, lower at the OP), consistently with the $L_\parallel$ simulations in Refs. [14, 20], and the well-known experimentally result that the laminar flux tubes (XP of the 4/1 island) are pathways of enhanced electron diffusion [21]. Finally, it is worth noting that, in a small domain right into the OP, $D_e \approx D_i$, which would bring a *vanishing radial electric field*, $E^r \approx 0$. Actually, this result is consistent with the findings in the LHD heliotron, where measurements of poloidal flow v_θ inside the 1/1 island show a plateau of $v_\theta \approx 0$ just right into the OP, which corresponds to $E^r \approx 0$ [26].

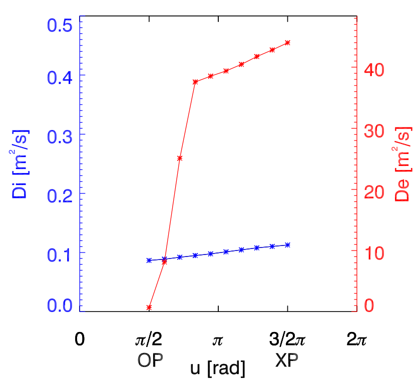

Figure 2: D_i and D_e values along the helical flux in between the OP and XP. On the x-axis the helical angle $u = m\theta - n\zeta + \phi$.

Measurements of plasma potential have been done in the region of the 4/1 island by means of a fast insertable probe located at the low field side of the TEXTOR device [27]. The island is generated as a bifurcation with island opening at a given threshold DED current (1.8 kA for this configuration). Then the island, once generated, is moved poloidally by changing the phase of the DED current from shot to shot and in each shot one radial plunge of the fast reciprocating probe is taken. Fig. 3 shows a colored map of the measured plasma potential V_p in the (r,θ) plane, together with the helical flux surfaces $\psi_h^{(4,1)}$ and the magnetic field Poincaré map are overplotted to V_p. A very clear correlation of the V_p shape with the magnetic topology is found. In particular, the correlation is very strong in the region outside of the separatrix, while inside V_p does not follow exactly the flux surfaces. On the basis

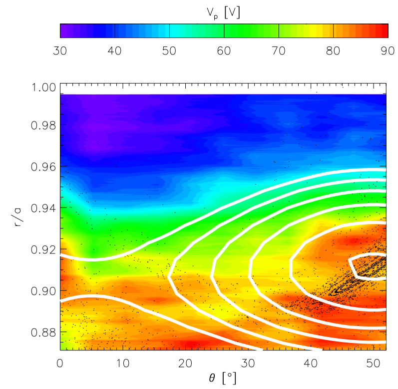

Figure 3: Map of the measured plasma potential V_p as a function of the poloidal angle θ and the normalized radius r. The helical flux surfaces $\psi_h^{(4,1)}$ (white contours) and the magnetic field Poincaré plot (points) are overplotted.

of the simulations of D and the measured V_p map, we find good reason to assume that the ambipolar potential Φ should possess the same geometry as the 4/1 island, similarly to the 0/1 and 1/7 island cases in RFX-mod [14, 9].

We now want to understand the link between the high electron diffusivity and the electric field structure. Therefore, we need to find a proper analytic form for Φ. To do that, we need to mix an experimental radial profile and simulation observations along θ, as previously done on RFX-mod [14]. In this way,

$$\Phi(\psi_p, \theta, \zeta) = \Phi_0 \Bigg(f_1 + \frac{1}{2}(f_2 - f_1) \\ \sin(-m\theta + n\zeta + \tilde{\phi}) \Bigg) , \tag{1}$$

where

$$f_i(\psi_p) = V_{p,i}^{min} + \frac{1}{2}(V_{p,i}^{max} - V_{p,i}^{min}) \\ \left(1 - \tanh\left(\frac{\psi_p - \psi_{p,i}}{\Delta\psi_{p,i}}\right)\right) , \tag{2}$$

with $i = (1, 2)$. f_1 and f_2 are the curves fitting the radial profile of V_p (normalized to $\langle V_p \rangle \approx 85\ V$ in the OP) at the poloidal positions of the XP ($V_{p,1}^{min} = 0.35$, $V_{p,1}^{max} = 0.94$, $\psi_{p,1} = 0.0145$, $\Delta\psi_{p,1} = 0.0005$) and the OP ($V_{p,2}^{min} = 0.41$, $V_{p,2}^{max} = 1.00$, $\psi_{p,2} = 0.0148$, $\Delta\psi_{p,2} = 0.0003$), respectively. By setting $\Phi_0 = 90\ V$ (the maximum amplitude in the measurements) and $\tilde{\phi} = \phi$, i.e. the same phase of $\psi_h^{(4,1)}$, we obtain a model Φ, identical to the measured plasma potential. This is not surprising, considering the radial modulation of Φ which coincides by construction with measurements; but the fact that the poloidal dependence follows the geometry of the island is a striking new result in the tokamak. This behavior was already found instead in the reversed-field pinch RFX-mod [9], and in gyrokinetic simulations in Stellarators [28]. In Fig. 4, we map the $E^r = \partial\Phi/\partial r$ amplitude together with the flux surfaces $\psi_h^{(4,1)}$ and magnetic field Poincaré plot, noting that E^r is modulated *both in the radial and in the poloidal directions.* In particular, a region of large positive E^r,

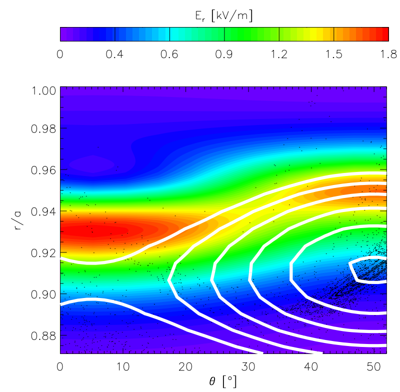

Figure 4: Map of the modeled E^r in the (θ, r) plane.

along the separatrix, can be noticed. This is a confirmation of the well known presence of a positive E^r in the stochastic edge [29, 30, 31]. But, if we focus on this region, we can note also a modulation in the poloidal angle, strictly linked to the magnetic topology, too: E^r has a minimum in between the XP and the OP, and an absolute maximum in correspondence of the XP. On the contrary, right into the OP, E^r almost vanishes, which is consistent with LHD results [26]. Therefore, the potential well is located near the XP, where the electrons are preferably lost, as shown in Fig. 2 and in Ref. [20]. This rather complicated behavior of E^r should be accounted for when analyzing data in presence of RMPs [11, 32], since E^r varies both over r and θ.

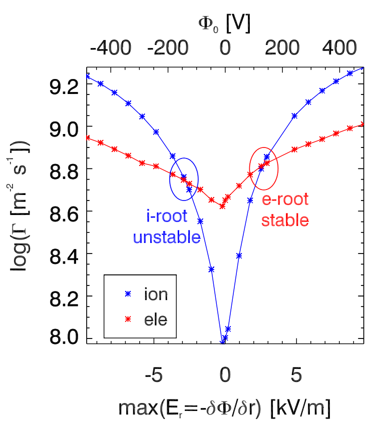

Figure 5: Ion (blue) and electron (red) fluxes as a function of Φ_0 and the maximum E^r.

As a final test, we check the ambipolarity of Φ by keeping $\tilde{\phi} = \phi$ (potential hill at the OP) and evaluating the electron and ion fluxes as a function of Φ_0: this is the algebraic way of determining the ambipolar solution, used in the stellarator community [22]. To do this, we adapted ORBIT guiding center equations [17] to correctly express electron drifts. We evaluate fluxes at ψ_h, with source at $q = 4$. In Fig. 5 we plot the ion and electron fluxes as a function of Φ_0 and the maximum E^r. The two curves show two roots, similarly to stellarators [22]: an unstable ion-root (at $\sim -150\ V$, $E^r < 0$) and a stable electron-root (at $\sim 120\ V$, $E^r > 0$), where the latter is found at $\sim 120\ V$ consistently with the experimental findings (see Fig. 3). This shows that two solutions are possible: one with the potential well (=maximum E^r) at the XP of the RMP (stable "electron root", which is the solution found in experiment), and the other with the potential well at the OP (unstable, "ion root"). With the $T_e/T_i \sim 0.9$ ratio of TEXTOR, the electron root is favored, but in principle it is possible, by acting on the T_e/T_i ratio, to make the system flip to the ion root: the opposite is seen experimentally in stellarators, where the electron root can be induced actively by electron cyclotron resonance heating (ECRH) [22]. Indeed, experimental results in the ASDEX-U and FTU tokamaks show that disruptions can be mitigated by ECRH targeted on the 2/1 island [33]. We speculate that ECRH can modify the E^r distribution in the edge, and in this way the overall magnetohydrodynamics stability at the edge. In principle, this can be also a way of overcoming the density limit, which critically depends on the E^r pattern, at least in the RFP [13]. Finally, it should be worth doing experiments of ECRH in conjunction with RMP, to assess the role of E^r on plasma stability with respect to the so-called edge localized modes [15].

In summary, we analyzed the local radial particle transport along a helical path from the OP through the XP of an $m/n = 4/1$ remnant island, created near the edge of TEXTOR. Electron diffusion is strongly modulated (larger at the XP, lower at the OP), which requires a large electrostatic potential to ensure quasi-neutrality. We developed a 3D model for the ambipolar potential on the basis of the geometry of the remnant island: the resulting E^r shows a large positive value near the separatrix, confirming a well known result in the RMP tokamak community. The mechanism of ambipolarity shows two possible solutions ("roots"), which suggests a way of acting on the edge E^r through additional heating.

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