Characterization of external electron temperature profiles in the RFX-mod Reversed Field Pinch

A. Scaggion, M.Agostini, L.Carraro, A.Fassina, R.Lorenzini,
B.Momo, S.Munaretto, M.E.Puiatti, G.Spizzo, M.Valisa and N.Vianello
Consorzio RFX, Associazione Euratom-ENEA sulla fusione, Padova, Italy

Introduction In RFX-mod, core confinement properties are closely related to the different magnetic topologies, which are tightly linked to the plasma current value. Up to 800 kA, several MHD modes with similar amplitudes are present: plasma is in the chaotic Multiple Helicity (MH) state characterized by flat electron density and temperature profiles. Increasing the plasma current the system achieves the so called Quasi Single Helicity (QSH) state, where only one mode dominates the spectrum (m=1, n=-7), while the energy of the other secondary modes decreases. For plasma current beyond 1 MA the separatrix can be expelled and the plasma evolves towards a helical equilibrium: the SHAx (Single Helical AXis) state is thus achieved. These states are characterized by the spontaneous appearance of an ordered structure in the plasma core with much higher temperature, peaked density and enhanced confinement[1]. This region of high confinement extends towards $r/a = 0.4$ and involves only one third of the plasma volume. On the other hand the remaining region, extending from $r/a = 0.4$ towards the last closed magnetic surface, seems to be not that sensitive to the different magnetic topologies. Given the large plasma volume enclosed in this domain, improvements of global confinement are closely linked to the identification of the physical mechanisms occurring there. Aiming at their comprehension we performed a wide-ranging characterization of electron temperature gradients extending across $0.7 < r/a < 0.95$.

Our analysis has been carried out on discharges collected from the beginning of 2007 to the end of 2010: plasma current varies from 200 kA to 2 MA and electron density covers two orders of magnitude, $2 \cdot 10^{18}\text{m}^{-3} < n_e < 1.3 \cdot 10^{20}\text{m}^{-3}$. The database contains only hydrogen discharges, performed with the ‘Clean Mode Control’ scheme[2] and includes MH, QSH and SHAx states. In the RFX-mod experiment electron temperature measurement is performed using the main Thomson Scattering (TS), which probes the region $-0.95 < r/a < 0.85$ with high spatial (7mm) and time resolution (40 Hz) [3]. Besides the main TS, an edge Thomson Scattering system[4] has been operating in a subset of discharges of this database. It enables the measurement of electron temperature and density in the region $0.7 < r/a < 0.95$ once in a discharge. Gradient evaluation has been performed using the *Fermi function* similarly to Tokamak community where the *tanh* fit is used[5]. To evaluate gradients using this fit, we took into account the region $0.65 < r/a < 0.85$ (10 main TS measurement points) or 0.65 < r/a < 0.95 (10 main TS + 6 edge TS measurement points), when possible. We will refer to gradients as the maximum gradient occurring in the region between $r/a = 0.7$ and $r/a = 0.8$. Given the mathematical properties of the Fermi function the maximum gradient is always located in the middle of the region where the temperature decrease occurs.

Scaling with current and density The positive scaling of plasma confinement with plasma current which characterizes the core plasma is found also in the edge. The edge ∇T_e increases almost linearly, as shown in Figure 1(a). This evidence extends the scaling reported in Ref.

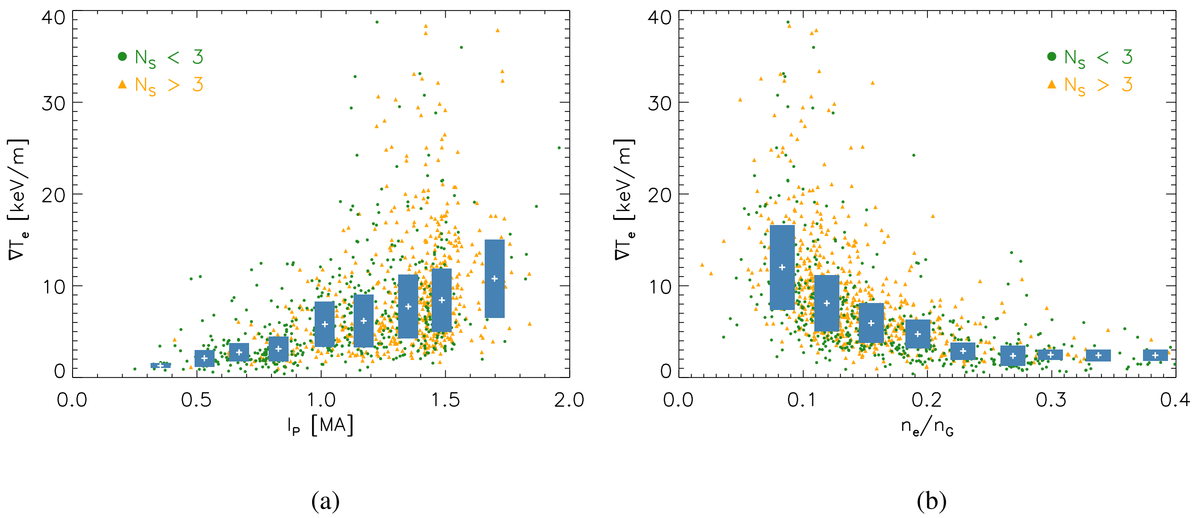


Figure 1: Edge electron temperature gradient as a function of plasma current (a) and Greenwald fraction (b) for different topologies: MH (green dots), QSH and SHAx (orange triangles). White crosses and blue boxes represent averages with their rms.

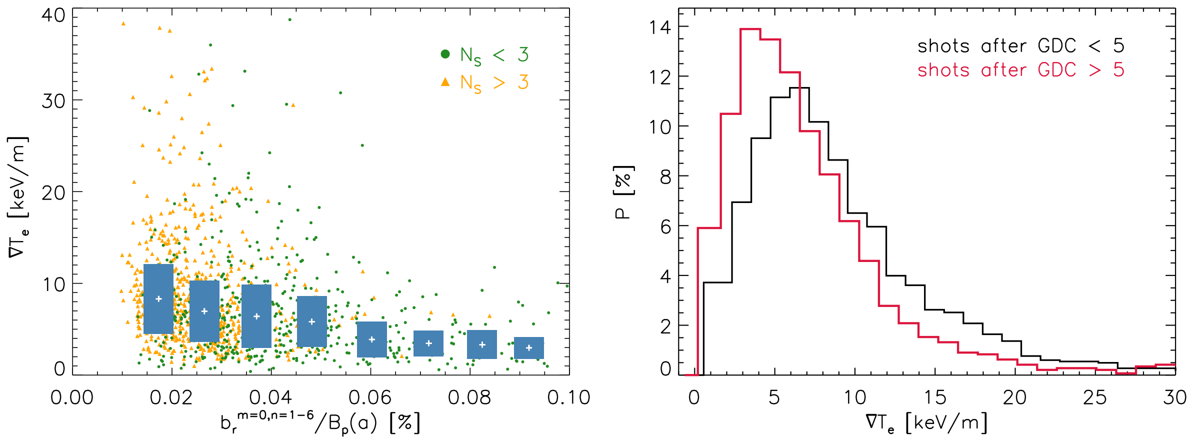
[6], regardless of the different magnetic topology. As a matter of fact, looking at Figure 1(a) no net differences arise between green dots, representing MH states, and orange triangles collected during QSH and SHAx states. The two populations are separated according to the spectral width $N_S = \left[\sum \left(W_{n,\varphi}/\sum W_{n,\varphi}\right)^2\right]^{-1}$, where $W_{n,\varphi}$ is the magnetic energy pertaining to the toroidal component of the $(1,n)$ MHD mode. N_S is the number of significant mode in the MHD spectrum ($N_S = 1$ for a pure single mode perturbation). $N_S = 3$ has been chosen as a threshold for the transition from MH to QSH state[7]. The observed linear dependence is due to the linear increase of core temperature with current[8], while the temperature of the outermost plasma region ($r/a > 0.95$) is almost constant[9]. More specifically, the proportionality coefficients between temperature and current at different radii are: 0.42(±2%) keV/MA in the plasma center,

0.32(±3%) keV/MA at $r/a = 0.75$ and 0.1(±6%) keV/MA at $r/a = 0.85$. A clear decrease of ∇T_e with normalized electron density is shown in Figure 1(b). The highest gradients occur only at low collisionality ($n_e/n_G \sim 0.1$), while at $n_e/n_G \sim 0.2$ ∇T_e assumes values of few keV/m. Further increasing the collisionality the edge region undergoes a strong degradation which in turn induces a degradation of global plasma parameters[11], emphasizing the importance of this region for good global performances. It has to be stressed that central electron pressure is found to increase almost linearly with current. So the decrease of ∇T_e with normalized density can not be ascribed to a fixed value of the product $n_e T_e$.

Extremely high gradients laying above the linear scaling may occur for current values above 1 MA (see Figure 1(a)). These discharges represent the promising External Temperature Barriers[10] that will be treated separately at the end of the paper.

Influence of plasma boundary As stated in [10] and previously recalled, a change of the magnetic topology does not directly affect the region outside the plasma core. Anyway, the improved plasma performances are also related to an amelioration of the magnetic plasma boundary conditions due to reduced chaos in the plasma edge. An experimental evidence is reported in [6], where the decrease of edge temperature gradients with increasing amplitude of the secondary $m = 1$ modes is shown. Furthermore, the presence of the helical topology induces some indirect benefits on plasma wall interaction (PWI) as well. In fact, when the helical topology is set, the dominant (1,-7) mode modulates the $m = 0$ island chain, namely the major responsible for the PWI[11]. The direct influence of the PWI on ∇T_e can be measured through the amplitude of the secondary $m = 0$ modes, which resonate at the plasma edge, as shown in Figure 2(a). When the amplitude of $m = 0$ modes decreases, a milder PWI is expected, and higher ∇T_e are measured. The two populations of discharges, again separated according to N_S value, do not show significant differences but the lower average amplitude of secondary $m = 0$ modes characterizing discharges with $N_S > 3$.

In order to highlight the impact of plasma boundary on temperature gradient we use the proximity of a given plasma discharge to a Helium Glow Discharge Cleaning (GDC) as an estimator of the wall condition. Figure 2(b) depicts how the probability distribution function of ∇T_e changes comparing shots performed just after a GDC (black curve) against shots performed later than that (red curve). When the first wall is conditioned (just after a GDC) the probability of obtaining higher gradient is larger compared to non-conditioned wall one. This evidence suggests that an amelioration of the edge condition can be obtained reducing the PWI (lower $m = 0$ amplitude) and its impact (wall conditioning). Moreover, the dependence of ∇T_e on wall conditions



(a) (b)

Figure 2: (a) Electron temperature gradient as a function of $m = 0$ secondary modes amplitude for different topologies: MH (green dots), QSH and SHAx (orange triangles). White crosses and blue boxes represent averages with their rms. (b) Probability distribution function of ∇T_e for different wall conditions: shots near a GDC (black), shots far from a GDC (red).

suggests that recycling processes play a role in determining the edge gradients[11]. It has to be stressed that the two populations of Figure 2(b) have the same current and density probability distribution function despite the different wall conditions.

Edge Temperature Barriers The extremely high edge gradients, $20\text{keV/m} < \nabla T_e < 40\text{keV/m}$, occur in a quite narrow parameter space: indeed they only appears at low collisionality and high current, even if they seem to be independent of the central electron temperature. As the standard gradients do, they are not linked to the magnetic topology and they are favored by conditioned first wall. When these high temperature shoulders develop, an enhancement of plasma energy content up to 30% is observed[10]. Anyway their characterization is still an ongoing work.

References

[1] R. Lorenzini et al *Nature Phys.* **5** 570 (2009)
[2] P. Zanca, L. Marrelli, G. Manduchi, G. Marchiori *Nucl. Fusion* **47** 1425 (2007)
[3] A. Alfier, R. Pasqualotto *Rev. Sci. Instrum.* **78** 013505 (2007)
[4] A. Alfier et al *Plasma Phys. Control. Fusion* **52** 035004 (2010)
[5] R.J. Groebner et al *Nucl. Fusion* **41** 1789 (2001)
[6] N. Vianello et al *Nucl. Fusion* **49** 045008 (2009)
[7] P. Martin et al *Plasma Phys. Control. Fusion* **49** A177 (2010) and reference therein
[8] P. Innocente et al *Nucl. Fusion* **49** 115022 (2009)
[9] M. Agostini et al *Rev. Sci. Instrum.* **81** 10D715 (2010)
[10] M. E. Puiatti et al *Nucl. Fusion* **51** 073038 (2011)
[11] P. Scarin et al *Nucl. Fusion* **51** 073002 (2011) and reference therein