Internal and edge electron transport barriers in the RFX-mod Reversed Field Pinch

M. E. Puiatti 1), M. Valisa 1), A. Alfier 1), M. Agostini 1), L. Apolloni 1), F. Auriemma 1), M. Baruzzo 1), T. Bolzonella 1), D. Bonfiglio 1), F. Bonomo 1), A. Canton 1), S. Cappello 1), L. Carraro 1), R. Cavazzana 1), S. Dal Bello 1), G. De Masi 1), D.F. Escande 2), A. Fassina 1), P. Franz 1), E. Gazza 1), M. Gobbin 1), S. Guo 1), P. Innocente 1), R. Lorenzini 1), G. Marchiori 1), L. Marrelli 1), P. Martin 1), E. Martines 1), S. Martini 1), S. Menmuir 1), B. Momo 1), L. Novello 1), R. Paccagnella 1), P. Piovesan 1), L. Piron 1), I. Predebon 1), A. Ruzzon 1), F. Sattin 1), A. Scaggion 1), P. Scarin 1), A. Soppelsa 1), G. Spizzo 1), S. Spagnolo 1), M. Spolaore 1), D. Terranova 1), M. Veranda 1), N. Vianello 1), P. Zanca 1), B. Zaniol 1), L. Zanotto 1), M. Zuin 1)

1) Consorzio RFX, Associazione Euratom-ENEA sulla fusione, 35127 Padova – Italy
2) Laboratoire PIIM, UMR 6633 CNRS-Aix Marseille Université, France

E-mail contact of main author: puiatti@igi.cnr.it

Abstract. An interesting result of the self-organization processes in RFX-mod high current discharges is the development of strong electron transport barriers. An internal heat and particle transport barrier is formed when a bifurcation process changes the magnetic configuration into a helical equilibrium (SH) and chaos reduction follows, together with the formation of a null in the q shear. Turbulence analysis shows that the large electron temperature gradients are likely limited by the onset of micro-tearing modes. A new type of electron transport barrier with strong temperature gradients develops more externally (r/a=0.8), independently on the presence of the helical equilibrium, accompanied by a 30% improvement of the global confinement time. Both types of barriers occur in high current low collisionality regimes. Analogies with Tokamak and Stellarators are discussed.

1. Introduction

Transport barriers are of crucial importance in the plasma studies towards the achievement of magnetically confined thermonuclear controlled power. They manifest as a significant reduction of the thermal and or particle diffusivity and have been experimentally found in all the major magnetic configurations, Tokamak, Stellarator and Reversed Field Pinch (RFP). On the other hand the formation of a thermal barrier is a bifurcation process, which is typical of all complex driven dissipative systems [1]. In Tokamaks the internal transport barriers have the additional appeal of providing a significant bootstrap current, which is an important ingredient for the achievement of steady state operations.

In the RFX-mod reversed field pinch, subject to ohmic electron heating only, two types of transport barriers have been documented on the electron channel. Internal electron transport barriers (eITB) spontaneously develop in the plasma core in conjunction with the formation of a new helical equilibrium, the single helicity; such regime is the result of a bifurcation process in which from a sea of many magnetic modes one single saturated tearing mode grows at the expense of the other ones and conforms to its own geometry the equilibrium of the entire configuration [2, 3, 4, 5, 6]. The internal transport barrier corresponds to a minimum of the thermal conductivity but represents also a region of reduced particle transport affecting both main gas and impurities. The favorable situation therefore is reached in which besides the presence of a thermal barrier, the electron density in the core may be refurbished via pellet injection while impurities remain confined in the external region.

In addition to this, though less frequently, a thermal electron barrier with large electron temperature gradients is observed more externally (r/a~0.8, where a=45.7 cm is the minor radius) inside the region where the safety factor q and the toroidal field change sign.
The latter barrier forms independently on the presence of a Single Helicity. The interest in it is that it extends the region of good confinement to a larger volume of the plasma. The simultaneous coexistence of the two barriers, internal and external respectively, has been found only in a few occasions but represents an appealing objective of the current research. This adds to the other important topic of the connection between barriers and density, as both types of barriers occur only at high current and at relatively low densities, whereby higher confinement is expected to be obtained with barriers developing at higher density.
In the following the transport barriers found in RFX-mod are described in detail and the similarities and differences with respect to corresponding processes in Tokamak and Stellarators are discussed.

2. Internal Barriers

2.1. Internal transport barriers and magnetic topology

In RFX-mod, characterized by the presence of several m=1 tearing modes internally resonant, when the ratio between the dominant and the secondary mode

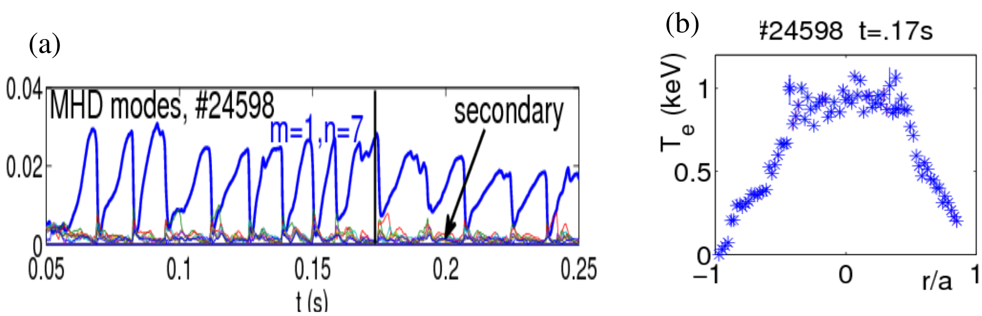

Fig. 1: (a) time evolution of m=1 MHD mode amplitude. (b) Electron temperature profile from Thomson scattering at the time marked by a vertical black line in (a)

amplitude exceeds a threshold (≈ 4%), the magnetic configuration develops an helical equilibrium, with one single magnetic axis corresponding to the axis of the dominant mode (SHAx, Single Helical Axis regime) [7]. The achievement of such regime is a necessary condition for the plasma to develop electron internal transport barriers with large temperature

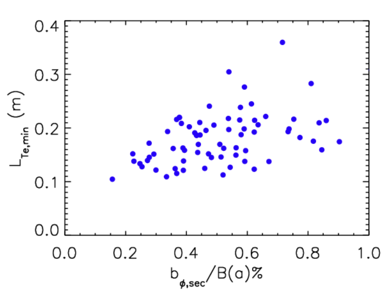

Fig.2: Electron temperature characteristic length at the barrier vs secondary MHD mode amplitude

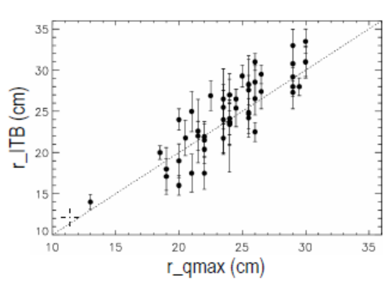

Fig. 3: Radial location of the ITB foot vs. the q shear null point

gradients. An example is given in fig. 1, showing the time trace of the MHD mode amplitude (fig. 1a) and a Te profile featuring a transport barrier obtained by the Thomson scattering diagnostic (1b).

The relationship between ITBs and the amplitude of the dominant mode is reinforced by the observation that the electron temperature gradient length scales inversely with the total amplitude of the secondary m=1 modes, as shown in fig.2, that is with the degree of field stochasticity produced by the overlapping of the secondary modes. Data in fig.2 show a lower limit for L_{Te}, around 0.1m, suggesting that above a threshold the temperature gradient increase may be prevented by other transport mechanisms adding to the residual magnetic chaos. This will be discussed in the next section.

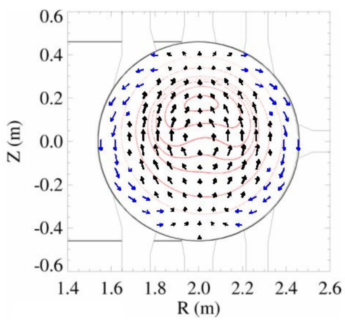

Fig. 4: Reconstruction of the poloidal flow pattern from passive spectroscopy

ITBs are always associated to a point of null shear in the q profile [8], well correlated with the barrier foot (fig. 3), which in the case of the RFP is a maximum of q. Simulations by the 3-D MHD code Specyl show that such point of null q shear is intrinsically associated to the helical topology of the new equilibrium and, in addition, the generation of the dynamo field necessary to sustain the configuration is accompanied by a flow field characterized by a strong shear in the poloidal component. The poloidal flow pattern has been experimentally reconstructed by means of passive spectroscopic flow measurements coupled to an impurity transport code estimating the ion impurity localization (fig. 4). A significant shear of the poloidal flow had been already documented in the outermost 4-5 cm of plasma at the edge [9]. The spectroscopic reconstruction in fig. 4 does indeed show an inversion of the flow internal to the field reversal surface, though the space resolution of such measurements is not sufficient to precisely localize the region with the strongest gradient with respect to the position of the q shear null [10].

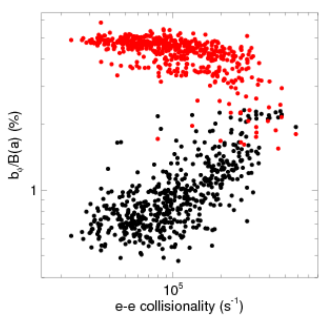

Fig:5: Dominant and secondary MHD mode amplitude as a function of collisionality

In RFX-mod ITBs develop at low values of the electron collisionality, corresponding to $n/n_G \leq 0.3$, where n_G is the Greenwald density. This is a consequence of the fact that experimentally the magnetic bifurcation process leading to the SHAx regime occurs at low collisionality. Fig. 5 shows the amplitude of the MHD modes as a function of the collisionality: the lower the collisionality the higher the ratio between dominant and secondary modes, where SHAx develop.

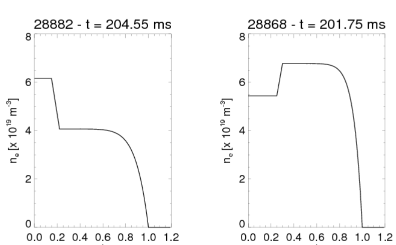

Fig.6: Inverted density profiles with pellet ablation occurring inside (left) or outside (right) the barrier

2.2. Transport in presence of internal transport barriers

Attempts have been made to fuel the plasma core inside the barrier and try to obtain ITBs at higher densities to further improve confinement. Hydrogen pellets have been injected to provide a particle source inside the helical structure [11]. The exercise is not straightforward as when they hit the already developed large temperature gradients, pellets are mostly ablated externally to the barrier and do not cross it. Only if pellets reach the plasma core just before the onset of the barrier then particles are significantly ablated in the centre and then confined inside the hot internal helical structure. Fig. 6 shows two density profiles obtained by the inversion of interferometer data: on the left is the case where particles are ablated in the centre, thus peaking the density, and on the right is the case when the pellet is ablated outside the barrier and the density profile remains hollow.

A similar conclusion could be inferred for impurities in experiments with Nickel LBO and Neon puffing showing that the barrier exerts a strong screening action such that impurities do not feature peaked profiles inside the barrier. The simulation of the radiation pattern by means of a 1-dim collisional-radiative impurity transport code indicates that such behavior is due to a strong outward pinch developing immediately outside the temperature gradient region, see fig.7 [12]. The outward pinch does not extend inside the barrier and impurities are not expelled outside the helical structure, as found for example with the impurity holes in LHD [13]. On the contrary, as for hydrogen, the helical structure tends to confine Ni when it is injected just before the formation phase.

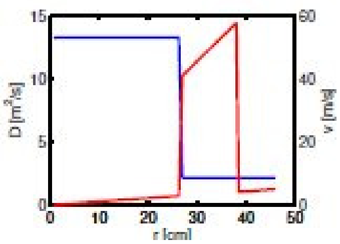

Fig.7:Iimpurity diffusivity and convection in presence of a transport barrier

The simulation of the experimental time evolution of the interferometer measurements and of the pellet ablation process shows that inside the barrier the particle (H) diffusion coefficient is reduced by about one order-of-magnitude, $D \approx 5$ m^2/s, with a negligible pinch velocity.

The guiding centre code ORBIT has been also applied to evaluate the radial diffusion of monoenergetic test particles (electrons and ions) subject to the real topology of the magnetic field in the edge of the RFX-mod and to Coulomb collisions with a background. The result is that in SHAx regimes the diffusion coefficient at low collisionality is reduced by about two orders of magnitude with respect to the situation dominated by magnetic chaos, leading to $D \approx 0.5$-5 m^2/s, of the same order than the experimental evaluation. On the contrary, the diffusivity of impurities experimentally evaluated remains about 10 times higher than the values from ORBIT [14,15]

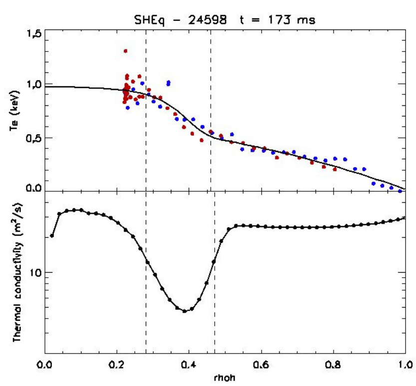

Fig.8: Example of electron temperature profile(top) and corresponding thermal diffusivity from power balance (bottom). The radial coordinate is the helical flux

The heat diffusivity χ at the barrier, evaluated by a power balance equation with the helical 3D magnetic equilibrium as an input decreases to values in the range 5-10 m^2/s. An example is given in fig. 8. In fig. 9 the minimum χ value is plotted as a function of the secondary mode amplitude for a number of discharges. Confirming the L_{Te} trend of fig. 2, and therefore the relation between transport barriers and magnetic topology, the lowest χ_{min} are obtained for the lowest modes amplitude. Also for χ_{min} a sort of lower limit can be seen, indicating that, besides the residual magnetic chaos, other gradient-driven mechanisms could take place. Gyrokinetic

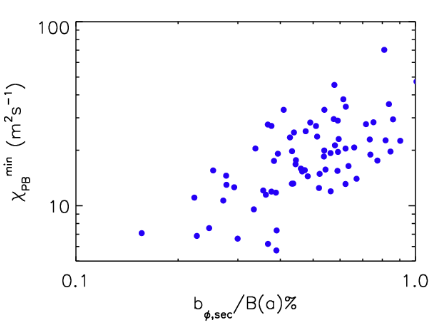

Fig.9: Minimum χ at the barrier vs secondary mode amplitude

calculations show that a strong candidate process that may limit the temperature gradient is the micro-tearing instabilities that appear as the dominant micro-turbulence mechanism acting on the ion Larmor radius scale [16,17]. Fig. 10 shows that in the Te gradient region micro-tearing modes are unstable. The quasi-linear estimate of the electron thermal conductivity related to such modes, $\chi \approx 5\div20$ m^2/s, is in the range of the experimental values. Estimates of the bootstrap current that may be driven by the observed electron thermal barriers indicate that it is negligible for realistic profiles, of the order of 1% [18,19].

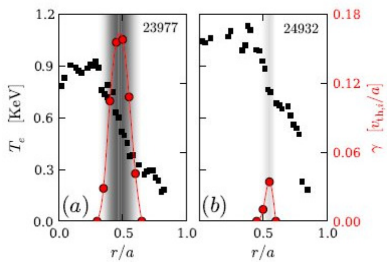

Fig. 10: Microtearing mode growth rate related to the temperature profile

3. Edge barriers

A barrier for the electron heat flux has been also observed to develop more externally with respect to the eITB, around r/a=0.8, inside the field reversal radius, not necessarily contextual with the ITB. An example of strong ETB is given in Fig. 11. Such barriers are characterized by very strong Te gradients that may reach values of 70-80 keV/m. They correspond also to a pressure barrier, where however the dominant contribution derives from the temperature gradient increase. While the internal barrier is clearly associated to the onset of a Single Helicity equilibrium, the external barriers do not appear to depend on a bifurcation step of the MHD dynamics. The ETB's develop in regimes in which the secondary modes are relatively low, at low collisionality and prefer regimes of shallow reversal. Fig 12 shows the relationship between edge ∇Te and the density normalized to the Greenwald density. The strongest barriers with ∇Te 50 keV/m and LTe< 2cm appear below 0.15 n/n_G. This range is presently more limited than that for the development of ITBs at high current, that as mentioned are observed up to $n/n_G \approx 0.3$, and is not related to a dependence on density of the secondary mode amplitude (fig. 12, right). Fig. 13 shows that the strong edge gradients develop for a large interval of the central electron temperature and are therefore uncorrelated with the processes occurring in the center. A detailed pattern of the MHD perturbations can be visualized by means of the FliT field line tracing code [20]. A typical feature of a strong ETB is shown in the Poincaré plots of Fig. 13 where two FliT reconstructions with (Fig 14 left) and without (Fig 14 right) ETB are compared. In presence of a strong barrier, the volume of the plasma characterized by short magnetic connection lengths is smaller. In Fig. 14 such volume is the one between the black irregular line around r=43 cm, corresponding to the last region with long connection lengths to the wall, and the wall itself at r =45.7

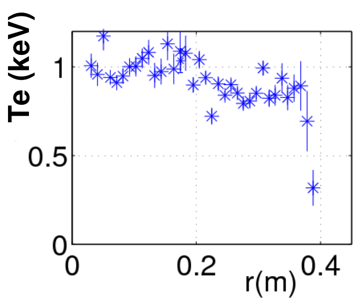

Fig.11: Example of external electron transport barrier

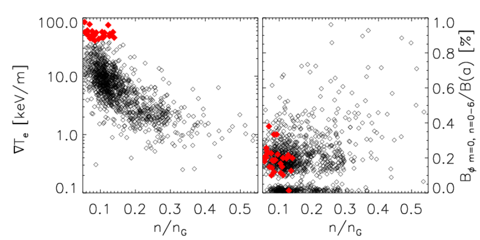

Fig. 12: ∇Te (left)and secondary m=0 mode amplitude versus the central electron temperature

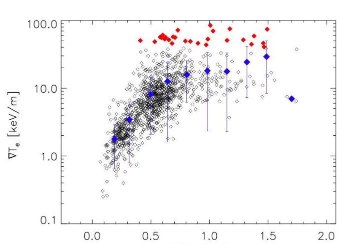

Fig. 13: ∇Te versus the central electron temperature

cm(straight line). The barrier develops around r=38 cm, where ordered magnetic surfaces start to show up out of the chaotic region at inner radii. Likely, the strength of the barrier reflects the local reduction of magnetic chaos. Work to quantify the impact on transport of the magnetic structures is ongoing.

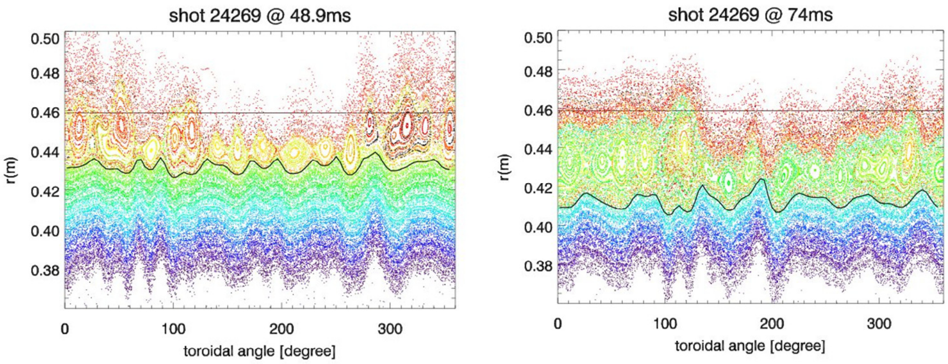

Fig.14: Poincarè plots of the detailed magnetic structure in two cases with (left) and without (right) strong ETB. Only the outboard portion beyond r= 36 cm is show.)

The onset of the ETB typically increases confinement by about 20% with respect to standard plasmas with similar density, and the electron heat diffusivity in the barrier region decreases to values as low as 6 – 10 m^2s^{-1}, of the same order as in the eITB cases.
Like for the internal barriers, also the L_{Te} associated to the ETBs appears to hit a lower limit, Fig. 15 shows the edge temperature characteristic length as a function of the Greenwald fraction. This fact is matter of current investigation.

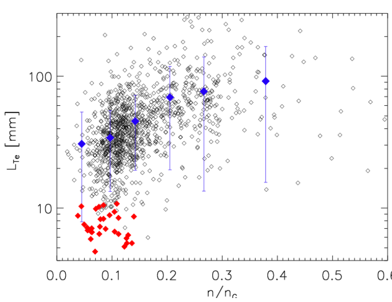

Fig. 15: Edge Te characteristic length as a function of the Greenwald fraction

4. Discussion and conclusion

The internal electron transport barriers triggered by the helical equilibrium spontaneously developing in RFX-mod at high plasma current correspond to the best values of the global electron energy confinement time (≈ 2.5-3 ms). Correspondingly, the electron heat diffusivity χ at the internal barrier decreases significantly, below 5-10 m^2/s. It is worth noting that the value of χ expressed in Bohm units ($\leq 10\ m^2T^2s^{-1}keV^{-1.5}$) intersects similar databases obtained in Tokamak or Stellarator confirming that in the region of the transport barriers the RFP is now approaching the transport quality of the other configurations. The increment of the global confinement that accompanies the presence of the internal barriers is however small compared to the improvement of confinement in the core. A large power, i.e. loop voltage, is still required to sustain the poloidal current flowing in the relatively resistive edge plasma. The presence of a significant fraction of trapped electron, not contributing to carrying the plasma current, is an additional term that enhances the effective plasma resistivity.
Regarding the comparison with other magnetic configurations we observe that in Tokamaks with dominant electron heating a reversed magnetic shear and especially a shear null represents a good condition for a strong electron barrier to develop [21,22,23,24]and the presence of a EXB flow shear is believed to just reinforce the probability to form the barrier. In a non-axisymmetric device like a Stellarator instead the EXB flow shear of neoclassical

origin and the interplay between turbulence and zonal flows is believed to be the origin of the eITBs [25].

The eITBs found in RFX-mod share a strong similarity with the Tokamak case whereby the maximum gradient of the thermal barrier is situated in the vicinity of the null of the magnetic shear, a situation in which the density of rational surfaces and thus the probability of mode coupling is lowered [24,26]. In the same time, two situations indicate a similarity with the Stellarator case. In RFX-mod both the eITB and the more external ETBs have been found so far in regimes of low collisionality. Whether this analogy is a signature of a similar physics favouring the barrier in both the configurations is an open question. In Stellarators a low collisionality regime is related to the development of a large positive radial electric field in the core, leading to the so-called electron root regime [27,28]. In RFX-mod, eITB's are strongly coupled to the onset of the Single Helicity equilibrium and the associated reduction of magnetic chaos, which are observed at low collisionality in the core region. Whether the neoclassical transport that originates from the 3D topology of the SHAx equilibrium may build up radial electric fields in analogy with the Stellarator e-root regime [29] is matter of current investigation. At the same time, work is in progress to provide by pellet injection a particle source internal to the barrier to fuel the core plasma thus increasing the confinement. Actually the best electron energy confinement times have been obtained in plasmas fueled by pellets. The second analogy with the Stellarator is the presence in the region of the barrier of an ExB shear flow. More spatially resolved flow measurements are needed to better correlate the shear of the poloidal flow to the onset of both internal and external barriers.

Another important analogy with the Tokamak is that in RFX-mod the electron temperature profile inside the barrier region is typically flat. In the Stellarator instead the large gradient of the electron temperatures extends to the plasma center. This difference between the T_e profiles in Tokamak and Stellarators has been ascribed to the different damping mechanisms of the zonal flows in the two devices by means of the radial electric field [25]. The flatness in RFX-mod is most likely due to a residual level of magnetic chaos inside the barrier, but the alternative hypothesis of fast rotating intermediate scale turbulence that would smear any gradient in the core has been also put forward [30]

The experimentally found shear flow could play a role also in the formation of the ETB's. Here we incidentally recall the experiments on TEXTOR where radial electric fields and consequently flow spin up has been obtained by applying rotating magnetic perturbation, thus inducing field stocasticity at the plasma edge[31]. Besides this little can be said about the possible origin of the ETB in RFX-mod but for the fact that the external barriers develop at the transition between an internal chaotic region and an external one where magnetic surfaces start to form, as shown by the field line tracing reconstructions of Fig. 14. Although in the latter case the degree of chaos reduction remains to be quantified, magnetic chaos reduction seems to be a reasonably common feature of both internal and external barriers in RFX.

The consistency of the ETB also as a pressure barrier does not justify any premature attempt to compare the ETB in RFX-mod with the H-mode of Tokamaks or Stellarators, also bearing in mind that several differences distinguish the H-mode in Tokamak and Stellarators. Even if the role of the X-point physics in the Tokamak H mode and of the analogous island divertor in the Stellarator could be somehow played by the X-points of the m=0 island chain at the edge of RFX-mod [32,33], there remain a variety of complex dependences of the L-H transition on power input, density , magnetic field as well as scrape off and target electron temperatures where analogies and differences should be investigated in detail. Certainly the existence of a significant transport barrier at the edge of RFX is an important finding that expands the possibilities of operating improved confinement regimes in the RFP's.

In conclusion we have described two types of electron transport barriers emerged spontaneously in the RFX-mod high current discharges. Both accompanied by an improvement of confinement through a strong reduction of the local heat diffusivity, they seem to develop after a significant reduction of the magnetic chaos takes place. The most striking analogy is the one existing between the eITB in RFX-mod and in the Tokamak, and is the presence in both cases of a null in the q shear, although analogies exist also with the Stellarator and more precisely the low collisionality and the presence of a significant flow shear. The eITB is also a region of reduced particle transport, for both impurities and main fuel. The external transport barrier cannot be at the moment associated to the H mode phenomenon although it is an edge process that represents a very interesting possibility of improved confinement regime in the reversed field pinch research.

Acknowledgment

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] HORTON W and ZHU P. 2000, Phys. Plasmas **7**, 4534 ; doi:10.1063/1.1308566
[2] CAPPELLO S. and ESCANDE D.F. 2000 *Phys. Rev. Lett.* **85** 3838
[3] VALISA M. *et al* 2008 *Plasma Phys. Control. Fusion* **50** 124031
[4] LORENZINI R *et al* 2009a *Nature Phys.* **5** 570
[5] PUIATTI M.e. et al. 2009, Plasma Phys. Control. Fusion **51** 124031
[6] MARTIN P. et al. 2009 *Nucl. Fusion* **49** 104019
[7] MARRELLI L. et al.," Three-dimensional physics studies in RFX-mod" this conference, paper EX/P5-10
[8] GOBBIN M et al., "Vanishing magnetic shear and electron transport barriers in the RFX-mod reversed field pinch", submitted to Phys. Rev. Lett.
[9] SPOLAORE M et al. 2010 "Parallel and perpendicular flows in the RFX-mod edge region" submitted to Journal of Nuclear Materials
[10] BONOMO F et al. 2010, 37th EPS Conf. On Plasma Physics, Dublin 21st-25th June 2010, paper O2.101
[11] TERRANOVA D et al. 2010 Nucl. Fusion **50** 035006
[12] MENMUIR S. et al. 2010 *Plasma Phys. Control. Fusion* **52** 095001 doi: **10.1088/0741-3335/52/9/095001**
[13] YOSHINUMA M et al., 2009 *Nucl. Fusion* **49** 062002 doi: **10.1088/0029-5515/49/6/062002**
[14] GOBBIN M. et al. 2010," Neoclassical transport in the helical Reversed-field pinch" submitted to Phys. Rev. Lett.
[15] CARRARO L et al. 2009 *Nucl. Fusion* 49 055009
[16] CAPPELLO S. et al**.,"**Equilibrium and Transport for Quasi Helical Reversed Field Pinches" this conference, paper THC/P4-03
[17] PREDEBON I. et al., "Microtearing Modes in Reversed Field Pinch Plasmas",submitted to Phys. Rev. Lett.
[18] GUAZZOTTO L., PACCAGNELLA R. 2009 *Plasma Phys. Control. Fusion* 51 065013
[19] GOBBIN M et al. 2009, J. Plasma Fus. Res. Series,vol.8, 1147
[20] INNOCENTE P *et al* 2007 *Nucl. Fusion* 47 1092
[21] KOIDE Y and the JT-60 TEAM 1997 *Phys. Plasmas* **4** 1623
[22] HOGEWEIJ G M D et al. 2002 *Plasma Phys. Control. Fusion* **44** 1155 doi: **10.1088/0741-3335/44/7/307**
[23] CODA S et al 2007 *Nucl. Fusion* **47** 714 doi: **10.1088/0029-5515/47/7/023**
[24] GARBET X, BOURDELLE C, HOANG G T, MAGET P 2001, Phys. Plasmas 8, 2793
[25] IDA K 2008 *J. Phys.: Conf. Ser.* **123** 012004
[26] KISHIMOTO Y et al 2000 Nucl. Fusion 40 667
[27] TERRANOVA D et al., "A 3D approach to equilibrium, stability and transport studies in RFX-mod improved regimes",accepted for publication in *Plasma Phys. Control. Fusion*
[28] TAKEIRI Y et al. 2003, *Phys. Plasmas* **10** 1788
[29] MINAMI T. et al. 2004, Nucl. Fusion 44 342
[30] SATTIN F., VIANELLO N., "Modelling the temperature plateau in RFX-mod SHAx states" submitted to *Plasma Phys. Control. Fusion*
[31] A. WINGEN, K.H. SPATSCHEK, 2010 *Nucl. Fusion* 50 034009
[32] MARTINES E et al. 2010 *Nucl. Fusion* **50** 035014 doi: **10.1088/0029-5515/50/3/035014**
[33] SCARIN P et al 2010, "Magnetic Structures and Pressure Profiles in the Plasma Boundary ofRFX-mod: High Current and Density Limit in Helical Regimes", this conference paper EX/P3-29