Edge transport properties of RFX-mod approaching the Greenwald density limit.

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Abstract. As in Tokamaks RFX-mod discharges are subject to the Greenwald density limit. The similarity between Reversed Field Pinches (RFP) and Tokamaks extends to many properties of the edge transport physics, including the electrostatic nature of turbulence, the presence of highly sheared **E**x**B** flows - sustained by the Reynolds' stress - and the presence of coherent structures emerging out of the turbulent background. The origin of the density limit in RFX-mod is sought along the legitimate idea that it should be similar to the Tokamak case. It is proposed that the poloidally symmetric and toroidally asymmetric strong radiation emission that develops where the plasma interacts with the wall, at high densities triggers a thermal instability that cools the plasma core. The process resembles the evolution of a MARFE in a Tokamak, but in the RFP the effect on the plasma core occurs well before the total radiated power approaches the (ohmic) power input and the result is a soft landing of the discharge.

1. Introduction

Among the operational limits of magnetically confined fusion plasmas the upper density limit is of particular importance for its direct impact on fusion performance, which depends on n_e^2 f(T), with f(T) a function of the plasma temperature. The density limit is experimentally found in all major magnetic configurations, including Tokamaks, Stellarators and Reversed Field Pinches (RFP) [1]. The power independent empirical scaling generalized by Greenwald after Murakami and Hugill [1 and ref. therein], binds the maximum line averaged density to the total plasma current density, $n_G \equiv I_p/\pi a^2$ (n_G in 10^{20} m^{-3}, I_P plasma current in MA, *a* minor plasma radius in m) and describes very well the threshold in Tokamaks and RFP's [1]. In additionally heated Tokamaks when internal transport is ameliorated and peaked density profiles develop, or when the particle source, which is generally at the plasma edge, is moved into the plasma with the injection of pellets, energetic beams or the use of supersonic gas puffing [2], the Greenwald limit may be largely exceeded. In such circumstances however the edge density remains below the limit. Therefore the empirical density limit is not fundamental and appears to be associated to physical mechanisms occurring at the plasma edge. In RFP's the input power is only ohmic and the upper density limit coincides almost exactly with the one defined by Greenwald [3]. In both Tokamak and RFP's the operational space extends slightly when the working gas is He instead of H or D [1, 3]. The same empirical scaling does not seem instead to organize well the Stellarators densities, which exceed the Greenwald limit by a factor three in various types of scans, like decreasing the magnetic field or the plasma duration [4].

In Tokamaks, the causes of the upper density limit are different: radiative instabilities, recycling instabilities or edge plasma instabilities leading to an increase of the edge anomalous transport. In [5] micro-turbulence was proposed as the origin of confinement degradation near the density limit on Text as well as of the non radiative collapses found on other experiments [6]. The various mechanisms may also act in synergy [7], each with a different weight. In general, however, the balance at the plasma edge between parallel and perpendicular transport is such that a thermal instability develops and preludes to a disruptive end of the discharge. This occurs along two typical channels: either the detachment of the plasma from the wall/divertor target or the development of a MARFE (Multifaceted Asymmetric Radiation From the Edge) at the inner edge or at the X point. On Textor the excitation of the Dynamic Ergodic Divertor changes the cause of the density limit from detachment to the onset of a MARFE, with a higher-than-typical power threshold [8]. On the Alcator C-Mod Tokamak has given experimental evidence of turbulent transport developing and expanding across the scrape-off-layer (SOL) into the main plasma as the density approaches its upper limit [9]. The nature of the turbulent transport in the SOL of C-Mod has been identified by a combination of electric and fast optical probes as made of dipole–like vortexes (blobs), whose average radial velocity has been measured [10].

In Stellarators standard regimes the density limit is attributed to an inward convection that accumulates impurities in the core till a radiative limit is reached, while in improved regimes, such as the High Density regime of W7-AS, the limit occurs when the impurity radiation forces the plasma to detach from the divertor plates [4].

In RFP's the density limit always leads to a soft landing of the discharge [3,11]. In general, if the Greenwald limit is hit a density pump out occurs and the trajectory of the discharge in the Greenwald plot tracks quite exactly the empirical boundary. On the limiter-less ETA-Beta II experiment the upper density limit, defined as a lower I/N limit (I being the plasma current and N the line averaged density) was experimentally established as the condition where the total radiative power approaches the Ohmic heating rate [12]. In RFX the difficult-to-diagnose effects of the vigorous plasma wall interaction ensuing from the wall locking of several magneto-hydrodynamic (MHD) modes, did not allow the unambiguous confirmation of the ETA-BETA II results [3]. Optical and electrical edge measurements on RFX could instead exclude that a general detachment occurs when the Greenwald limit is reached, as the edge electron temperature was never observed to be below the ionization potential of the working gas (either H or He). In addition, the deliberate injection of neon or xenon was found to lower the limit.

A number of models have been proposed to explain the density limit. Many of them consist of analytical or semi-analytical approaches to evaluate the competition between the heat flux that supplies the edge and the high radiative cooling rates of the impurities [7, 13] including assumptions to qualify the edge transport. In [14] it was proposed for both Ohmic Tokamaks and RFP's that the density limit is a radiation limit, and a dependence of the density limit on the considered impurity species was found. Other papers focused on more specific aspects such as two dimensional transport issues in the SOL [15] to explain the detachment at the divertor plates, the physics of the H-mode pedestal [16] or explored the physics of the X point to study the formation of MARFE's. Other papers again investigated transport degradation induced by turbulence as the primary cause of the density limit [17]. In [18], the density limit boundary in the phase space of the plasma edge was identified as caused by resistive ballooning modes when the diamagnetic term is sufficiently low. To justify the C-Mod findings [19] used blob models based perpendicular energy flux scaling, where blobs enhance heat transport and, in association with an X point cooling, produce the energy losses analogously to a radiative process.

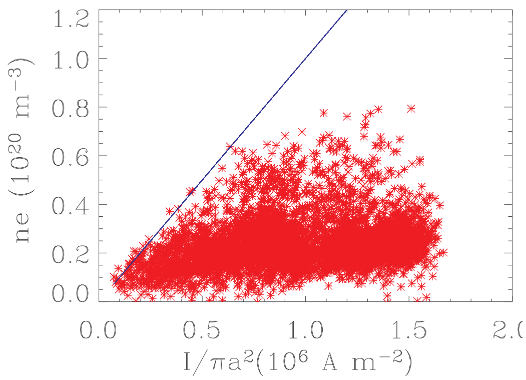

Fig. 1. RFX-mode densities vs n_G

All above represents the background of this contribution, in which the experimental evidences of the density limit on RFX-mod is presented and its edge transport properties in the vicinity of the limit are analyzed in the spirit of a comparison with the findings in the other magnetic configurations. The striking similarity between Tokamaks and RFP's in sharing the same density limit can hardly be considered a merely coincidence while a common physics could instead regulate in a similar manner the edge plasma of the two configurations and be the cause of the upper density limit.

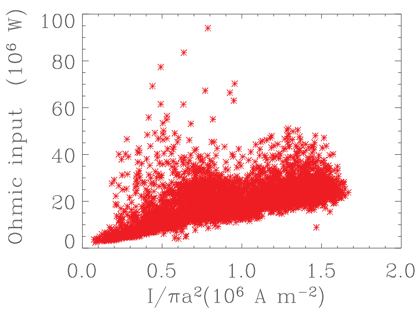

Fig. 2. For the same database of Gig. 1: Ohmic input power vs n_G

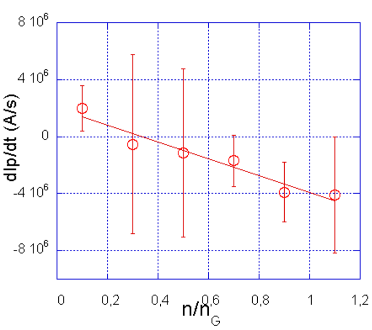

Fig.3. Current time derivative vs n/n_G

2.1 General phenomenology The significant modifications that turned RFX into RFX-mod [20] did not bring any changes in the density parameter space if we exclude the expansion of the lower boundary. The latter result most probably reflects the remarkable improvement of the magnetic boundary in RFX-mod obtained with the installation of an external array of saddle coils that can act as a nearly ideal conducting shell [21]. The better magnetic front end of RFX-mod has reduced by a factor ten the radial magnetic field at the edge, allowing an improvement of more than 50% of the global confinement time and a prolongation of the discharge duration. Despite this, the upper density boundary cannot be distinguished from that of the older machine version. Nor has had any effect in this sense the modification of the shape of the carbon tiles that cover almost completely the vacuum vessel, namely the minimization of the leading edges to avoid hot spots and carbon blooms. Fig. 1 shows the Greenwald plot for a number of RFX-Mod hydrogen discharges, whose upper values match remarkably well the empirical limit. The plot includes discharges with plasma current from about 0.2 to 1.1 MA, though at high current mostly low density plasmas have been experimented. The levels of the Ohmic input power applied at the various plasma currents, as shown in Fig. 2 vs. n_G, clearly imply that the upper density is not a mere engineering limit of the machine. The power necessary to drive low density, high current discharges, surpasses the power that drives low current discharges with density at the Greenwald limit. Experimentally, in absence of additional heating, if one increases the applied power adding poloidal flux to an established RFP discharge, the result is an increase of the plasma current. Conversely, if one puffs additional gas into the flat top phase of a discharge trying to raise the density, the plasma cools down, becomes more resistive and the current decreases. As a matter of fact, on RFX-mod it has not been possible to approach the density limit in a situation of well sustained current. This was the case also on RFX and ETA-Beta II. In general it is found that the closer the discharge to the density limits the higher the plasma current decaying rate. This is shown in Fig. 3, which relates the plasma current derivative to the normalized density for a number of discharges. A further aspect that is worth noticing is that in such circumstances the toroidal flux decay rate is typically faster than for the current, meaning that the resistive diffusion is too high for the intrinsic flux converter mechanism of the RFP, the dynamo [21], to counteract it. As a result the current profiles change and the region of toroidal magnetic field reversal moves deeper into the plasma. This is one major difference from the Tokamak: in a RFP the plasma current decay is automatically accompanied by a decay of the toroidal flux, turning the excessive plasma resistivity into a soft landing of the discharge.

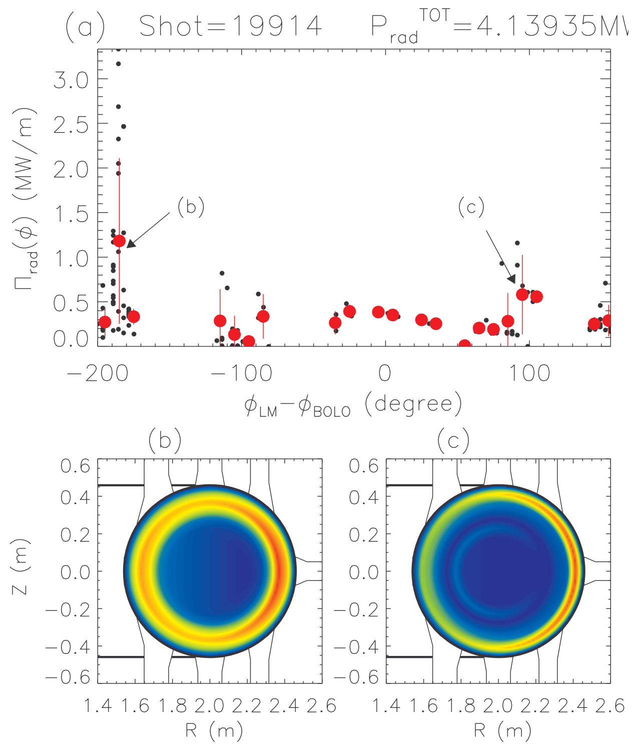

Fig. 4 a) Reconstruction of the radiated power per unit of toroidal length for shot 19914 vs the toroidal angle. The bolometer section is at 0°..b) Tomography of the radiation pattern when, during its toroidal motion, the maximum of the emission crosses the bolometer position at 0°. c) Tomography of the radiated power outside the strong emission peak.

2.2 Radiation and locked modes

The reduction of the radial magnetic field at the edge of RFX-mod has drastically improved the plasma wall interactions. However, a residual local displacement of the plasma column of about 1 cm still exists where the several m=1 and/or m=0 modes overlap, so that the plasma wall interactions are still non axysimmetric and so is the radiative power. To evaluate the ohmic input to radiated power ratio it is therefore necessary to sum the radiation profile all along the torus. The possibility to drag around the modes by means of the saddle coils system provides the means for the purpose [20]. By imposing the external coils system to produce a number of (typically) m=1 rotating modes of predefined amplitude, chosen among the internal resonant ones, while feedback quenching all other modes of different helicity or phases, the modes of the plasma easily couple to the applied ones and start rotating at the same frequency (10-50 Hz). In this way also the bulge produced by the in-phasing of the modes rotates and a full tomography reconstruction of the radiation pattern can be made. Fig. 4 shows for shot 19914, featuring n/n_G~0.9, the power radiated per unit of toroidal length as a function of the toroidal position and the tomography of the plasma cross section obtained at two different times, corresponding respectively to the cases outside and inside the maximum perturbation. The total radiated power for the specific discharge of fig. 4 was approximately 30 % of the input power, despite the average density was close to the limit. Outside the region of maximum interaction the radiation emission is poloidally asymmetric and concentrated in a relatively narrow layer (~5cm) while

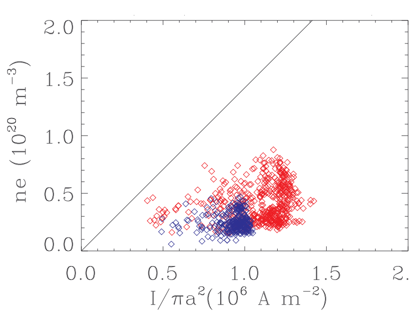

Fig.5. Ne (red) and Xe (blue) seeded discharges , to be compared with Fig.1

it quite symmetric and thicker (15cm) inside the highly radiating structure. Impurity injection experiments on RFX had demonstrated that doping the plasma with highly radiating elements reduces the density operational space even further. Fig. 5 shows an ensemble of discharges with Ne and Xe that should be compared with the hydrogen discharges of Fig.1. With impurities of high cooling efficiency such Ne and Xe in RFX radiation is poloidally symmetric all over the torus [22] and the limit can hardly be approached.

2.3 Edge measurements

The outer regions of RFP's and other magnetic configurations such as Tokamaks and Stellarators share several analogies. Edge particle transport is mainly driven by electrostatic turbulence and is characterized by a highly sheared v_{ExB} flow, whose spontaneous evolution can lead to transport reduction [23]. Experiments on the reversed field pinch Extrap-T2R have shown that the Reynolds' stress, which is known to drive the E×B flow against anomalous viscosity, exhibits a strong gradient in the layer of high velocity shear and, despite the high level of magnetic turbulence which characterizes the RFP configuration, this gradient is almost entirely due to the electrostatic component [24]. This represents a remarkable similarity with respect to Tokamaks and Stellarators, pointing towards a mechanism for momentum transport independent of magnetic topology. Coherent structures emerge as intermittent bursts from the turbulent background, rotating mainly in the direction determined by the local mean velocity shear. In RFX as well as in Extrap-T2R such structures have been identified as dipolar and monopolar vortices that, interacting with the bulk plasma and themselves, contribute up to 50% of the total radial diffusivity [25]. Another means to underline the analogy with Tokamaks of the edge behavior is the observation that the probability distribution function (PDF) of the electrostatic fluctuations at the edge of an RFP is typically non Gaussian [26]. The analogy extends to the fact that the deviation from a pure Gaussian, which would imply a completely incoherent turbulent sea of fluctuations, decreases as one move from the far scrape off layer (SOL) into the plasma, as shown in Fig.6. Coherent structures therefore emerge out of the turbulent background particularly at the far edge, and this is reminiscent of the observations reported from C-Mod [9]. In RFX-mod this is seen in radially resolved measurements of electrostatic fluctuations and also in chord integrated Gas Puffing visible Imaging (GPI) measurements when discharges with different SOL thickness are compared. In the limiter-less RFX-mod this is possible because the last closed magnetic surface is defined by the overlapping of a number of m=1 and m=0 MHD modes and the SOL thickness can be varied from a few centimeters to less than one by feedback controlling the modes amplitude. The number of

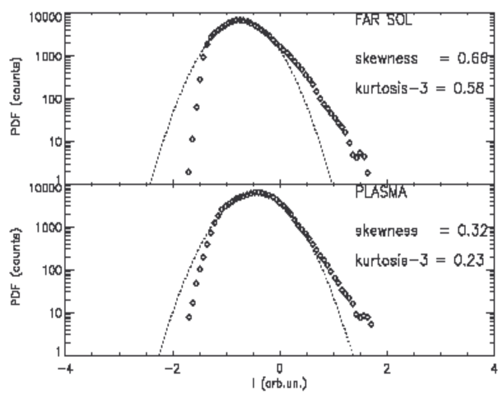

Fig. 6. PDF of GPI signals in the SOL (top) and plasma (bottom)

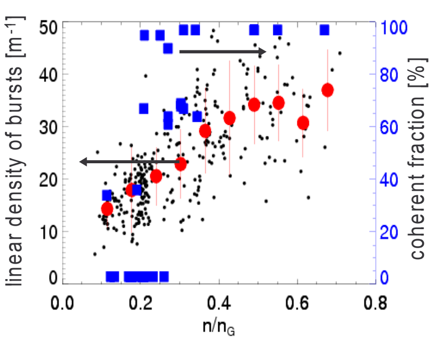

Fig. 7. Linear density of intermittent edge events and (blue) portion of coherent events form statistical analysis of GPI signals

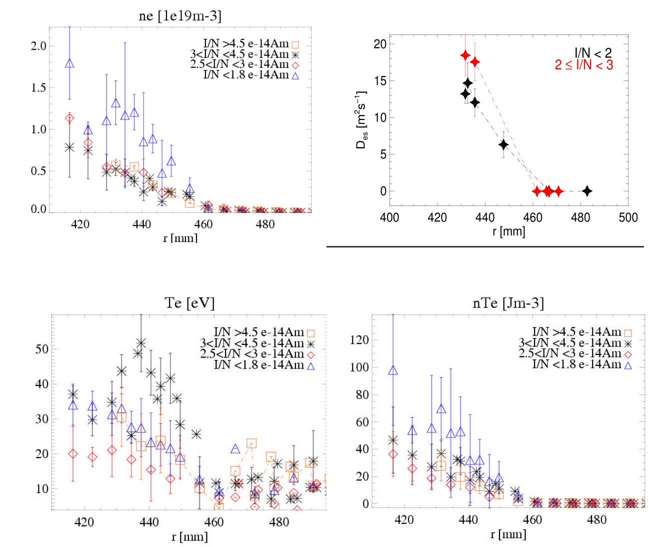

Fig 8: Electron Te, ne and pressure values from the Langumuir probe array and the deduced edge particle diffusivity, for different I/N ranges

intermittent events in the GPI signals increases with density up to about n/nG = 0.5 where it seems to saturate, as shown in Fig.7 where the linear density of such events is plotted as a function of the normalized density. Fig. 7 contains also the evaluation of the portion of the coherent content of the signals evaluated from their PDF. These PDF can in fact be fit by the sum of two Gamma functions that have been interpreted as representation of the coherent and the uncorrelated fluctuations respectively [26]. The saturation of the estimated coherent portion at low and high density reflects the choice of which value of the fitting functions parameters represents the thresholds defining coherent and pure turbulent dominated regimes. These results are found also in the analysis of density and temperature fluctuations measured by Langmuir probes at the edge. The confirmation regards both the radial dependence of the intermittent events density and the dependence of these events with the normalized density. It is interesting also to notice that the velocity with which intermittent events travel toroidally along the **E**x**B** direction at the edge, decreases with density but saturates beyond n/nG > 0.35. Measurements of temperature and density at the edge confirm the findings of RFX (see Fig. 8). The density gradient at the edge increases with density and the pressure profile behavior reflects that of density. The particle diffusion derived from the measured fluxes and density gradients is of the order of 10-20 m^2s^{-1}, in agreement with Bohm's scaling. The electron temperature is not a simple function of density but never decreases below 10 eV. This is confirmed also by the edge measurements of the Thomson scattering. Given the error bar of the measurements it is not possible to individuate saturations in the density or pressure profile increase with the average density. It is important to say that all these edge measurements and observations were carried out outside the region of maximum interaction generated by the overlapping of MHD modes.

3. Simulations

The trajectory of the plasma discharge in the high density region has been modeled by means of the code RITM adapted to the RFP [27]. This 1 dimensional description of the RFP resolves the energy and particle equations self-consistently. The mean fields are those pertaining to the prescribed plasma current according to a "μ and P" model [21] and the predefined values of the poloidal and toroidal fields at the edge normalized to the average toroidal field. Heat and particle diffusivities, along the Rechester–Rosenbluth (RR) model, depend on the normalized magnetic field fluctuations, which are taken from the experiments. At the edge instead, following the experimental observation on RFX, Bohm particle diffusivity is chosen. The convective term includes two contributions: one proportional to the RR diffusivity and the second proportional to **E**x**B**. Particle transport equations include the evolution of the impurities so that the radiated power can be self-consistently computed. In the present form the model cannot describe the time evolution of the plasma current whose time trace is therefore taken from the experiment. The preliminary results reasonably reproduce the behavior of density, temperature and radiated power. In the simulation of the high density discharges the particle diffusivity reaches quite high values: about $20 m^2s^{-1}$ in the core decreasing towards the edge ($\sim 15\ m^2s^{-1}$), of the same order of the experimental findings (see Fig. 8). Transport in the core is found to be about a factor two lower in low density discharges with sustained current. Further development is necessary to bring the model to a self-consistent treatment of the current evolution, for which the magnetic dynamo and the field diffusion have to be introduced.

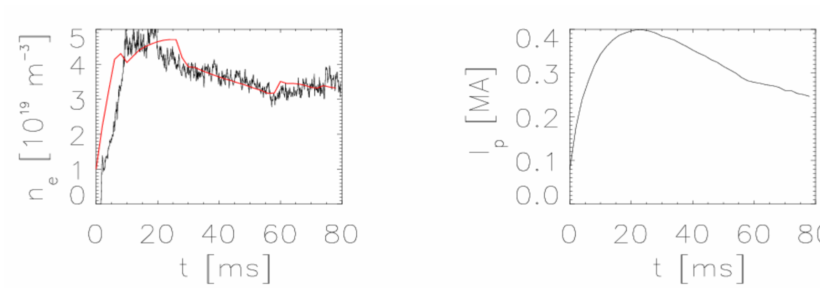

Fig.9. Experimental and simulated by RITM (red) electron density (left) and experimental plasma current (right) of shot 19914 .

4. Discussion and conclusion

Many of the observations described in the previous paragraphs indicate that the region *outside* the strong plasma wall interactions that characterize all the RFX-mod discharges has none of the characters of the Greenwald density limit phenomenology in Tokamaks. In that portion of the edge we have not identified signatures of an increased transport at high normalized densities. At the highest densities the radiated power fraction, including the contribution of the region of the locked modes, reaches relatively low values, around 30%. In this sense in RFX-mod, as in RFX, the density limit is not a truly radiation limit since 100% of the power input is never radiated. According to edge measurements, particle diffusion in the last few centimeters of the plasma does not change significantly in conditions close to the density limit and in particular it does not increase. The edge electron temperature does not decrease below 10 eV, indicating absence of plasma detachment. Also the sophisticated analysis of the edge fluctuations indicates that at high densities there are no particular signs of increased activity and transport.

The radiation pattern in the region of the locked modes instead resembles the MARFE of a Tokamak, though with opposite geometry (poloidally symmetric in the RFP and toroidally symmetric in the Tokamak) because of the opposite ratio between toroidal and poloidal fields in the two configurations [21]. A MARFE in a Tokamak is usually interpreted as a thermal instability that can grow up to modify the current density profile: if an MHD unstable configuration is reached the plasma disrupts. Indeed the width of the radiating layer shown in Fig. 4 is remarkable, about 1/3 of the minor radius, and could well be the reason for the plasma core cooling, the increased resistivity and the subsequent current decay. In the RFP the soft nature of the current decay is favored by the intimate link between current and toroidal flux, both driven by one single circuit [21]. Radiation structures like the one shown in Fig. 4, 15 cm thick in the radial direction and about 5-10 toroidal degrees large, are allowed by the topology of the RFP, whereas at the edge the field lines are mainly poloidal and therefore transport in the toroidal direction is mainly perpendicular to the local field. When sustained by enough density, the *local* radiation cooling at the edge caused by the plasma wall interaction can compete with the power rate flowing from the plasma center and can expand radially. Indeed, from rough estimates, in the case of Fig.4 the power radiated at the maximum of the plasma wall interaction is about equal to the power flowing from the core into the affected volume. By cooling the core, the plasma becomes more resistive, the fields diffuse and the amplitude of the magnetic fluctuations increases. As a consequence, core transport increases and density experiences a pump out, as shown in the simulation. An experimental fact is that neither on RFX nor on RFX-mod the database contains discharges with densities close to the limit and, simultaneously, sustained plasma current, which instead is always decaying at very high densities (see fig. 3). The transport increase in the core, however, is a consequence rather than the cause of the entire process. In conclusion, in a picture that still needs to be validated by a more punctual modeling and experimental work, the Greenwald limit in RFX-mod appears to be caused by a thermal instability developing in a toroidally localized portion of the plasma in strong analogy with the MARFE phenomenon in Tokamaks. The issue is different in that in the RFP the discharge ends with a soft rather than a hard termination.

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5. References

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