Confinement properties in RFX-mod with active control of the boundary magnetic field

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Introduction: The establishment of the scaling laws of the global confinement properties of fusion devices in stationary conditions is a crucial point both to design new experiments than to propose improvement to the operating devices. In that prospect the modified RFX (RFX-mod) experiment provide new information for the RFP devices thank to the thin shell, the active control of the boundary radial magnetic field[1] and a good set of magnetic and kinetic diagnostics. The thin shell confinement properties with and without radial field active control can also be directly compared to those of the previous thick shell operation since RFX-mod keeps the previous magnetic and geometric parameters.

RFX confinement database: To perform reliable scaling studies, a database has been realised and, to reduce errors, all kinetic quantities are carefully qualified. In particular Thomson Scattering[2] measurements are used for electron temperature profiles, electron density profiles are computed from multi-chord interferometer measurements[3] and medium radius ion temperature is deduced by Doppler broadening of OVII lines. Poloidal beta (β_p) and energy confinement time (τ_E) are computed integrating temperature and electron density profiles, while the ion temperature profile is assumed equal to the electron temperature profile.

In fig.1 the allowable data-points are plotted for the three main RFX operation modes: the old thick shell experiments and the new thin shell experiments without and with active control of boundary radial field (Virtual Shell). The figure shows that the new experiments do not completely overlap the previous one in the (I_p, I_p/N) parameters space ($N=\pi a^2 <n>$ is the line density), in particular
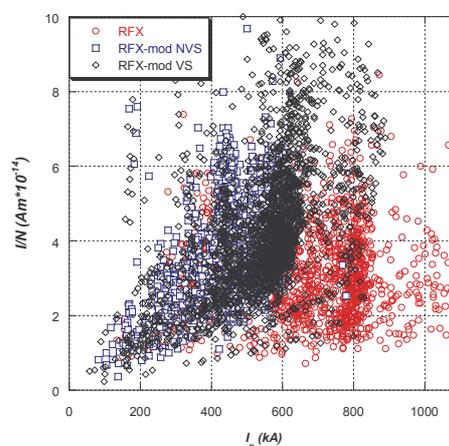

Fig. 1 Confinement data-points for RFX thick shell, RFX-mod standard operation (NVS) and RFX-mod with radial field active control (VS).

currents over 700 kA were explored only by the previous RFX configuration. Furthermore RFX-mod operates typically at a larger I_p/N parameter than the old one.

The following confinement analysis has been performed assuming $T_i=T_e$ to compute β_p and τ_E because after boronization procedure the OVII line emission is blended with Boron lines and the measurements of T_i became very uncertain. The $T_i=T_e$ assumption has been verified by comparing T_i with T_e, where both are allowable. As an example, for Virtual Shell operation, figure 2 shown that the two temperatures are approximately equal, with larger T_i at lower temperature and smaller at larger temperature. To ascribe the difference to ion heating mechanisms is not possible at the moment, since it could be due to uncertainty in evaluating OVII radial position. The measurements of T_i with a neutral beam, recently installed on RFX-mod, will clarify the situation. In
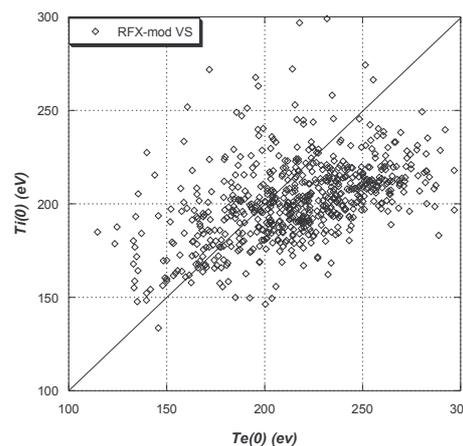

Fig. 2: Central ion temperature versus central electron temperature.
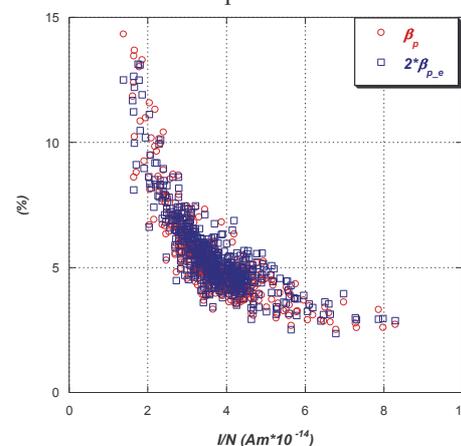
Fig. 3: Total poloidal β and two times electron poloidal β versus I_p/N parameter.

any case previous difference does not seem to affect scaling law as confirmed from figure 3 where β_p (computed using both measured T_e and T_i) and $2\beta_{p\_e}$ shown the same dependence from I_p/N parameter.

Confinement properties: The results obtained for the three RFX experimental conditions are summarized in figure 4, where poloidal beta and energy confinement time are plotted for all the allowable data. From the figure it is already possible to extract some information: poloidal beta is similar for both operation modes of the thin shell RFX-mod experiments and is slightly larger than that of the thick shell RFX. Energy confinement time instead is on average 50% larger for the Virtual Shell operation compared the old RFX and about two times larger than the RFX-mod standard operation.

Previous results are better quantified averaging β_p and τ_E in a small parameter interval in stationary discharge condition (low dI_p/dt). The I_p=550÷600 kA, I_p/N=3.5÷4.0·10^{-14} Am and F=-0.25÷-0.05 ($F=B_t(a)/<B_t>$) interval is selected because a large number of data is

allowable in it. The following average values are obtained: $<\beta_p>=3.4$ %, $<\beta_p>_{NVS}=4$ % and $<\beta_p>_{VS}=4.6$ % for poloidal beta and $<\tau_E>=0.58$ ms, $<\tau_E>_{NVS}=0.36$ ms $<\tau_E>_{VS}=0.80$ ms for energy confinement time.

Scaling laws: To get some insight on the phenomena underlain present results we study the dependence of the confinement from the main plasma parameters.

The β_p presents the strongest scaling of the two confinement quantities, all the virtual shell data of stationary discharges can be fitted by a single I_p/N parameter exponential fit (fig. 5). The same fit reproduces very well the RFX-mod standard discharges also. The situation is slightly different for the RFX thick shell discharges: those with a plasma current lower than 700 kA (the same explored by the RFX-mod experiments) are better described by a two parameters fit $\beta_p(\%)=7.2\cdot10^{-9}I_p^{-0.51}(I_p/N)^{-0.55}$ (A,Am).

Less evident is the scaling law for the energy confinement time, the data of the three RFX configurations are not compatible with the Connor-Taylor[4] scaling law: $\tau_E=ca^2I_p^3/N^{3/2}$ (where c is a constant theoretically equal to 10.2) which was derived assuming that resistive fluid turbulence (g-modes) limit the energy confinement. The inability of the Connor-Taylor to fit RFX data was expected since the same scaling law predicts also a constant poloidal beta. Indeed it has to be mentioned that the RFX-mod energy confinement times of the better discharges is not far from the value expected from Connor-Taylor scaling law with c obtained fitting the energy confinement time of smaller RFP devices[5].
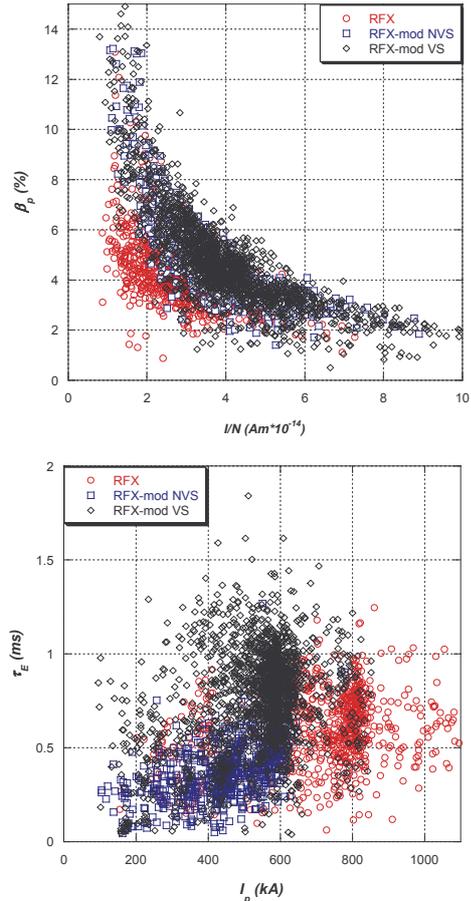

Fig. 4: Poloidal beta and energy confinement time for all the tree experimental conditions.
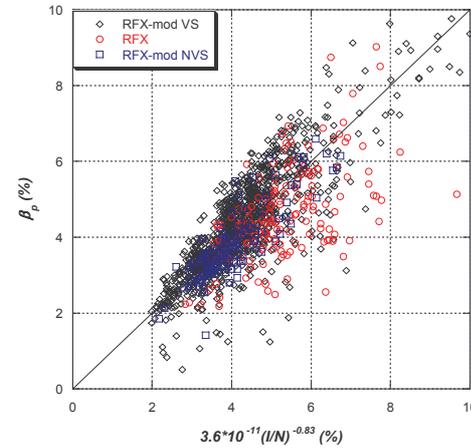

Fig. 5: Poloidal beta single parameter least square fit of the virtual shell experiments. The same fit is used for RFX-mod standard discharges and RFX discharges.

A good scaling law has been obtained for the VS data by a three parameters fit using I_p, I_p/N and the square of the normalized internal radial field $b=<b_r^2(r)/B_p(a)^2>^{1/2}$ of modes with m=1 and n=-15÷-8. For F=-0.23÷-0.18 the least square fit of τ_E is drawn in figure 6. In the same figure RFX-mod standard discharges results are plotted using the fit obtained with the VS data only. It is possible to see that the fit is able to describe relatively well both situations although there is a factor of about 5 in b between standard and VS discharges. For RFX-mod similar, but less good fit, can be obtained for other F intervals, while for RFX only worst correlations can be found. The beneficial effect of the boundary control to the internal plasma apparent from the explicit dependence of τ_E from b is confirmed by the peaking of the temperature profile lowering b as shown in figure 7.

Conclusions: The first statistical analysis of RFX confinement properties has been presented, first results confirm that the thin shell solution supplemented by a feedback system to control edge radial field improves confinement properties while allowing in principle stationary discharges. First scaling law of the new configuration provide better plasma current dependence than the thick shell RFX, allowing also a large poloidal beta, probably thank to a better first wall.
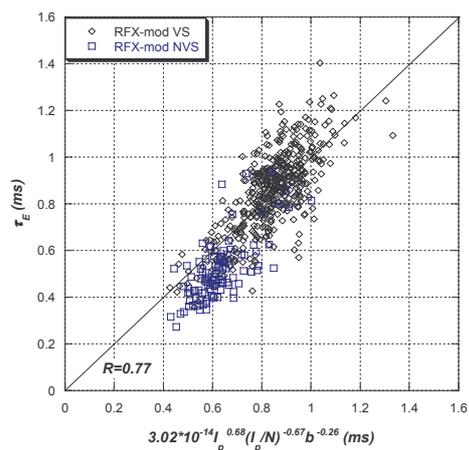

Fig. 6: Three parameters fit of τ_E of VS discharges applied to both VS and standard RFX-mod discharges.
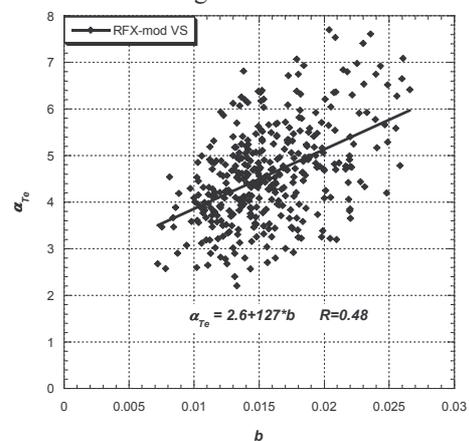

Fig. 7: Profile exponent of the electron temperature profile $T_e(r)=T_{eo}(1-r^\alpha)$.

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