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Abstract. The energy confinement time of TCV ohmic, L-mode plasmas is observed to depend strongly on the shape, improving slightly with elongation and degrading strongly with positive triangularity. This dependence can be explained by a combination of geometrical effects on the temperature gradient and power degradation, without invoking a shape dependence of the transport coefficients.

In a thermonuclear reactor, the minimum requirement that the energy loss from the confined plasma should be smaller than the energy produced by fusion reactions yields a condition on the energy confinement time [1]. In the field of Tokamak research, extrapolations to future demonstration devices still rely on empirical power laws for the energy confinement time. In these laws, the exponent of both plasma current and elongation are of the order of unity [2]. Moreover, the maximum achievable plasma current is a quadratic function of the elongation, giving potential advantages to highly elongated plasma shapes. Recently designed Tokamaks and ITER [2] have adopted a plasma shape with a conservative elongation of about 1.6. As a consequence, the experimental database for the confinement is rather sparse for higher elongations.

The distinctive features of TCV (Tokamak à Configuration Variable) are primarily a vacuum vessel and poloidal magnetic field coil system permitting high elongation up to 3 and an extreme flexibility in the plasma shape. The machine therefore offers the unique capability to extend the confinement database and to improve understanding of the transport in highly shaped plasmas.

In the work presented in this letter, the influence of plasma shape on the energy confinement of ohmic, L-mode discharges has been investigated by way of a large variation of the plasma shape, from circular to high elongations and from strongly D-shaped configurations with high positive triangularity to inverse D equilibria with negative triangularity. The energy confinement time of these plasmas improves slightly with elongation and degrades strongly with positive triangularity. Assuming that the energy losses are dominated by thermal conduction, so that the energy flux is proportional to the temperature gradient, an associated thermal diffusivity can be experimentally deduced. This is found to be independent of the plasma shape but to increase with the temperature gradient itself. The observed variations in the global energy confinement time with the shape will be shown to a result only of modifications to the temperature gradient introduced by geometrical effects of the shaping in combination with a power degradation effect. It should be noted that these experiments were carried out at low normalised pressure ($\beta \leq 1.5\%$) and hence that the conclusions drawn may not apply to other operational regimes, such as auxiliary heated plasmas or near stability limits, as pointed out by DIII-D [3] and JT-60U [4] results.

The experimental material for this work is obtained from ohmic L-mode discharges whose outer shape is defined by the analytical contour, $R = R_0 + a\cos(\theta + \delta\sin\theta)$, and $Z = a\kappa\sin\theta$, where a and R_0 are the minor and major radius, as described in Ref. [5]. The elongation, κ and triangularity, δ have been systematically varied in the following ranges: $\kappa = 1.06 \rightarrow 1.86$ and $\delta = -0.41 \rightarrow 0.72$. It is impossible to maintain constant plasma current with such a wide range of shapes, due both to variation in the edge safety factor, q_a

and because the smallest configurations cannot accommodate large currents and the largest cannot be produced at low currents. A current scan has thus been performed in each configuration in order to encompass a variation in q_a from 2.3 to 6, corresponding to plasma currents from 105kA to 565kA. These current scans are necessary to separate any influence of the shape on the confinement from an intrinsic dependence on the plasma current. The line average density, $\bar{n}_e$, has also been scanned from $2.85\times10^{19}\mathrm{m}^{-3}$ to $8.5\times10^{19}\mathrm{m}^{-3}$ to elucidate any confinement dependence on the density. All data are obtained during stationary conditions with the plasma laying on the graphite tiles of the central column, $R_o = 0.88\mathrm{m}$, $a = 0.25\mathrm{m}$, toroidal magnetic field 1.43T, D_2 filling gas. The resulting data set contains 230 different plasma conditions in four classes of elongation, triangularity, density and safety factor.

The confinement properties of these plasmas are quantified by the electron energy confinement time, $\tau_{Ee} = W_e/P_{oh}$, where P_{oh} is the ohmic input power. The total electron energy, W_e, is obtained by volume integration of Thomson scattering measurements at 10 spatial positions. For a given plasma shape, τ_{Ee} follows the usual Neo-Alcator scaling [6], showing an increase with q_a and a linear dependence on the density. This study has been restricted to values of $\bar{n}_e$ below which τ_{Ee} saturates on TCV. In all conditions a strong dependence of τ_{Ee} on the plasma shape is observed: for fixed q_a, a slight improvement with elongation and a marked degradation with positive triangularity. For the range of triangularity studied, the relative variation in τ_{Ee} is typically 2 and reaches 3 at the highest density. This shape dependence is presented in figure 1. Amongst the possible causes for this variation (treated in more detail in [7,8]), changes in the radiated power ratio P_{rad}/P_{oh} are observed to be far too small to account for the change in confinement. Internal disruption (sawteeth) amplitudes are also observed to vary strongly with triangularity, being largest at positive triangularity and sometimes vanishing at negative triangularity. However, thermal energy promptly released from the core in this way can at most account for 25% of the time average power conducted to the edge. The loss of the sawtooth at negative triangularity coincides with the onset of MHD activity, which may sometimes cause confinement deterioration seen in figure 1. These effects excluded, the principal remaining cause of the confinement variation, examined below, would appear to be the shaping itself.

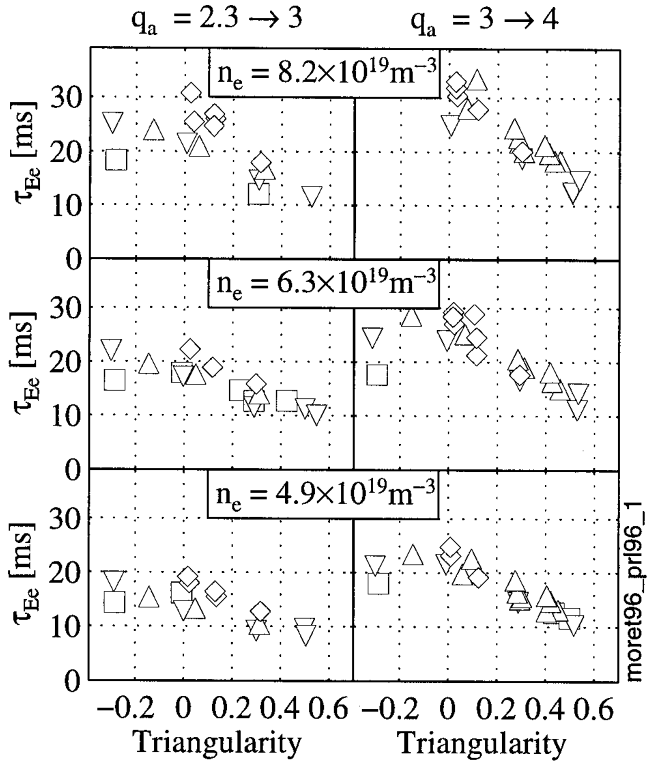

Fig. 1 Shape dependence of the electron energy confinement time in various plasma conditions. Symbols represent elongation classes: squares 1 → 1.25; down triangles 1.25 → 1.75; up triangles 1.5 → 1.75; diamonds 1.75 → 2.

A direct geometrical effect of the shaping is a modification of the flux surface separation and consequently of the gradients of plasma parameters such as the temperature and density. This will influence the conducted energy fluxes, $q = -n\chi\nabla T$, with χ the thermal diffusivity. Owing to large thermal conduction along magnetic field lines, the temperatures, T, of both the ions and the electrons are assumed constant on a magnetic flux surface. Since the poloidal magnetic flux distribution, ψ, depends not only on shape but also on the current distribution, it is not suited to account only for shape effects. Profiles are therefore mapped onto a real spatial coordinate r, chosen as the distance from the magnetic axis measured at the outer midplane and normalised such that $r = a$ on the last closed flux surface (LCFS). The energy flux may then be written as $q = -n\chi(dT/dr)(dr/d\psi)\nabla\Psi$. The spatial distribution of the gradient geometrical factor, $(dr/d\psi)\nabla\Psi$, is illustrated in figure 2 for two different shapes corresponding to negative and positive triangularity. The compression of flux surfaces toward the outer tip of a positive triangularity shape creates an extended region with increased gradients. At negative triangularity, this region shrinks due to increased separation of the flux surfaces away from the equatorial plane and a larger volume of the plasma can benefit from locally decreased gradients and hence reduced thermal conduction. The large variation in this gradient geometrical factor means that it must be included in any analysis of the local energy balance.

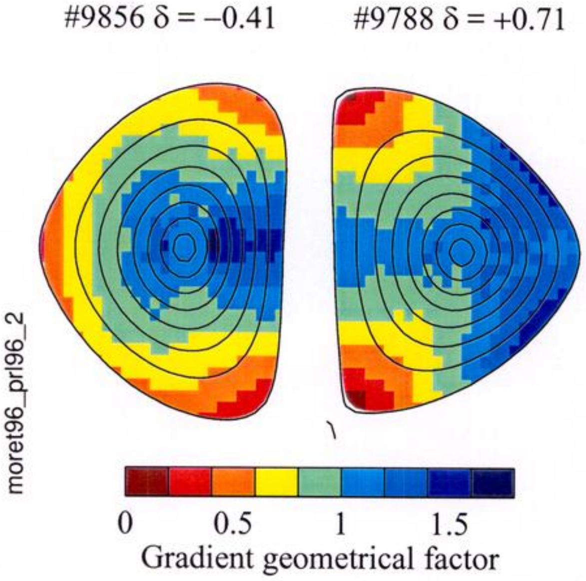

Fig. 2 (colour) Spatial distribution of the gradient geometrical factor for a negative and positive triangularity shape. Machine axis is on the left hand side in each case.

A simplified radial power balance has been established in which: (i) the thermal diffusivity is assumed to have no poloidal variation, so that flux surface average of the thermal conduction flux including the gradient geometrical effect may be written as $\langle q\rangle = -n\chi\langle\nabla T\rangle = -n\chi(dT/dr)(dr/d\psi)\langle\nabla\Psi\rangle$; (ii) the radiated power, localised near the plasma edge and smaller by an order of magnitude than the input power in the plasma core, is neglected; (iii) due to the absence of an adequate measurement of the ion temperature profile, ion and electron channel losses are not separated. Combining the power balance of both species leads to the definition of an effective thermal diffusivity, χ_{eff} such that $q_{oh} = -n\chi_{eff}\langle\nabla T_e\rangle$ with $\chi_{eff} = \chi_e + \chi_i(\nabla T_i/\nabla T_e)$, where q_{oh} is the input energy flux. In figure 3 the energy flux is plotted versus the temperature gradient for the gradient region $r/a = 0.7 \rightarrow 0.9$ for all shapes and all plasma currents but at fixed density. Within the limited accuracy of the measurement, no significant influence of either the elongation or the triangularity on the effective thermal diffusivity is observed. There is however a clear temperature gradient dependence, suggestive of a thermal diffusivity of the form $\chi = \chi_o + \chi_1\nabla T$. Such a dependence would contradict the hypothesis of poloidal invariance and would yield an effective thermal diffusivity, $\chi_{eff} = -\langle q\rangle/(n\langle\nabla T\rangle) = \chi_o + \chi_1\langle\nabla T\rangle(\langle(\nabla\psi)^2\rangle/\langle\nabla\psi\rangle^2)$. It turns out that the geometrical factor, $\langle(\nabla\psi)^2\rangle/\langle\nabla\psi\rangle^2$ for the configurations studied lies between 1.01 and 1.065. This implies that a local dependence of the thermal diffusivity on ∇T cannot be distinguished from an identical dependence on $\langle\nabla T\rangle$.

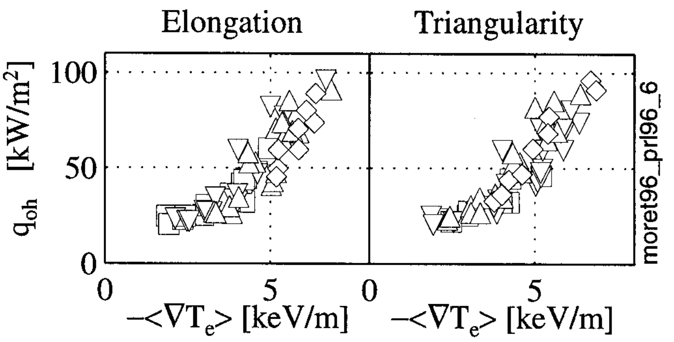

Fig. 3 Plot of the energy flux versus the temperature gradient in the region $r/a = 0.7 \rightarrow 0.9$ for all shapes and all plasma currents at $\bar{n}_e = 6.3\times10^{19}\ m^{-3}$. Symbols represent elongation and triangularity classes: left, see figure 1; right: squares –0.45 → –0.15; down triangles –0.15 → 0.15; up triangles 0.15 → 0.45; diamonds 0.45 → 0.75.

The global energy confinement time is a complicated average of the profiles of density, thermal diffusivity, power deposition and geometrical factors. To quantify the influence of the geometry alone, the energy confinement time of a shaped plasma can be compared with that of a cylindrical plasma with concentric flux surfaces having the same horizontal width, thermal diffusivity and energy flux, q_{in} associated with the input power deposition profile. Assuming as a first step that the thermal diffusivity depends neither on the poloidal angle nor on the temperature gradient, the temperature profile and the corresponding energy confinement time can be simply derived. It is then convenient to define a Shape Enhancement Factor (SEF) as the ratio of this confinement time to that of the reference cylindrical plasma (indexed o):

$$H_s = \frac{S_o \int_0^a \left(\int_r^a \frac{q_{in}}{n\chi} \frac{1}{\nabla\Psi} \frac{d\Psi}{dr} dr' \right) dV}{S \int_0^a \left(\int_r^a \frac{q_{in}}{n\chi} dr' \right) dV_o},$$

where S symbolises the LFCS area and where a flat density profile is assumed. Values of $H_s > 1$ imply an improvement of energy confinement with respect to a circular plasma. The SEF can be understood as a weighting of all intervening geometrical factors by the profile $q_{in}/(n\chi)$. This is chosen as $-dT_o/dr$ where T_o is the average of the normalised temperature profile, $T_e(r)/T_e(0)$ of all plasmas studied. For the experiments described here, these profiles are essentially trapeozidal, a characteristic of discharges with internal disruptions. This weighting function is then essentially zero up to mid-radius and constant outside so that gradient geometrical effects are most effective in the outer region of the plasma. If, as before, a dependence of the thermal diffusivity on either ∇T or $\langle \nabla T \rangle$ is introduced but now restricted to constant χ_1/χ_o, for trapezoidal profiles of T_o, the derived temperature profile has the same shape multiplied by a numerical factor. This factor is unity for small energy flux and behaves asymptotically as $q_{in}^{-1/2}$. In addition and more importantly, it has no geometry dependence and cancels out in the SEF. Thus, the previously defined SEF can still be retained to account for gradient geometrical effects on the energy confinement time in the presence of a temperature gradient dependent thermal diffusivity or heat flux degradation. The SEF is plotted in figure 4 for all conditions studied and takes values increasingly higher than unity with increasing elongation and decreasing triangularity. As shown in figure 5, correcting the electron energy confinement time by the factor H_s

cancels all dependence on elongation and significantly reduces the triangularity dependence.

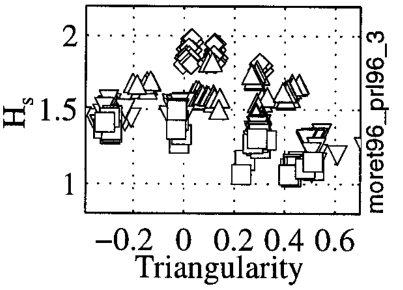

Fig. 4 Shape Enhancement Factor value for all studied conditions (symbols see figure 1).

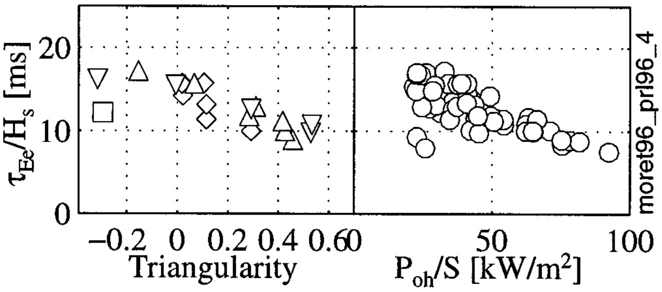

Fig. 5 Electron energy confinement time corrected for the shape enhancement factor at $\bar{n}_e = 6.3\times10^{19}$ m^{-3}. *Left: shape dependence at* $q_a = 3 \rightarrow 4$ *(symbols see figure 1). Right: heat flux degradation for all shapes and all plasma currents.*

The decrease in confinement time with triangularity persisting after correction by the SEF is a result of an increase of the heat flux at the LCFS as triangularity increases, leading to enhanced power degradation and hence reduced energy confinement. The heat flux increase is due both to higher plasma current for fixed q_a and to reduced confinement leading to lower temperature and higher loop voltage. This reasoning can be extended to all shapes and all plasma currents with the result that the residual variation of the electron energy confinement time can be interpreted as a heat flux dependence with an exponent equal to -1/2, as seen in figure 5. Note that the pertinent quantity is not the total power, which would predict too low a confinement time for high elongations, but the heat flux. This is in agreement with the previously proposed dependence of the thermal diffusivity on the temperature gradient.

In summary, the large variation in the measured energy confinement time within the domain of explored equilibria may be explained by direct geometrical effects of shaping combined with heat flux degradation. This conclusion is based on the observation that the heat diffusivity deduced from a local energy balance accounting for the geometrical effects of shaping on temperature gradient is independent of the plasma shape but increases with increasing temperature gradient. Under these circumstances, the influence of shape on the global energy confinement may be simply expressed in the form of a Shape Enhancement Factor that multiplies the energy confinement time of a cylindrical reference plasma. This factor depends only on the plasma geometry and may be better suited to describe shape effects in energy confinement time scaling laws. This work also suggests that a global confinement optimisation can be achieved by tuning the plasma shape. Negative triangularity is not the only option and more general shapes can be envisaged which could result from a compromise between the benefits of the geometry and the drawbacks of other constraints such as poor MHD or vertical stability at low triangularity.

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[1] J. Wesson, *Tokamaks*, Clarendon Press, Oxford, 1987.

[2] International Thermonuclear Experimental Reactor, *Interim Design Report*, IAEA 1995.

[3] A.W. Hyatt, E.A. Lazarus, T.H. Osborne, Europhysics Conference Abstracts, 21st EPS Conference on Controlled Fusion and Plasma Physics, Montpellier, 1994, edited by E. Joffrin, P. Platz and P.E. Stott, Vol. 18B, p. I-14.

[4] K. Kamada *et al.*, *High triangularity discharges with improved stability and confinement in JT-60U*, 16th IAEA Fusion Energy Conference, Montréal, 1996 (unpublished).

[5] F. Hofmann, M.J. Dutch, J.-M. Moret, Europhysics Conference Abstracts, 22nd EPS Conference on Controlled Fusion and Plasma Physics, Bourne-

mouth, 1995, edited by B.E. Keen, P.E. Stott and J. Winter, Vol. 19C, p. II-101.

[6] R.R. Parker *et al.*, Nuclear Fusion 25, 1985, p. 1127.

[7] J.-M. Moret *et al.*, *Influence of the shape on TCV plasma properties*, 16th IAEA Fusion Energy Conference, Montréal, 1996 (unpublished).

[8] H. Weisen *et al.*, *Measurement and modelling of light impurity behaviour in TCV*, 23nd EPS Conference on Controlled Fusion and Plasma Physics, Kiev, 1996 (unpublished).