The Greenwald density limit in the Reversed Field Pinch

M. Valisa, F. Auriemma, A. Canton, L. Carraro R. Lorenzini, S. Ortolani, R. Paccagnella, M.E. Puiatti, F. Sattin, P. Scarin, G. Spizzo, M. Spolaore, N. Vianello , A. Alfier, V. Antoni, L. Apolloni, M. Bagatin, W. Baker, O. Barana, F. Basso, D. Bettella, P. Bettini, T. Bolzonella, D. Bonfiglio, A. Buffa, S. Cappello, R. Cavazzana, M. Cavinato, G. Chitarin, A. Cravotta, F. D'Angelo, S. Dal Bello, M. Dalla Palma, A. De Lorenzi, L. De Pasqual, D. Desideri, D.F. Escande, P. Fiorentin, P. Franz, L. Frassinetti, G. Gadani, E. Gaio, L. Garzotti, E. Gazza, L. Giudicotti, F. Gnesotto, L. Grando, S.C. Guo, P. Innocente, A. Luchetta, G. Malesani, G. Manduchi, G. Marchiori, D. Marcuzzi, L. Marrelli, P. Martin, E. Martines, S. Martini, A. Masiello, F. Milani, M. Moresco, A. Murari, P. Nielsen, R. Pasqualotto, S. Peruzzo, R. Piovan, P. Piovesan, N. Pomaro, G. Regnoli, G. Rostagni, V. Schmidt, G. Serianni, P. Sonato, E. Spada, C. Taliercio, D. Terranova, V. Toigo, P. Zaccaria, P. Zanca, B. Zaniol, L. Zanotto, E. Zilli, G. Zollino, M. Zuin.

Consorzio RFX, Associazione ENEA-Euratom sulla Fusione, Padova , Italy

e-mail contact of main author: marco.valisa@igi.cnr.it

Abstract. In the Reversed Field Pinch RFX the upper boundary of the density operating space matches fairly well the Greenwald limit. Typically reaching the ceiling procures a soft termination; hard terminations may however occur at high currents (>0.9 MA) in presence of particularly large error fields. Radiation losses are always a relatively small fraction of the ohmic input power but the injection of highly radiating impurities shrinks the density operating space. The contribution of localized plasma wall interactions (PWI) to the total radiation is of difficult determination so that a detailed power balance cannot be performed. The limit is never exceeded even in the region of privileged PWI, where the density can be higher than elsewhere, suggesting that in the RFP the limit is valid locally. In He plasmas the limit can be exceeded and the electron density source profile estimated by Monte Carlo modelling with experimental edge temperature and densities is substantially similar to the hydrogen case. Preliminary self-consistent simulations of high density hydrogen discharges with the RITM transport code illustrate that realistic combinations of electron temperature and particle diffusivity can lead to a saturation of the density build up as the influx is increased.

1.Introduction

The values of plasma density at which magnetic fusion devices can operate are bounded by both upper and lower limits regardless of the type of magnetic configuration, whether, for example, Tokamak, Stellarator or Reversed Field Pinch (RFP)[1]. The upper boundary deserves a particular attention for various reasons: primarily the fact that fusion reactivity depends quadratically on density as well as the fact that Tokamak operation near the limit is susceptible of a disruptive termination, which is clearly undesirable. Moreover in the RFP energy confinement time increases with density. The empirical generalisation of the limit introduced by Greenwald is described by the expression: $n_e < 10^{14} \kappa < J >$ [SI international units], where n_e is the average plasma density, $< J >$ the average current density and κ the plasma elongation. One remarkable and intriguing aspect is that such generalisation based on volume averaged quantities is representative of the upper density limit in many different fusion devices, different in size and performances and also in magnetic topology and, typically, transport quality. The hypothesis that a common physics underlies the phenomenology of the Greenwald limit is therefore plausible. Actually the Greenwald limit is not an insuperable limit and several conditions allow in fact to exceed it. A variety of stationary and transitory operations well above the Greenwald limit have been reported and can be obtained routinely [1]. These conditions include the modification of the particle source profile, as in the case of pellet injection or strong Neutral Beam Heating, and the improvement of core transport, leading to a peaked density profile. In both cases the average density increases. Altogether the above considerations have led to concentrate the attention around the role of the plasma edge and more specifically to the search for the reasons that ultimately lead the edge to cool, such as thermal instabilities driven by excessive radiation backed up or not by modes that increase transport. A clear cut explanation of the Greenwald limit based on first principles, i.e. the detailed mechanisms that cause the thermal instability, has not been given as yet.

In this paper the experimental evidence regarding the upper density limit in the Reversed Field Pinch RFX [2] is presented in detail. Indeed in RFX the density operating space hits an upper boundary that is well described by the Greenwald limit [3] thus confirming the general validity of the latter description.

2. The RFX Experiment

RFX is a large RFP toroidal device (minor radius a =0.46 m, major radius R = 2 m), so far operated with plasma current Ip = 0.2-1.2 MA , on-axis electron temperature Te of the order of 200- 400 eV, volume averaged electron densities n_e in the range $2\text{-}10 \cdot 10^{19}$ m^{-3} and typical discharge duration of about 0.12 s. The Inconel vacuum vessel is evenly covered all over by graphyte tiles. Carbon, oxygen and boron are the main impurities. Metal contamination is negligible. The plasma is ohmically heated and the loop voltage is of the order of 20- 60 V depending on the type of discharge. The density behaviour is maintained under control by standard wall conditioning techniques, including wall baking and glow discharge cleaning and boronization. The wall is typically at “room” temperature but campaigns with wall baked up to 300°C have also been performed. Multiple pellet injection can be used to refuel the plasma. High-density discharges have been so far dominated by fuel recycling at the wall, hydrogen being the working gas. The magnetic field at the plasma edge is mainly poloidal with only a minor toroidal component. One specific aspect to consider is that the resonant interference of several MHD modes determines toroidally localised kink-like deformations of the plasma column that concentrate the power exhaust onto a relatively narrow region of the wall. Power density fluxes to the wall may locally depart from the average 1-2 MWm^{-2} and reach the remarkable level of 100 MWm^{-2}. The footprint of the locked modes on the wall is a helically shaped region that extends for approximately 40 to 60 toroidal degrees and contributes for 30% to 50% to the total particle influx and radiated power [4]. When this structure locks to the wall the density behaviour can be unpredictable, especially at high current (~ 1 MA), depending on the amplitude of the field error and the degree of hydrogen saturation of the wall. Forcing by external means the structure to unlock has been successful in many circumstances but the very high density discharges of interest here have all been characterized by the presence of stationary wall locking of the tearing modes.

3. General phenomenology of the density limit in RFX

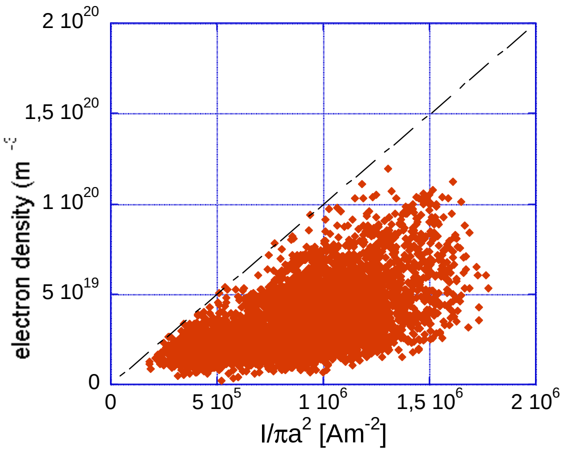

Fig 1. The RFX density operating space in the Greenwald plot. Data are averages over 10 ms of hydrogen discharges. Shots with density measurements perturbed byl wall mode locking are not included.

The region or the Greenwald plot n_e vs $I/\pi a^2$ explored in ordinary RFX campaigns in hydrogen is shown in Fig.1. Each point corresponds to density and current values averaged over 10 ms. The data ensemble of Fig.1 exclude shots where the wall mode locking was in the region of the interferometer measuring the electron density. The wall mode locking in fact causes also a local increase of the density [5]. However when considering also shots with density measurements0 affected by wall mode locking the Greenwald limit is only marginally exceeded and also the region just below the Greenwald limit at high current, empty in Fig. 1, is populated. Fig 2 shows the evolution of the density in one high density hydrogen discharge. The plasma current decreases and when the trace reaches the Greenwald limit also the density diminishes, following the limit. The cases affected by wall mode locking are similar but in general much more fluctuating. It is still not clear whether these fluctuations are originated by MHD activity or just intermittency of the strong interactions due to self-screening processes [6].

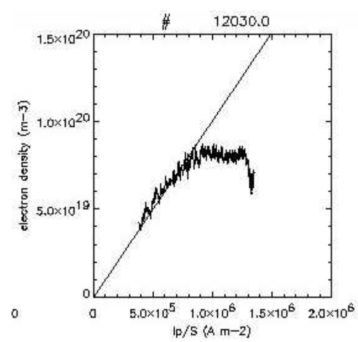

Fig. 2 Trajectory in the Greenwald plane of a H discharge.

3.1 The role of Radiation- Impurity seeded discharges

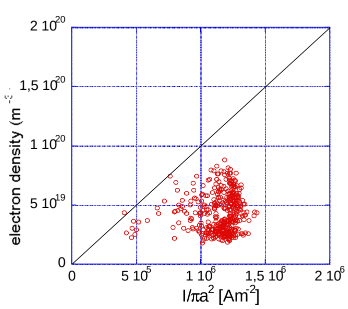

Fig. 3 Greenwald plot of RFX shots with impurity seeding.. The operating space seems to lower with respect to ordinary discharges, though some points lay on the limit.

The radiated fraction of the power input is in general relatively small, only seldom reaching 50%. Optimization of the impurity content by wall boronisation has only slightly increased the density limit. It should be mentioned that Z_{eff} is very small, i.e. around 2, at high densities at all currents and after boronization is close to one. Fig. 4 shows the radiated power fraction as a function of n/n_{Gf} for ordinary hydrogen shots and for discharges seeded with Ne or Xe. The injection of highly radiating impurities moves the density limit downward as it evident also from Fig. 3, showing impurity seeded discharges in the Greenwald plane. As for the

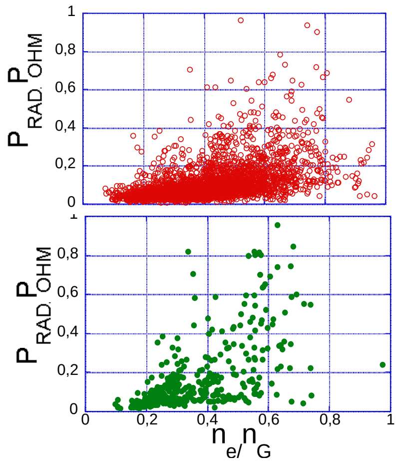

Fig. 4– Radiated power fraction as a function of n/n_G for ordinary H discharges (top) and impurity seeded shots(bottom)

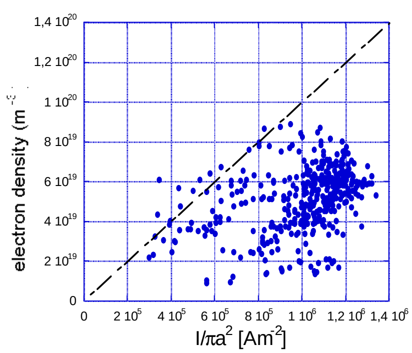

Fig. 5 He discharges in the Greenwald plane

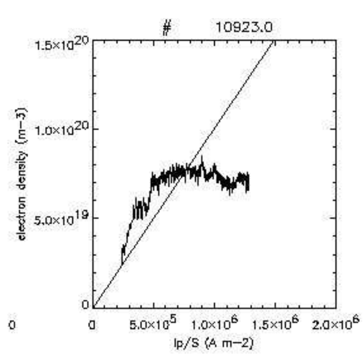

Fig 6 . - Ttrajectory in the Greenwald plane of a helium discharge

ordinary discharges also the impurity doped shots with density measurements affected by wall locking are close to the Greenwald limit, but without overtaking it.

3.2 He discharges

He discharges correspond to a favourable condition for the density to exceed the upper limit as shown in Fig. 5. Similar findings were seen also in ASDEX-UG [7]. Fig. 6 shows the evolution in the Greenwald plot of a single He discharge with mode locking far from the interferometer, where the electron density goes well beyond the Greenwald limit. He discharges are characterized by higher radiated power fraction and higher Z_{eff} with respect to the hydrogen case. Also in the case of He the wall mode locking represents a region of privileged source where density can be slightly higher than elsewhere. According to a Monte Carlo model of the plasma edge the source term of the electrons in the helium case in substantially similar to the hydrogen case unless the edge temperature is below 4-6 eV. As it will be shown in the following paragraphs the edge temperatures in RFX as measured by Langmuir probes are always well above 10 eV in the H case and 20 eV in the He one, suggesting that the reason for the wider density operating space with He in RFX is not due to a higher fuelling capability of He.

3.3 Fast terminations

The high-density limit occurs in general as a non-disruptive limit. When density increases, the plasma current quenches until the RFP configuration (i.e. the magnetic field reversal) is lost. However at high current a fast termination may happen. It starts as a sudden electron temperature drop followed after several ms by the loss of the magnetic field reversal at the edge, a necessary condition for a RFP to exist, and eventually by the fast current quench. Electron density behaves

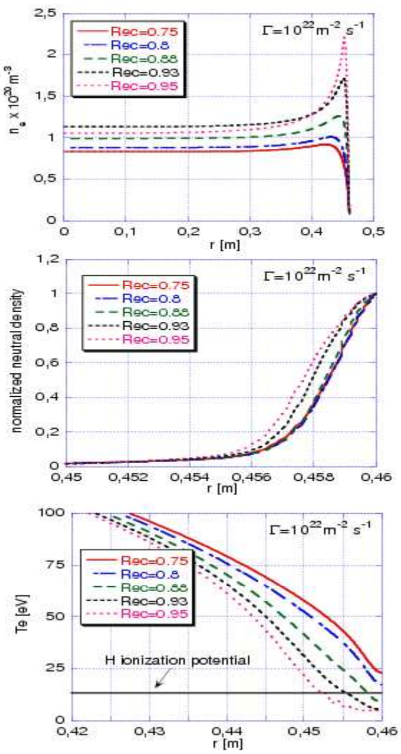

Fig.7. Predictive RITM runs for various values of particle recycling. Top: electron density profile. Centre: edge neutral density profile. Bottom: edge electron temperature profile.

differently from case to case; however a fast termination always occurs at a value of the ratio I/N lower or equal to 2.5 10^{-14} Am. The detailed mechanism that leads to the fast loss of confinement is still unclear but has been associated to large error fields at the wall mode locking region and to the large power involved. The association with the observation that at the wall mode locking region the density limit is anyhow not exceeded (or only marginally exceeded) suggests that the density limit could play a role in the evolution of the fast termination that leads to a rapid cooling of the plasma core.

4. Simulation of the high density discharge

High density discharges in hydrogen have been simulated by means of the semi-empirical transport code RITM [8]. RITM is a 1-D self-consistent model that solves the continuity equations for electrons, background ions and impurity ions and the energy balance equations for electrons and background ions. The power density profile is evaluated according to the Spitzer resistivity and to the μ and p model. [9]. The dependences of energy and particle fluxes on the main parameters, are prescribed according to the transport theory by Rechester and Rosenbluth [10]. The relationship between magnetic field fluctuation level and the electron density is from the experiment. Predictive runs of the code reproduce fairly well the experimental evolution of the typically flat electron density profile [11], which becomes more and more hollow and with an increasing edge gradient as the density is raised, with a corresponding decrease of the edge temperature (Fig. 7). As the influx is raised the average density keeps increasing till the point where the decreasing edge temperature approaches the hydrogen ionisation potential. At this point the neutral hydrogen density profile stretches inward and the average density stops increasing.

In the exercise of Fig 7 the particle diffusion at the edge does not change significantly. The effect of a different edge particle diffusion is instead analysed in Fig. 8 where the case of Fig. 7 corresponding to Rec.=0.85 has been compared to two cases with higher and lower diffusion respectively. As expected, forcing a higher diffusion at the edge lowers the electron temperature, enlarges the neutral density profiles and, overall, reduces the average density. For a comparison with the experiments at high densities Langmuir probe data of electron temperature and density profiles are available, though only at low current. Fig. 9 shows temperature and density profiles for helium (top) and hydrogen (bottom) for discharges at different values of n/n_G. In Fig. 9 it is interesting to notice that in the case of He, where densities above Greenwald are

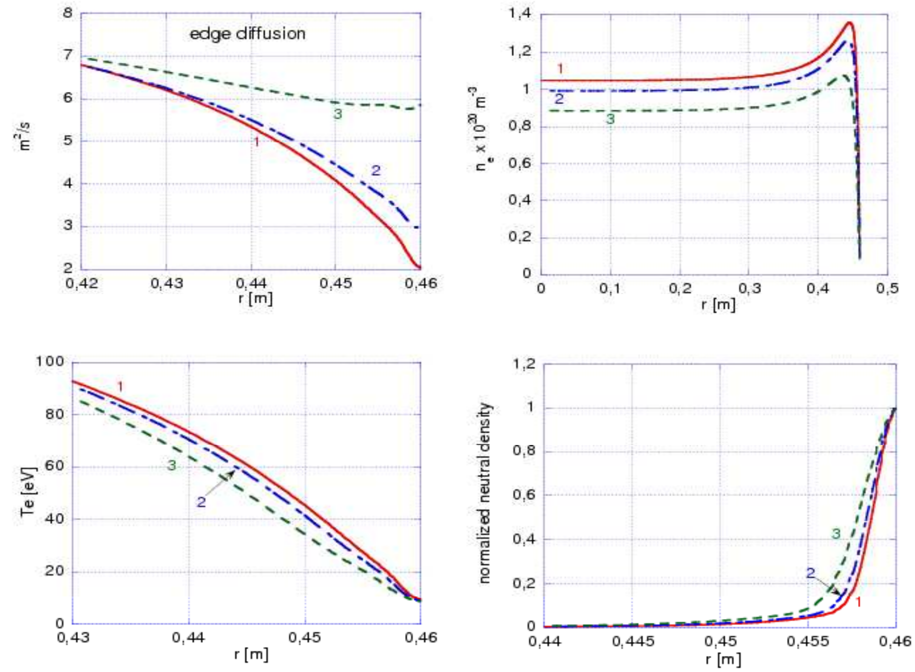

Fig.8. Results of the RITM transport code showing the effect of varying the particle diffusivity at the edge. Case 2 corresponds to the case with REC= 0.85 of Fig. 7. Increasing diffusion (case 3) causes the temperature to decrease, the hydrogen neutral density to broaden its profile and the average density to decrease.

accessible,the electron temperature does not decrease below the ionization potential. For the hydrogen case, at the highest densities available, around $n_G/n= 0.9$, the edge temperature is still higher than the hydrogen ionization potential. Diffusion values evaluated from the ion fluxes and density gradients at density close to or across the limit is of the order of 10 m^2s^{-1} and similar for He and H. These findings together with the simulations above suggest that in RFX the limit is probably associated to a transport that remains fairly high near the density limit while temperatures leading to plasma detachments are not reached.

The code RITM can self-consistently estimate also the fraction of radiated power. For typical carbon and oxygen densities, corresponding in the analysed cases to Z_{eff}= 1.5, the code predicts a relatively low power radiating fraction, of the order of 15-20 %, in analogy with the experiment.

5. Discussion and conclusion

RFX shows an upper boundary of the operating space that matches well the Greenwald density limit and helium discharges can exceed the operating space of hydrogen discharges. This mirrors the phenomenology of Tokamaks despite the quite different global transport properties of the two configurations. Preliminary simulations of RFX plasmas with a self consistent semi-empirical transport code suggest that the combination of edge temperature and transport values like those experimentally evaluated are likely to cause a saturation of the average density building up against an increasing influx at density levels not far from the Greenwald limit. The specific

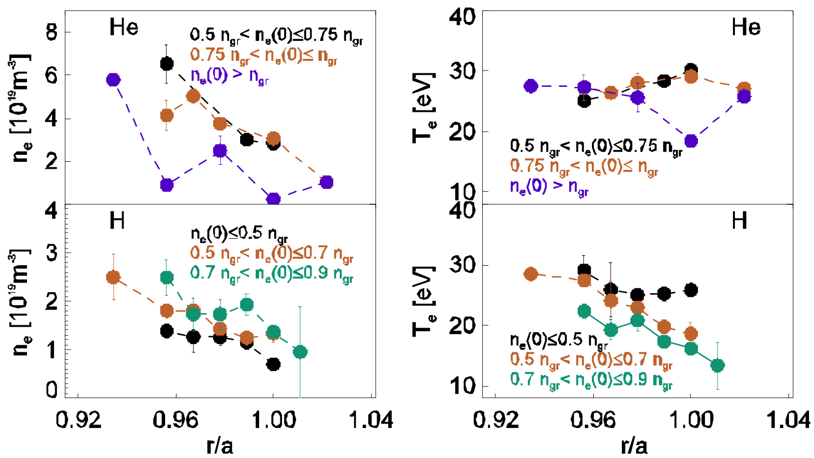

Fig. 9. Edge density and temperature profiles for hydrogen and helium shot resolved by average density.

instabilities that drive transport at the edge of a RFP are matter of current investigation but have not been identified yet. It has however been shown that the nature of the turbulence at the edge of RFX as well as other RFP's is electrostatic, which by the way constitutes a further analogy with Tokamaks [12].

Several aspects however require further clarification, overall the contribution of the wall mode locking to the total radiated power. The radiated fraction of the input power is in general not enough to explain the limit but, in general, the contribution from the privileged PWI region is excluded. The role of this region appears to be more important at high current, where more power is involved and the plasma wall interaction is stronger. Indeed the density operating space at high current does not reach the Greenwald limit, similarly to what happens at all currents in highly radiating impurity seeded discharges. When we include the shots at high current with density evaluated in the region of the wall locked mode the empty region just below the Greenwald limit fills in again, without exceeding the limit. These observations raise the question whether a local limit exists. This is only apparently contradictory with the global nature of the Greenwald limit if we consider that in a RFP, in presence of large toroidally localized error fields the edge, where the magnetic field is mainly poloidal, may have relatively short parallel connection lengths and be topologically isolated from the rest of the plasma.

At low current, presumably the wall mode locking region is not so important, since ensembles with and without densities affected by wall mode locking are not different in the Greenwald plane. Visible CCD images of the wall mode locking region at low currents do not show in fact evidence of strong interaction and radiation. In this case it is possible to state that the Greenwald limit in RFX at low current is not a radiation limit and for a given power input the limit is determined by the transport driven electrostatic instabilities, whose detailed nature is matter of current investigation.

Acknowledgments

The authors wish to thank M. Tokar for the modification to the transport code RITM allowing its application to RFX

References

[1] M. GREENWALD, Plasma Phys. Contr. Fusion 44(2002) R27R80
[2] G. ROSTAGNI, Fus. Eng. and Des., 25 (1995), 301
[3] R. BARTIROMO. et al. Proc. 27th Eur. Conf. on Contr. Fus. And Plasma Phys. (Budapest 2000) vol. 24B (ECA) pp 1380-1383
[4] M.VALISA et al., Journ. Nucl. Mat., vol. 290-293 (2001) .980
[6] M. VALISA et al., Journal of Nuclear Materials 241-243 (1997) 988
[7] A.STABLER et al., Nuclear Fus. 32 (1992) 1557
[8]] Tokar', M.Z., Plasma Phys. Control. Fusion 36 (1994) 1819.
[9] S. ORTOLANI, D. SNACK , Magnetohydrodianmics of Plasma Relaxation,World Scientific, Singapore (1993)
[10] A. B. RECHESTER and M.N. ROSENBLUTH 1978 *Phys. Rev. Lett.* 40 38
[11] D. GREGORATTO et al. *Nucl. Fusion* 38 (1998) 1199-1213
[12]V. ANTONI V.Antoni Recent Res. Devel. Plasmas 2 (2002) 19-34