Influence of Plasma Shape on Transport in the TCV Tokamak

J.-M. Moret, S. Franke, H. Weisen, M. Anton,* R. Behn, B. P. Duval, F. Hofmann, B. Joye, Y. Martin, C. Nieswand, Z. A. Pietrzyk, and W. van Toledo

Centre de Recherches en Physique des Plasmas, Association EURATOM-Confédération Suisse, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

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The energy confinement time of TCV Ohmic, *L*-mode discharges is observed to depend strongly on the plasma shape, improving slightly with elongation and degrading strongly as triangularity is increased from zero to positive values. The thermal conductivity of these plasmas is found to be independent of the shape. This observation, combined with geometrical effects on the temperature gradient and a degradation with increasing input energy flux, can explain the observed variation in the energy confinement time. [S0031-9007(97)03967-7]

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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, making highly elongated plasma shapes potentially advantageous. Recently designed tokamaks and ITER [3] have adopted a plasma shape with a conservative elongation of about 1.6. As a consequence, the experimental energy confinement database 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 elongations of 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.

This Letter presents the results of experiments in which the energy confinement dependence on shape has been investigated by varying the plasma elongation and triangularity over a large range. The equilibria studied include circular and highly elongated plasmas and D shapes with positive and negative triangularity. The energy confinement time of these plasmas improves slightly with elongation and degrades strongly as triangularity increases from zero to positive values. The coefficient of thermal conductivity, assumed to be the dominant energy loss, is found to be independent of the plasma shape but to increase with the temperature gradient. Using this observation, the variation in the global energy confinement time can be shown to result from modifications of the temperature gradient introduced by geometrical effects of the shaping in combination with a power degradation effect.

The confinement data described in this Letter is obtained in Ohmic *L*-mode discharges whose outer shape is defined by the analytical contour, $R = R_0 + a\cos(\theta + a\sin\delta\sin\theta)$, and $Z = a\kappa\sin\theta$, where a and R_0 are the minor and major radii, respectively, as described in Ref. [3]. The elongation κ and triangularity δ have been systematically varied to produce the 16 shape classes shown in Fig. 1. At the time of these experiments, the range of possible triangularity and elongation was limited by the capability for vertical position stabilization. For such a wide range of shapes, variations in the edge safety factor q_a preclude a constant plasma current. 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 105 to 565 kA. These current scans are necessary for any influence of the shape on the confinement to be separated from an intrinsic dependence on the plasma current. To elucidate any confinement dependence on the density, where permitted by the operation domain for a given condition, the line average density $\overline{n}_e$ has been scanned from 2.85×10^{19} to 8.5×10^{19} m^{-3}. All data are obtained during stationary conditions with the plasma limited by the graphite tiles of the central column, $R_0 = 0.88$ m, $a = 0.25$ m, toroidal magnetic field 1.43 T, D_2 filling gas. The resulting data set contains 230 different plasma conditions in four classes of δ, κ, $\overline{n}_e$, and q_a.

The confinement properties of these plasmas are quantified by the electron energy confinement time

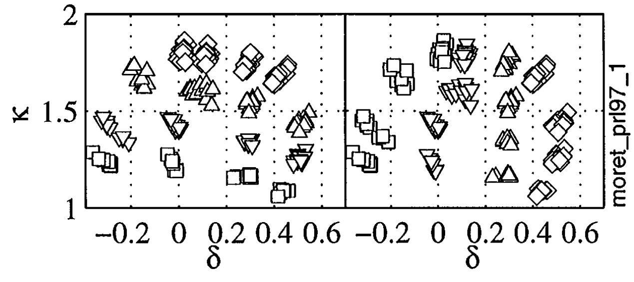

FIG. 1. Coverage of the (κ, δ) plane by the 16 shapes studied. Symbols represent either the κ or δ classes used in later figures.

$\tau_{Ee} = W_e/P_{\rm oh}$, where $P_{\rm oh}$ is the Ohmic input power. The total electron energy W_e is obtained by volume integration of Thomson scattering measurements at ten spatial positions. For a given plasma shape, τ_{Ee} follows the usual neo-Alcator scaling [5], showing an increase with q_a and a linear dependence on the density. This study has been restricted to values of $\overline{n}_e$ 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 compared with zero or slightly negative 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 Fig. 2. Under conditions in which the total thermal energy can be reliably derived from the magnetic equilibrium reconstruction, similar behavior is observed in the energy confinement time so deduced.

Amongst the possible causes for this variation (treated in more detail in [6,7]), changes in the radiated power ratio $P_{\rm rad}/P_{\rm oh}$ are observed to be far too small to account for the change in confinement. Internal disruption (sawteeth) amplitude is also observed to vary strongly with triangularity, being largest at positive triangularity and sometimes vanishing at negative triangularity. Thermal energy released from the core in this way can account for at most 25% of the thermal losses. The inversion radius remains constant over each scan in triangularity, indicating no important changes in the current distribution and excluding any indirect effect of this distribution. The disappearance of the sawteeth at negative triangularity coincides with the onset of MHD activity, which may sometimes cause the confinement deterioration seen in Fig. 2. These effects excluded, the principal remaining loss channel governing the confinement is thermal conduction. Since changes in geometry modify the temperature gradient ∇T, the shaping would clearly be expected to influence the conducted energy flux $q = -n\chi\nabla T$. It is also possible that the thermal diffusivity χ is directly affected by shape variations. Both effects are examined below.

Concentrating first on the geometrical effect, the shaping locally modifies the separation between surfaces of constant poloidal magnetic flux ψ. If T is assumed to be constant on a flux surface, the temperature gradient may be expressed as $\nabla T = (dT/d\psi)\nabla\psi$. However, ψ depends not only on shape but also on the current distribution and is thus not a suitable parameter with which to account for shape effects alone. Temperature profiles are therefore mapped onto a real spatial coordinate r, chosen as the distance from the magnetic axis measured at the outer midplane. To handle varying Shafranov shifts, r is normalized such that $r = a$ on the last closed flux surface (LCFS). Using this coordinate, ∇T may then be written as $(dT/dr)(dr/d\psi)\nabla\psi$. The spatial distribution of the gradient geometrical factor $(dr/d\psi)\nabla\psi$ is illustrated in Fig. 3 for two example shapes. The flux surface compression toward the outer tip of a shape with positive triangularity creates an extended region with increased gradients. At negative triangularity, this region shrinks due to increased

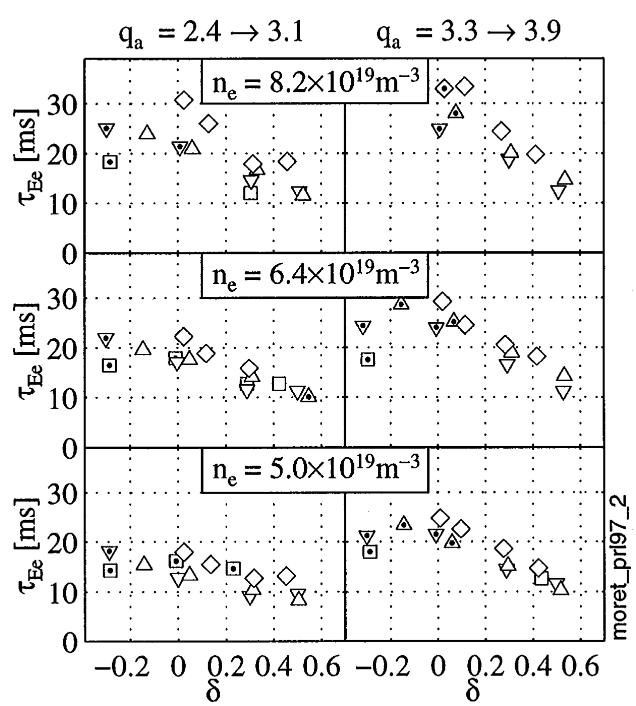

FIG. 2. Shape dependence of the electron energy confinement time for various plasma conditions. Symbols represent κ classes (see Fig. 1). Dotted symbols indicate conditions in which significant MHD activity is visible on the soft-x-ray emissivity.

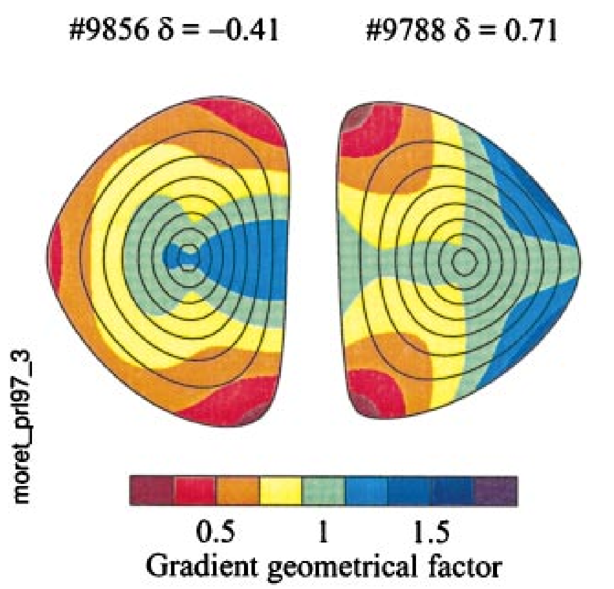

FIG. 3(color). Spatial distribution of the gradient geometrical factor for two example shapes with negative and positive triangularity. The machine axis is on the left hand side in each case.

separation of the flux surfaces away from the midplane. A larger volume can thus benefit from locally decreased gradients and hence reduced conduction losses. The large variation in this gradient geometrical factor means that it must be included in any analysis of the local energy balance.

In order to determine the influence of the shape on the thermal diffusivity, a simplified radial power balance has been established in which (i) χ is assumed to have no poloidal variation, so that flux surface average of the conducted flux including the gradient geometrical factor may be written as $\langle q\rangle = -n\chi(dT/dr)(dr/d\psi)\langle\nabla\psi\rangle$; (ii) the radiated power, localized near the plasma edge and an order of magnitude smaller than the input power in the plasma core, is neglected; and (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 $q_{\mathrm{in}} = -n\chi_{\mathrm{eff}}\langle\nabla T_e\rangle$, where $\chi_{\mathrm{eff}} = \chi_e + \chi_i\nabla T_i/\nabla T_e$, and q_{in} is the input energy flux. In Fig. 4, the energy flux at fixed density is plotted versus the temperature gradient for the gradient region $r/a = 0.7 \rightarrow 0.9$ for all shapes and all plasma currents. Clearly, within the limited accuracy of the measurement, neither the elongation nor the triangularity has any significant influence on the effective thermal diffusivity. There is, however, a clear nonlinear relationship between the energy flux and the temperature gradient, indicating a dependence ∇T of thermal diffusivity. This would contradict the hypothesis of a poloidally invariant χ, but it turns out that for the configurations studied, a local dependence of the thermal diffusivity on ∇T cannot be distinguished from an identical dependence on $\langle\nabla T\rangle$. Figure 4 also shows that MHD activity appears at low input energy flux, when τ_{Ee} is high and P_{oh} is consequently reduced [6]. The associated low edge temperature is thought to favor resistive instabilities which are expected to be stabilized by additional heating in future experiments.

The gradient geometrical factor and the fact that the thermal diffusivity does not depend on the shape can now be combined to quantify the influence of the geometry on the global energy confinement time. To do so, each shaped plasma is compared to a reference case with concentric circular flux surfaces, taking identical profiles of χ and q_{in} in each case. The temperature profile and the corresponding energy confinement time can be simply derived for both cases. It is then convenient to introduce a "shape enhancement factor" (SEF) defined as the ratio of confinement time of a shaped plasma to that of the reference cylindrical plasma (indexed 0):

$$H_S = \frac{S_0\int_0^a(\int_r \frac{q_{\mathrm{in}}}{n\chi}\frac{1}{\langle\nabla\psi\rangle}\frac{d\psi}{dr}\,dr')dV}{S\int_0^a(\int_r^a \frac{q_{\mathrm{in}}}{n\chi}\,dr')dV_0}\,. \tag{1}$$

where S symbolizes the LCFS 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. To compute the SEF, the profile of $q_{\mathrm{in}}/n\chi$ can be deduced from the experimental or from a prescribed temperature profile. In the case of the results described here, this profile is chosen as the average of $(dT_e/dr)/T_e(0)$ over all conditions studied. In deriving Eq. (1), χ was assumed to depend neither on the poloidal angle nor on ∇T, but the observed dependence of the thermal diffusivity on $\langle\nabla T\rangle$ can be shown to introduce only negligible changes. Thus, the previously defined SEF can be retained to account for gradient geometrical effects on the energy confinement time in the presence of a degradation with heat flux. Figure 5 compiles the SEF for all conditions studied and shows how the factor becomes increasingly higher than unity with increasing elongation, reaching a maximum for zero or slightly negative triangularity. This can be more clearly seen in the case of the SEF computed for theoretical TCV equilibria with $\kappa = 1.67$ and for a wider range of triangularity (solid line in Fig. 5). This trend is already visible on the experimental data but remains to be confirmed by experiments at more negative triangularity. As shown in Fig. 6, correcting the electron energy confinement time by the factor H_S cancels all dependence on elongation and significantly reduces the triangularity dependence.

The decrease in confinement time with triangularity persisting after correction by the SEF is a result of an increase of the Ohmic power as triangularity increases,

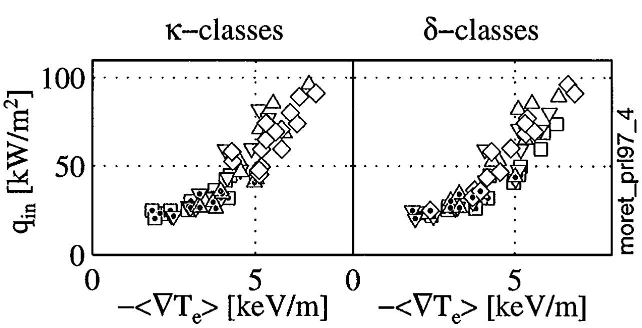

FIG. 4. Plot of the energy flux versus the temperature gradient in the region $r/a = 0.7 \rightarrow 0.9$ for all shapes and all plasma currents at $\overline{n}_e = 5.0 \times 10^{19}\ \mathrm{m}^{-3}$ (for symbols see Figs. 1 and 2).

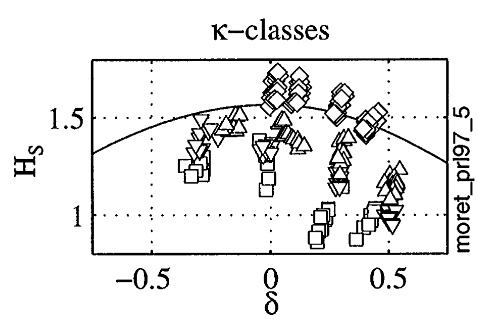

FIG. 5. Shape enhancement factor for all conditions studied (for symbols see Fig. 1) and for theoretical TCV equilibria with $\kappa = 1.67$ (solid line).

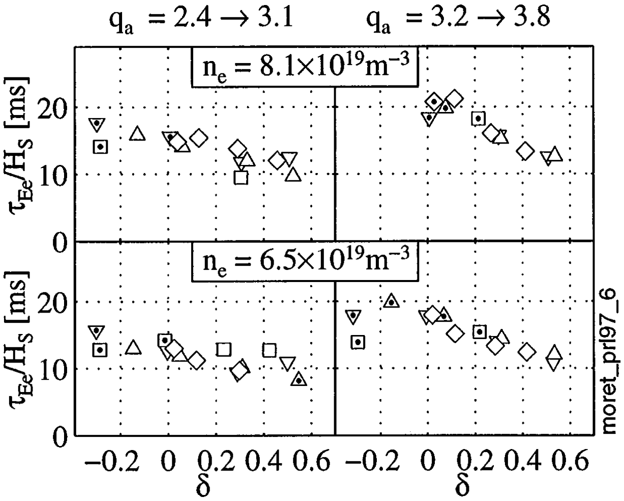

FIG. 6. Shape dependence of the SEF corrected electron energy confinement time for various plasma conditions (for symbols see Fig. 2).

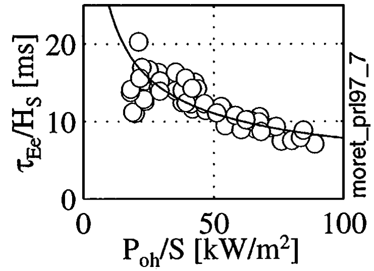

FIG. 7. Heat flux degradation of the SEF corrected energy confinement time for all shapes and all plasma currents at $\overline{n}_e = 5.0 \times 10^{19}$ m^{-3}. The solid line corresponds to a -0.5 exponent.

leading to enhanced power degradation and hence reduced energy confinement. This power increase is due both to higher plasma current for fixed q_a and to reduced confinement leading to lower temperature and higher loop voltage. In fact, as shown in Fig. 7, the variation of the SEF corrected electron energy confinement for all shapes and all plasma currents can be interpreted as a heat flux dependence with an exponent equal to -0.5. 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 consistent with the choice of a fixed input energy flux in the SEF expression.

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 the 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 but, since κ and δ alone are insufficient to parametrize an arbitrary shape (especially in diverted configurations), a full description of the poloidal flux surfaces is required if energy confinement times of different tokamaks are to be properly compared. Inclusion of the SEF in the databases currently used to derive energy confinement scaling laws would, for example, seem particularly appropriate. The energy confinement dependence on plasma shape observed in TCV differs markedly from that reported previously in other tokamaks [8,9]. These latter studies were, however, concerned with high performance regimes whose transient nature and stability are such that, aside from the difficulty of the shape parametrization by κ and δ, comparisons with the stationary, Ohmic conditions characteristic of the experiments reported in this Letter may not be valid. Nevertheless, the TCV results suggest that optimization of the global confinement can be achieved by tuning the plasma shape. This optimum could be a compromise between the beneficial effects of the geometry and the drawbacks of poor MHD or vertical stability or other engineering constraints.

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*Present address: Max Planck Institut für Plasmaphysik, D-8046 Garching, Germany.

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