RFX-mod performance towards 2 MA plasma current operation

Fulvio Auriemma, Paolo Franz, Paolo Innocente, Rita Lorenzini, Emilio Martines,
Paolo Piovesan, Monica Spolaore

Consorzio RFX, Associazione Euratom-ENEA sulla Fusione, C.so Stati Uniti 4, 35127 Padova, Italy

Introduction

The Reversed Field eXperiment (RFX-mod), is the only reversed field pinch (RFP) machine operating at plasma current above 1.0 MA. Such current level is one of the ingredients needed to spontaneously trigger the enhanced energy and particles confinement regime, named Single Helical Axis (SHAx) [1] , where a single tearing mode grows up to saturation at expenses of the other modes, and the configuration develops a helical equilibrium.

Data from last year experiments extended the RFX-mod database to higher current, up to 2.0 MA, its maximum project value. In this work a set of discharges including a wide range of plasma current and density has been selected to study the confinement scaling laws as a function of the main plasma parameters. The assessment of such laws is a key factor to control the mechanism ruling the performance and also for potential upgrades of the facility. Once the behavior of RFX-mod has been discussed, a comparison in terms of confinement properties with other RFP devices will be presented.

The plasma parameters considered in the analysis are the plasma current and density, as in classical scaling laws [2,3] and their impact on the electron temperature and energy confinement time. Furthermore the amplitude of the magnetic field fluctuation at the edge has been included in the analysis, indeed a peculiarity of RFX-mod is a full-covering saddle coils system for the control of the MHD instabilities [8].

The database

The database has been built with the following selection (fig. 1): the plasma current ranges from 0.5 to 2.0 MA, the density from 0.05 to 0.4 of the Greenwald density $n_G=(I_p/\pi a^2)\ x\ 10^{20}$ m^{-3}, where Ip is the plasma current in MA and a=0.459 m is the minor radius of the plasma column. The safety factor at the edge $q(a)=a/R_0 B_t(a)/B_p(a)$ ranges from -0.02 to -0.001, being R_0=2 m the major radius of the torus, $B_t(a)$ and $B_p(a)$ respectively the toroidal and poloidal field at the edge. In figure 1(a) the colors refer to different density ranges: going from purple to brown the average n/n_G are 0.05, 0.12, 0.18 and 0.30. Data for each discharge has been computed as an average in the time period where the spectral width of the magnetic perturbations N_s is below 1.3 ($N_S = \left(\sum_{n=-7-15}\left(b_n^2/\sum_i b_i^2\right)^2\right)^{-1}$ where b_n is the toroidal harmonic of the perturbation with poloidal number m=1 and toroidal number n), in order to include in the analysis only the SHAx regimes. If during the discharge more than one time interval with $N_s < 1.3$ occurs (this is the typical situation), then the data from all the periods are averaged in order to obtain a single point for each discharge.

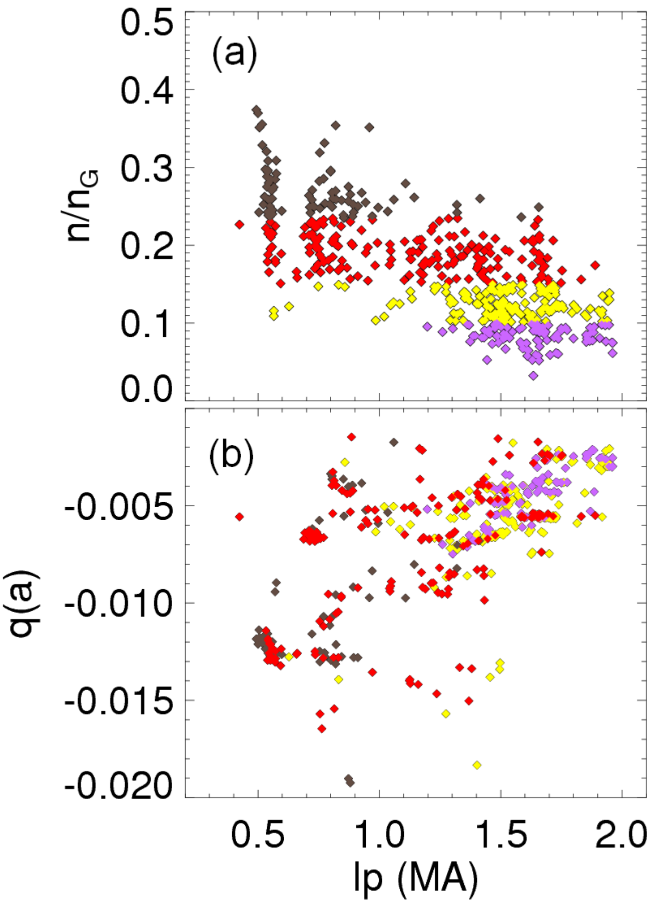

Figure 1 (a) plasma density and (b) safety factor at the edge for the database presented as functions of the plasma current, different density classes are identified by different color.

The energy confinement time

The extension of the plasma current range up to 2 MA confirms that the normalized amplitude of both the toroidal and radial secondary modes

$$(b^{t,r}_{sec} = \frac{\left[\sum_{n=-8}^{-15} (b^{t,r}_{n})^2 \right]^{0.5}}{\left[B_p(a)^2 + B_t(a)^2 \right]^{0.5}} ,$$

where the ñt,rò suffix indicates the toroidal or radial component) decreases with the plasma current, whereas the dominant mode (m=1, n=-7) increases. The electron temperature, measured by the double filter and the Thomson scattering diagnostics, shows an almost linear increasing trend, reaching 1.4 keV at 2.0 MA.

The global energy confinement time τ_E shows a similar increasing behavior up to I_p = 1.8 MA, whereas at higher current it does not increases its value, as shown in figure 2 (a). This is due to a mix of causes: as first the operational regime at the highest currents has been reached in a small number of discharges and it is not yet well optimized, where slightly higher magnetic fluctuations amplitude are present, inducing a degradation of the confinement. Hence, in order to limit the total power released to the first wall, a more safe low density regimes has been explored, as shown in figure 1. Moreover the low density limits itself the τ_E, as shown by the purple and yellow points related with the two lower density classes. Figures 1 and 2 show also that the highest density values (brown dots) have been accessed only at I_p<1 MA, where low τ_E value are obtained. Anyway some experiment aimed at obtaining high current and high density plasma have been performed with Hydrogen iced pellet injection. Figure 2(b) shows the τ_E as a function of the plasma density normalized to Greenwald limit. The pellet injection effect is shown by the blue dots linked by the arrow: after the pellet enters the plasma the τ_E increases transiently of 70% going back to the pre-injection value after about 5 ms.

Two multiparametric regression analysis have been performed: the first computing the best fit of the τ_E as a function of plasma density, current and amplitude of the secondary modes. It confirms the past analyses [4], carried out on a database with a plasma current 20% lower.

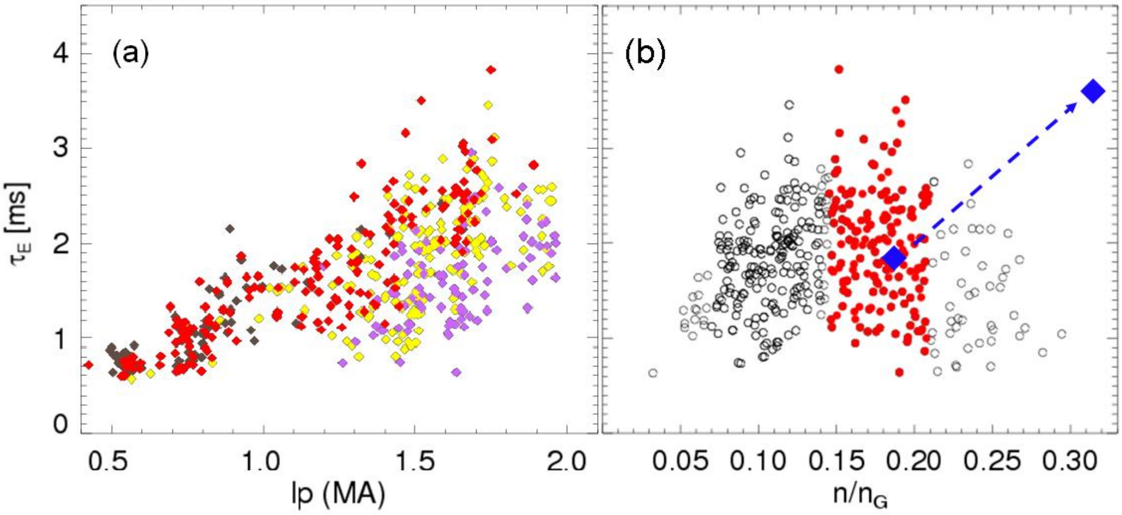

Figure 2: (a) linear increase of the energy confinement time with the plasma current. The τ_E shows a linear trend with I_p in the density class marked in red (n/n_G = 0.15-0.25) (b) τ_E as a function of the n/n_G. The blue diamonds shows the τ_E increase after the pellet injection, as indicated by the arrows.

The main difference is that the dependence on the secondary modes amplitude is slightly weaker, going from (-0.8) to (-0.6). The regression result turns out $\tau_E = C_1\left(I_p^{0.8} n^{0.5} b_{sec}^{t}{}^{-0.6}\right)$. The second regression analysis has been computed assuming only a dependence from plasma current and density normalized to Greenwald limit: $\tau_E = C_2\left[I_p^{1.2}\left(n/n_G\right)^{0.6}\right]$. The Connor and Taylor CT scaling law [2], based on the resistive fluid turbulence (g-mode) theory, gives $\tau_E^{CT} \propto I_P^{1.5}\left(n/n_G\right)^{-1.5}$, with a decreasing trend with the density, not observed in the RFX machine. A behavior similar to the CT has been found experimentally instead in TPE devices [3]: $\tau_E^{TPE} \propto I_P^{0.6}\left(n/n_G\right)^{-0.6}$, where a much weaker increase with plasma current is also observed.

Multi-device comparison

The Werley and Di Marco database [5] has been based on best published results of old small experiments. Plotting in a log-log scale the product $n\tau_E$ as a function of the current, a linear relation is found, as shown in figure 3 by the black full diamonds. Extrapolating that trend we have an indication of the theoretical performance of RFX-mod at 2.0 MA. This goal requires operating the machine at high current, with density Greenwald fraction close to 1. The 4 density classes (colored diamonds) are well ordered: data align along parallel line, going close to the Di Marco fit when density increases (in figure 3 the red line represents the experimental fit of the red data). This effect is confirmed also by pellet injection experiments (blue diamonds) that show how the point moves towards the Werley and Di Marco prediction when density goes up. It is important to notice a similar behavior also at low current, where higher n/n_G are easily accessed: the brown full diamonds at Ip ~0.5 MA are closer to the black data

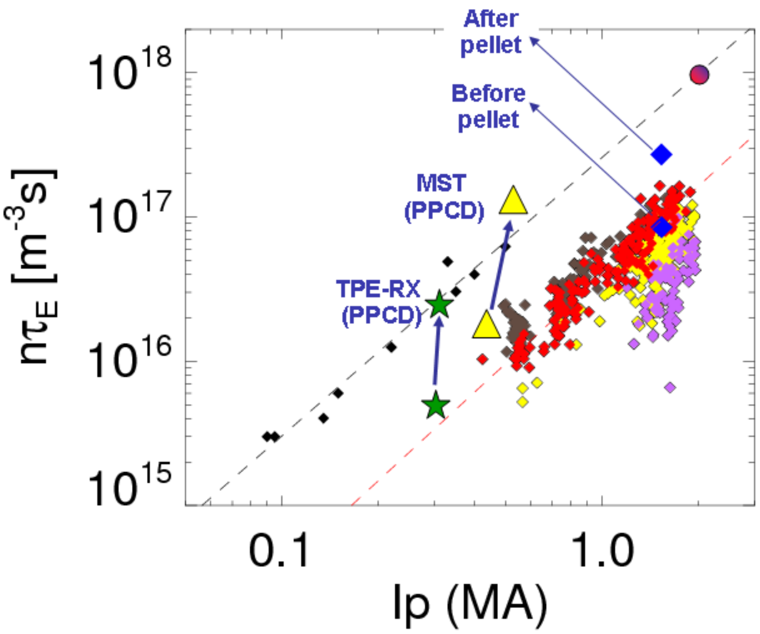

Figure 3: $n\tau_E$ product versus the plasma current for old devices (black diamonds). The RFX-mod data are plotted in coloured diamonds, with the same meaning of figure 1 and 2. The stars and triangles represent recent data from TPE and MST devices respectively, during standard and PPCD experiment. The full red/blue circle is the theoretical extrapolated value for RFX-mod at 2 MA.

than the other density classes. Finally, the TPE-RX (star) [3] and MST (triangle) [6,7] data are shown: also for these machines the standard operation point is compatible with RFX-mod database and the performance can be increased with transient technique, as the Pulsed Poloidal Current Drive.

Conclusion

The τ_E has been computed at RFX-mod on a wide range of the main operational parameters, in particular extending previous analysis at higher current, up to 2.0 MA. The observed trends suggest on the one hand that the high density regimes are favorable in term of confinement properties. This could be explained in the framework of a reduced but still present stochastic transport mechanism at least in a region of the plasma, where the higher collisionality limits the parallel transport. On the other hand the increased τ_E value at higher plasma current and at lower amplitude of the magnetic perturbations, points out that the path towards a regime with lower and lower secondary modes shall be covered to achieve high confinement regimes in the RFP magnetic configuration.

Acknowledgements: *This work, supported by the European Communities under the contract of Association between EURATOM/ENEA, was carried out within the framework of the European Fusion Development Agreement.*

References

[1] R. Lorenzini et al., Nature Physics **5** (2009) 570-574
[2] Connor and Taylor, Phys Fluids, 27, 2676 (1984)
[3] Yagi et al., Nucl. Fusion 43, 1787 (2003)
[4] Innocente *et al.* Nucl. Fus. 49 (2009)
[5] Werley *et al.*, Nucl. Fusion 36, 629 (1996)
[6] Chapman et al., Phys. Plasmas, Vol 9, No. 5, 2066 (2002)
[7] Chapman et al., Nucl. Fusion 49, 104020 (2009)
[8] Marrelli L. et al 2007 Plasma Phys. Control. Fusion 49 B359