Observation and interpretation of “profile consistency” features in the TCV tokamak

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A large variety of plasma conditions has been created in TCV (Tokamak à Configuration Variable, B_T<1.5T, R_0=0.88m, a<0.25m). They include limited and diverted discharges with elongations in the range 1 to 2.58, triangularities between -0.7 and 1 as well as ‘square’ shapes with plasma currents in the range 0.1-1MA. Over the entire range of quasi-stationary ohmic conditions investigated we observe a correlation between electron pressure profiles and conductivity profiles, suggesting that $\langle p\rangle/p(0) \approx \langle j\rangle/j(0)$, where $\langle\ \rangle$ refers to an average over the volume or respectively the cross sectional area of the plasma. The profiles become broader as the average current density is increased. These “profile consistency” features are in apparent agreement with theoretical considerations based on minimum energy states of the plasma [1,2] or on stationary entropy [3]. We show that these observations can also be accounted for by the effects of sawtooth activity.

Experimental observations and theoretical models supporting the idea that electron temperature and/or the pressure and/or current density in tokamaks preferentially assume certain privileged profile shapes have been reported for more than two decades [1-5]. Arunasalam et al [5] have proposed a practical working definition of this principle motivated by tearing mode stability considerations. It postulates the existence of unique, natural profile shapes for j(r) and because of ohmic relaxation, for the shape of T_e(r) or $T_e^{3/2}(r)$. The consequences of the postulate, as given in [5], are 1) that the normalized sawtooth inversion radius, $\rho_{inv}= r_{inv}/a$ and 2) the broadness of the temperature profile $\langle T_e\rangle/T_e(0)$ are device independent and are functions of $1/q_a$ only. The same authors propose a third consequence expressed as $T_{e0}^{3/2} \propto I_p R_0/(c_\sigma a^2 V_{loop} F(1/q_a))$, which merely combines the postulation of universal current profiles characterized by $\langle j\rangle/j_0 = F(1/q_a)$ and the assumption of Spitzer conductivity, $\sigma_{Spit} = c_\sigma T_e^{3/2}$. The widths of “natural” current and pressure profiles from minimum energy models [1,2] are given by $j/j(0)=p/p(0)=(1+(q_a/q_0-1)\rho^2)^{-2}$ with profile widths equal to $1/q_a$ if q_0=1 is assumed for the safety factor on axis. Stationary entropy models [3] also lead to the observable prediction j/j(0)=p/p(0). Such a relation is indeed observed in ohmic L-modes in TCV. The observation is expressed as $\langle p_e\rangle/p_e(0) \approx \langle T_e^{3/2}\rangle/T_e^{3/2}(0)$, where the brackets indicate a volume (or practically equivalently cross sectional area) average and is shown in fig. 1 for a wide range of plasma shapes including elongations up to 2.54, triangularities in the range -0.5 to +0.7, ’square’ and ’rhomboidal’ shapes and diverted ohmic L-mode plasmas. The electron temperature and density measurements were obtained using a multichord Thomson scattering system with 10-25 measurement locations in the plasma depending on plasma size. The confinement properties of this set of some 300 discharges have been reported in ref. [6].

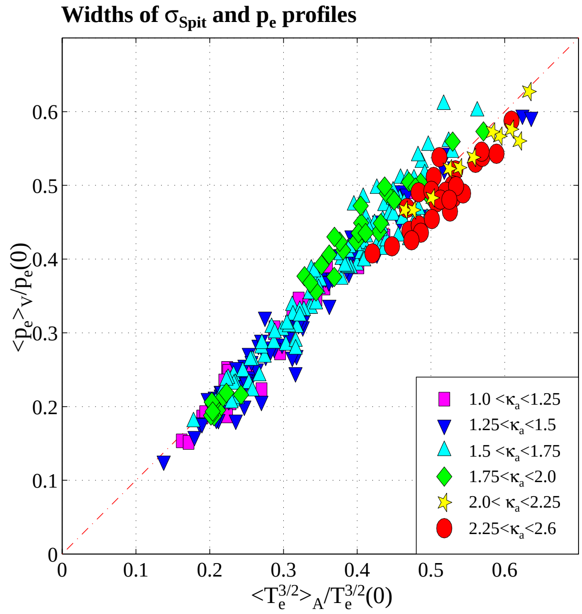

Fig. 1. Width of electron pressure profile versus width of Spitzer conductivity profile.

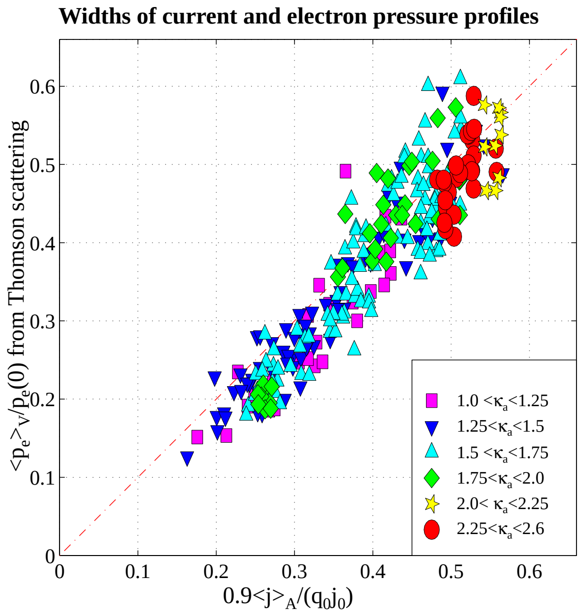

Fig. 2. Width of electron pressure profile versus width of current profile (assuming q_0=0.9).

The widths of the pressure and Spitzer conductivity profiles increase approximately as the inverse safety factor at 95% of the poloidal flux, $1/q_{95}$. A better scaling, shown in figure 2, is expressed by a relation directly with the width (up to a factor q_0) of the current profile,

$$\frac{\langle p_e\rangle}{p_e(0)} \propto \frac{\langle j\rangle}{q_0 j_0} = \frac{\langle j\rangle^* \cdot B_{0vac}}{(\kappa_0 + 1/\kappa_0)\cdot B_0} \quad (1) \text{ where } j_0 = \frac{(\kappa_0 + 1/\kappa_0)B_0}{\mu_0 R_0 q_0} \text{ and } \langle j\rangle^* = \frac{\mu_0 R_0 \langle j\rangle}{B_{0vac}}$$

is the dimensionless average current density, j_0 being the current density on axis, B_0 the toroidal field on axis, B_{0vac} the corresponding vacuum field, R_0 the major radius of the magnetic axis and κ_0 the central elongation.

TCV is equipped with a 200-channel X-ray tomography system which was used to measure the sawtooth inversion radius in these discharges [7]. For shaped plasmas we define the effective inversion radius as $\rho_{inv} = \sqrt{A_{inv}/A_p}$ where A_p is the plasma cross sectional area and A_{inv} is the area enclosed within the flux surface at which sawteeth invert. Remarkably (fig. 3), ρ_{inv} scales as already shown for $\langle p_e\rangle/p_0(0)$. We could declare that the mechanisms implied in the various theories are responsible for shaping these profiles and that the only generalisation required is to replace $1/q_a$ by $\langle j\rangle/(q_0 j_0)$ as a scaling parameter in shaped plasmas. Such a view is unsatisfactory because neoclassical conductivity, not Spitzer conductivity, should apply. Moreover, because of sawtoothing, the tokamak core, although quasi-stationary on average, is never in resistive equilibrium.

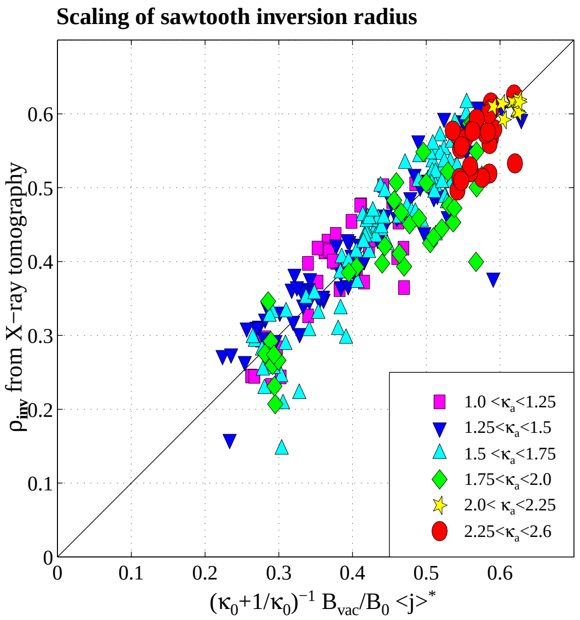

Fig. 3. Inversion radius from X-ray tomography versus width of current profile in shaped plasmas.

Another concern is the applicability of the above theories to plasmas dominated by gross MHD phenomena. As we'll show the effects of sawtoothing can lead directly to profile relationships which are not distinguishable from the above mentionned predictions. We propose a temptative model current profile given outside the sawtoothing zone as $j=E\sigma_{neo}+j_{boot}$ where $E = V_{loop}/(2\pi R_0)$ is the externally induced electric field, σ_{neo} is the neoclassical conductivity and j_{boot} is the bootstrap current, which in these ohmic plasmas only contributes a few percent to the total current. Inside the q=1 surface a prescribed safety factor profile of the form $q(\rho) = q_0 + (1-q_0)(\rho^2/\rho_1^2)$ is assumed, where ρ_1 is the normalized radius of the q=1 surface. For $\rho\leq\rho_1$ the corresponding current profile is

$$j_{in}(\rho) = j_0 \cdot \frac{q_0}{q(\rho)} \cdot \frac{B(\rho)}{B_0} \cdot \frac{(\kappa(\rho)+1/\kappa(\rho))}{\kappa_0+1/\kappa_0} \cdot \left\{1-\frac{\rho^2\cdot(1-q_0)}{\rho_1^2\cdot q(\rho)}\right\}. \quad (2)$$

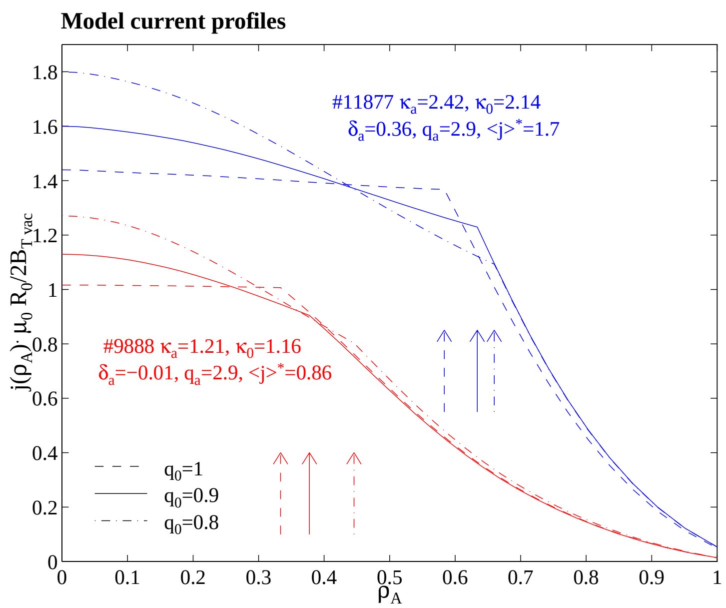

Fig. 4. Examples of model current profiles for two different TCV discharges with q_a=2.7 and three choices of q_0.

For any choice of the free parameter q_0, we determine ρ_1 from the condition $\int j dA = I_p$. Examples of the resulting profiles are shown in fig.4 for κ_a=1.2 and 2.4. The figure also illustrates the beneficial effects of elongation on the current carrying capacity of the discharge. The inversion radius from the model is consistent with the first consequence [5] of "profile consistency". The best overall match of ρ_1 and ρ_{inv} is obtained for q_0=0.9. The scaling of ρ_1 (fig.5) is seen to be identical to that of ρ_{inv} (fig. 3).

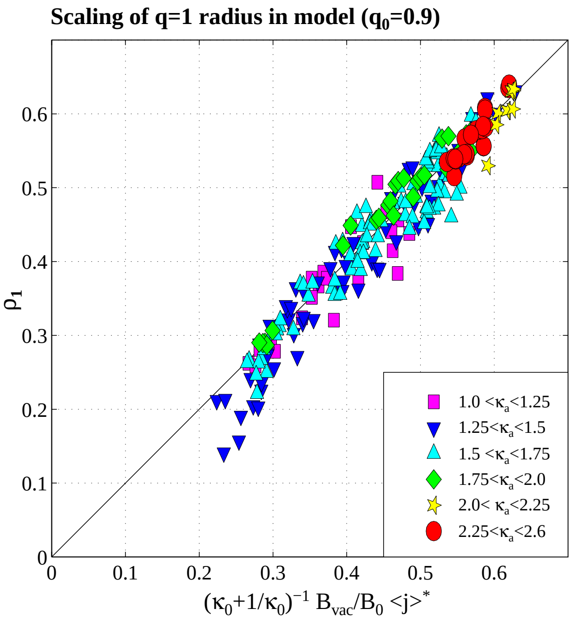

Fig. 5. Scaling of q=1 radius from model with width of current profile.

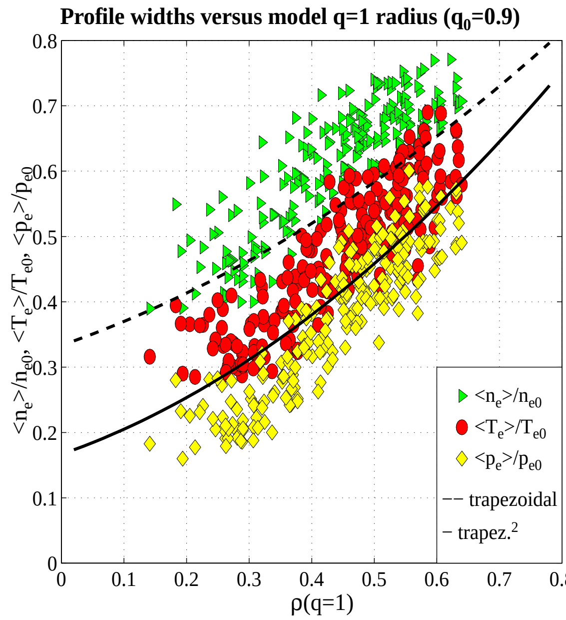

Fig. 6. Widths of electron density, temperature and pressure profiles versus q=1 radius.

We propose that the scaling of the widths of the other plasma profiles also result from the flattening effect of sawtoothing and are related to the q=1 surface. Fig. 6 shows the widths of n_e, T_e and p_e as function of ρ_1. These widths are close to those expected if the profiles were merely trapezoidal (broken line) or trapezoidal squared (continuous line) with a flat portion up to ρ_1. It appears that profile widths, expressed as $<x>/x_0$ are not very sensitive to details of the profiles and hence to transport in the confinement zone ($\rho>\rho_1$). We conclude that profile relations such as $<j>/j_0 \approx <p>/p_0$ are a consequence of sawtoothing and result from the limitation of the central current density and from the flattening of the core profiles of temperature and density. Despite the apparent agreement, the observations reported here should therefore not be considered as supportive of the above-mentioned theories.

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