High density limit in Reversed Field Pinches

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1. Introduction: In Reversed Field Pinches (RFPs) a high density operational limit has been observed [1,2]. As for Tokamaks, in RFPs it can be well described by the Greenwald density[3] $n_G=I_p/\pi a^2$ (10^{20} m^{-3}, MA, n_G max line averaged density). Actually the Greenwald density has been transiently exceeded by pellet injection or careful control of the plasma-wall interaction in both the magnetic configurations, while Stellarators can more easily overcome the limit [4]. This contribution reports the experimental studies carried out in the RFP device RFX-mod to ascertain the physical mechanism underlying the density limit, aiming at discriminating if the Greenwald density represents an intrinsic boundary in the RFP operational space or if methods to overcome it may be found.

2. Experimental pattern: The Greenwald plot found in RFX-mod is shown in fig.1. In the figure plasma currents between 0.3 and 1.5MA are included, showing that at high current low density plasmas are usually produced. In fact, it seems that at high densities it is difficult to obtain the enhanced confinement regimes (QSH, Quasi Single Helicity), which are otherwise spontaneously observed at high current. The QSH is a state where a single tearing mode dominates the m=1 spectrum, thus avoiding magnetic chaos associated to the phase-locking of multiple m=1 modes (multiple Helicity, MH) [5]. The results presented in this paper therefore refer to MH states. When the density approaches the Greenwald value, due to the plasma cooling the resistivity increases, the toroidal flux decreases with a decay rate higher than that of the current, causing a shrink of the current profile and leading to a soft landing of the discharge, rather than to a disruptive end as often observed in Tokamaks The current decays faster with increasing n/n_G, as shown in fig.2.

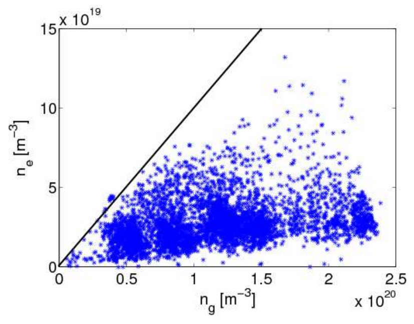

Fig1:RFX-mod Greenwald plot

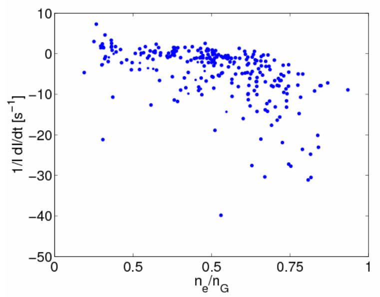

Fig2:normalized current decay rate vs n/n_g

A still open question is whether the high density limit corresponds to a radiative limit or not. In high density discharges a radiation belt, poloidally symmetric and toroidally asymmetric, is observed, whose structure is strictly related to the magnetic topology of the MHD m=0 modes, which resonate at the reversal radius r_s, $q(r_s)=0$ (it is worth mentioning that the RFP magnetic configuration is characterized by the reversal of the toroidal field at the edge, at r/a ~0.9 in the discharges analyzed in this paper). Though the improved control of the radial field at the edge in RFX-mod allows a better control of the plasma-wall interaction, a residual local displacement of the plasma column due to m=1 and m=0 modes is still present. The radiation belt develops at the toroidal position where the plasma shrinks due to the m=0 mode (fig.3a,b) and edge m=0 magnetic islands are well detached from the wall (toroidal angle ≈100° in fig.3). To reconstruct the toroidal pattern of radiation, the modes have been dragged around the torus by means of an externally prescribed rotating perturbation [6], in order to complete at least one toroidal turn during a discharge, providing a full toroidal data-set for each of the time-resolved diagnostics. The radiating belt extends radially by about 1/3 of the plasma radius. Inverted data from the multichord interferometer show that in correspondence to the radiating belt the electron density becomes very hollow, with an edge peak twice as the value in the core (fig.4), locally exceeding the Greenwald value. At the same toroidal position, as shown by Thomson scattering, the electron temperature decreases to values ≤ 20 eV. On the contrary, the main particle source is not localized at the same position as the density peak: the H_α data show a strong increase corresponding to the maximum m=1 bulging (toroidal angle=0° in fig.3), where the plasma-wall interaction is stronger (fig.3b). The edge plasma flow has been measured by the Gas Puffing Imaging diagnostic, showing (fig. 3a) that the velocity changes sign in the region where the m=0 deformation shrinks, corresponding to an inversion of the radial electric field. Particles, mainly produced at the m=1 bulging (maximum H_α), are then conveyed toroidally towards the region of the m=0 shrinking, where, in absence of any additional diffusion mechanism, they can accumulate, resulting in a local increase of

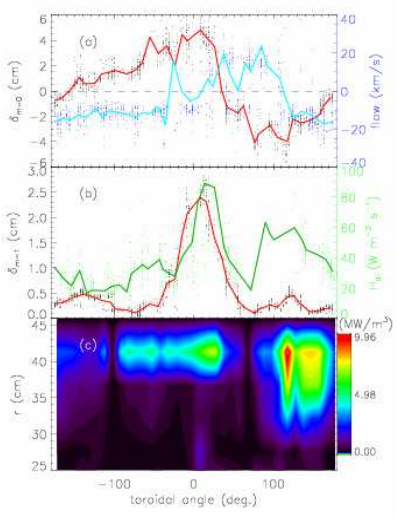

Fig3: as a function of the toroidal angle: (a) m=0 displacement (red) and plasma flow(cyan) (b)m=1 displacement (red) and Ha brightness(green) (c) plasma radiation contour plot

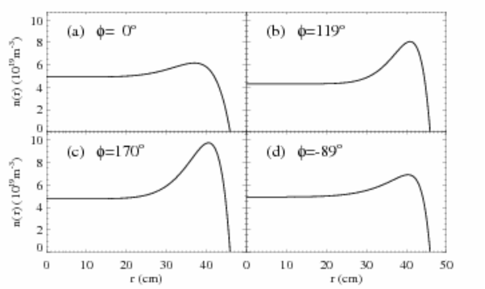

Fig. 4 density profiles at times corresponding to different toroidal location of the magnetic perturbation

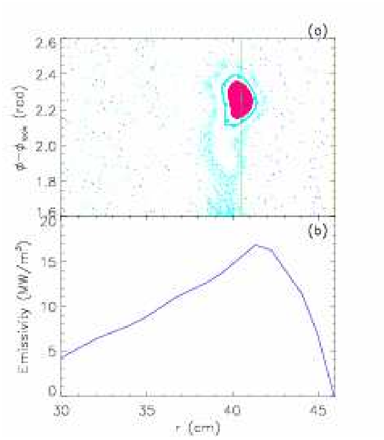

Fig5 (a) reconstruction of the magnetic topology by ORBIT (b) total radiation emissivity profile

density and radiation. In order to verify this pattern a reconstruction of the magnetic topology with ray tracing (FLIT,[7]) and guiding centre (ORBIT,[8]) codes has been done: an example is shown in fig.5. The radial location of the maximum value of radiation is correlated with the reversal radius r_s, i.e. the m=0 island. The thickness of the radiating layer (about 15 cm) is larger than the radial extension of the island, suggesting that the radiation is not only due to particles accumulated inside the island, though the m=0 perturbation plays a crucial role in determining the density limit

3. Discussion: The decay of the plasma current when approaching the Greenwald density has been reproduced by means of a new numerical tool, originating from the integration of two 1D transport codes. The first one solves the safety factor q(r,t) evolution assuming an Ohm's law with an alpha-dynamo term and a Spitzer's like resistivity, together with the main gas transport equations, continuity and heat balance. The second one, derived from RITM [9], computes the neutral and impurity related terms in the main gas equations (e.g. radiation losses, sources from neutrals, Zeff profile) solving the transport equations for every impurity species. Since, as mentioned, in the high density experiments discussed here the core transport is likely to be dominated by magnetic field chaos, the main gas transport has been described by a collisional chaotic model [10] for the main gas, whereas the transport for impurities is assumed to be ruled by fixed transport coefficients experimentally determined [11]. As a boundary condition, q(a)<0 has been fixed. The evolution time scale is determined by the resistive time τ_R (~0.5s). Fig. 6 shows the effect of an increase of the density on plasma current and temperature at the steady state. At t=0.7 τ_R a density boost takes place, by means of a forced linear increase of the main gas influx. As a consequence, the density increases as a whole by a factor about 3, turning into a hollow shape, Fig 6a. The impact on current density and electron temperature is shown in frames (b) and (c). The density increase leads to a decrease of temperature, accompanied by a decrease of the plasma

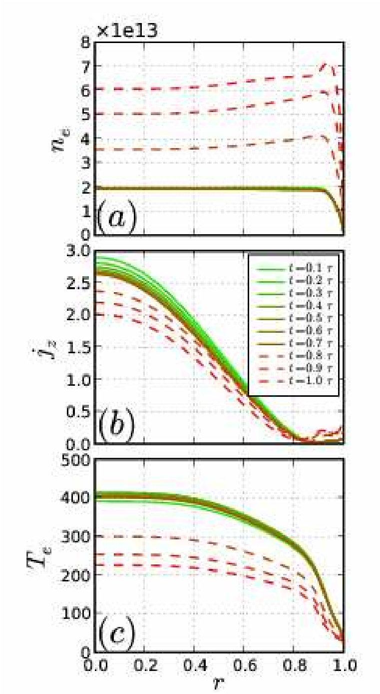

Fig.6: density(a), current density (b) and Te (c) of a simulated discharge with a linearly increasing influx injection (dotted lines).

current. Indeed the dynamo field, assumed to be fixed as it is at the beginning of the particle influx, is not able to sustain the current against the increased resistivity. It is worth noting that P_{rad} becomes locally of the same order than P_{ohm}, as measured by the bolometric tomography . The phenomenology described for the radiation in high density discharges, i.e. localized increase of density with consequent increased radiation and decreased temperature resembles that of MARFES, observed in Tokamaks [1,12]; as in Tokamaks and Stellarators, also in RFPs the high density limit can be associated to a radiative localized instability. The application of a simple linear estimate as explained in [13] can help in determining whether the density gradient measured at the edge can develop a radiative instability or not : the condition for a radiative instability may be written as:

$$\phi \frac{a\nabla n}{n} > (1-\phi)^2 E_\phi I / 2\kappa T_a$$

where $\phi = P_{rad}/P_{ohm}$, T_a is the edge temperature and κ is the edge thermal diffusivity. At fixed ϕ, a certain normalized density gradient can destabilize the discharge proportionally to the parameter $h=E_\phi I/2\kappa T_a$, ("instability parameter" for the radiative limit): the higher h, the larger density gradient is necessary to develop an instability. High current discharges in RFX-mod are characterized by smaller h values when compared to the low current ones, which is consistent with the operative difficulty in sustaining high density and high-current discharges.

4. Conclusion: In RFX-mod when the plasma approaches the Greenwald limit, due to the enhanced plasma resistance a soft landing of the discharge is observed: this behavior has been reproduced by means of a 1-dim transport model with self consistent resistivity and dynamo field maintained fixed during the density increase. At the same time, a poloidal high radiation belt appears, well correlated to detached m=0 islands (m=0 shrinking), and corresponding to a local inversion of the plasma flow and to an increased edge density. The clear relation between the development of the highly radiating belt and the magnetic topology points towards a reduction of the m=0 activity as a path to overcome the Greenwald density.

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