Energy Confinement in Shaped TCV Plasmas with Electron Cyclotron Heating

A. Pochelon, S. Coda, T.P. Goodman, M. Henderson, J-M. Moret, Ch. Nieswand,
Z.A. Pietrzyk, H. Reimerdes, O. Sauter, C. Angioni, R. Behn, I. Furno,
J-P. Hogge, F. Hofmann, B. Joye, N. Kirneva[1], J.B. Lister, Y. Martin, R.A. Pitts,
F. Porcelli[2], J. Rommers, A. Sushkov[1], M.Q. Tran, H. Weisen

*Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Fédérale de Lausanne
Association EURATOM-Confédération Suisse, CH-1015 Lausanne EPFL, Switzerland
[1] Russian Research Centre Kurchatov, 12182 Moscow, RF
[2] Politecnico di Torino, I-10129 Torino, Italy*

Abstract The effects of plasma shape on confinement and sawtooth stability are studied for positive and negative discharge triangularity and for different elongations with 1.5 MW centrally deposited ECH power.

Introduction After extensive studies of Ohmic confinement as a function of plasma shape [1] and initial studies of confinement with additional EC heating at a power level of 0.5-1 MW [2], extensive studies of confinement with ECH started in 1998 at the 1.5 MW power level, using the first cluster of three gyrotrons at second harmonic, 82.7 GHz [3]. During the initial ECH campaign in 1997, the effect of the power deposition location on confinement was studied at low power [4]. The location of the power deposition was obtained from power modulation or power shut-off techniques, from ray tracing and qualitatively from sawtooth shapes [5]. These low power studies confirmed the good confinement properties of power deposited inside the $q = 1$ surface, relative to outside.

Studies of energy confinement time in EC heated discharges have been started as a function of plasma shape in TCV (Tokamak à Configuration Variable, achieved parameters: κ=2.58, -0.7<δ<0.9, I_p=1MA). The elongations and triangularities explored with additional heating to date are in the range 1.1<κ<2.15 and -0.65≤δ≤0.5. For these studies, an additional power of 1.5MW ECH is injected at the second harmonic, which typically represents a power ratio of P_{EC}/P_{OH}~2-3 during ECH, up to ten in extreme cases. Central power deposition, well inside the q=1 surface, is used in this campaign as a rule. Two values of the engineering safety factor q_{eng} ($q_{eng} = 5abB/RI_p$ = 1.7 and 3) were used (2.3 < q_a < 6; 0.2 < I_p < 0.7 MA). Maintaining q_{eng} constant keeps the normalised radius of $q = 1$ approximately constant while changing the plasma shape [6]. The electron energy content is obtained during stationary periods from repetitive Thomson scattering measurements (~150 Hz), averaged typically over 10 time-slices to reduce the influence of MHD fluctuations.

Confinement Analysis To obtain a simple general power law over the full data set describing the dependence of the electron confinement time τ_{Ee} on average line density n_{e_av}, total power P, edge elongation κ, edge triangularity δ and plasma current I_p, we have applied a multi-variable regression. The dependences on κ and I_p cannot be separately determined, owing to the strong correlation between these quantities in the present data. The power law must therefore contain a free parameter, and takes the following form:

$$\tau_{Ee}\text{[ms]} = 2 \; n_{e\_av19}{}^{\alpha_n} \; P^{\alpha_P} \; (6 \; I_p)^{\alpha_I} \; \kappa^{\alpha_\kappa} \; (1+\delta)^{\alpha_\delta} \; \text{[m}^{-3}, \text{MW, MA]} \qquad (1)$$

with α_n=0.46±0.2, α_P=-0.7±0.1, α_δ=-0.35±0.3, α_κ=1.4(1-α_I)±0.4 and α_I remains undetermined. The uncertainties have been estimated assuming a 25% error on τ_{Ee}. Good fits are obtained with α_I in the range 0 ≤ α_I ≤ 0.7, an example at α_I=0.5 is shown in **Fig. 1.**
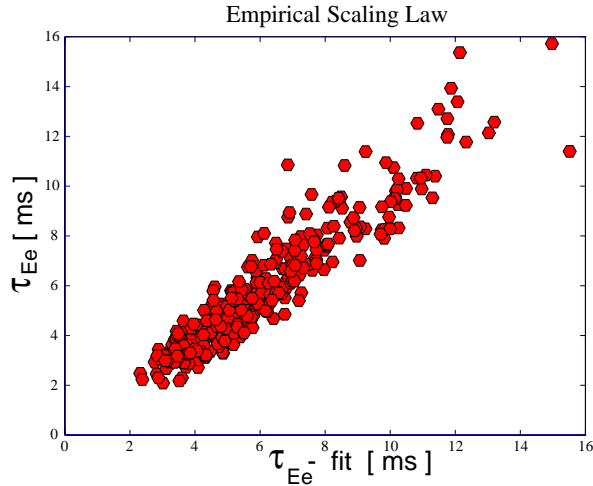
Empirical Scaling Law

Fig. 1. Empirical scaling law for TCV ECRH data set, see equation (1), in the representative case $\alpha_I=0.5$.
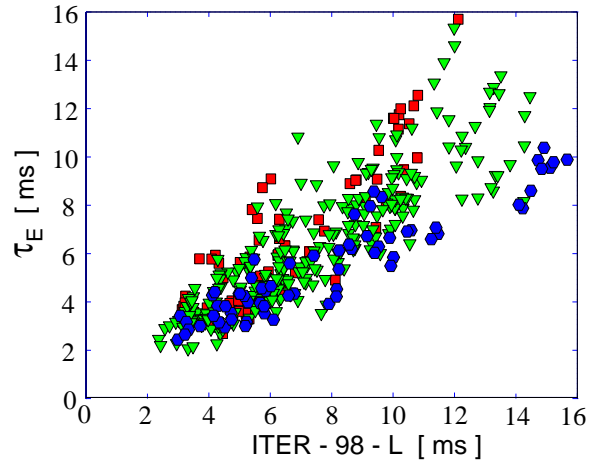
Fig. 2. Fit to ITER-98-L mode scaling law. Since triangularity does not appear in ITER-98-L, it is explicitly indicated by the symbols: negative δ appear favourable (red squares: $\delta<0$, green triangles: $0<\delta<0.3$, blue hexagons: $\delta>0.3$).

In spite of the unresolved confinement dependence on current and elongation, this scaling appears favourable, as the main motivation for creating elongated discharges is indeed to increase the plasma current with the aim of increasing the energy confinement and pressure limits. Further data are needed at moderate elongation to separate the contributions of plasma current and elongation.

The general scaling (1) displays qualitative similarities with the recent scaling laws found using a multi-tokamak database, such as the ITER-98-L mode scaling, where $\alpha_n=0.40$, $\alpha_P=-0.73$, $\alpha_I=0.96$, $\alpha_\kappa=0.64$ [7]. Clearly, the α_n and α_P exponents are in good agreement with our scaling within the uncertainties; however, α_κ and α_I are not both compatible with our scaling. Plotting our data against ITER-98-L highlights the beneficial effect of negative triangularities, particularly at low powers, i.e. at the large confinement times, as shown in **Fig. 2** [3].

Confinement time versus triangularity

The TCV confinement time in ECRH conditions shows good agreement with the Rebut-Lallia-Watkins critical gradient confinement scaling [3], as already shown earlier for ohmic TCV conditions.

Naturally, the general scaling (1), which is based on the entire data set, overlooks more detailed effects in specific regions of the parameter space.

For instance, in a triangularity scan at $\kappa=1.5$ ($P_{tot}/P_{OH}\sim3-9$), the confinement time is larger at small or negative triangularities. This effect is particularly visible at low total input power, as shown in **Fig. 3**.
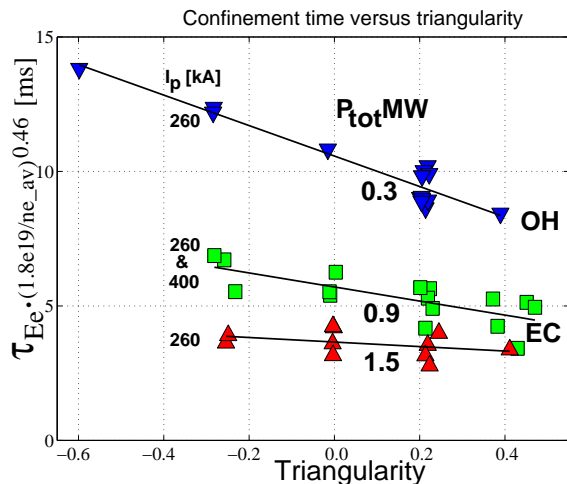
Fig. 3. Triangularity dependence of confinement time for different total power classes with centrally EC deposited power, normalised to $n_{e\ av}=2\times10^{19}\,m^{-3}$ (density range: $1.3<n_{eo19}<3$). The power range for the low power 0.3 MW class, the largest, is $\pm16\%$ wide; the higher confinement at negative triangularity reflects therefore predominantly an effect of plasma shape.

Within the present available power range, it cannot be stated clearly whether the confinement power degradation is more pronounced at negative triangularity than at positive

triangularity in these central power deposition conditions. The addition of the second cluster of 1.5 MW will help to see whether the present trend is maintained.

In the same triangularity scan, the β values are also higher at negative triangularities in both ohmic and ECH.

Confinement Transitions   In the process of enlarging the database to decouple the I_p and κ dependences in the confinement scaling, we have started to complement the database with elongated low current shots. Very high safety factor discharges ($\kappa\sim2$, $I_p\sim80$ kA, $q\sim20$) have been successfully produced and are vertically stabilisable. With the gyrotron frequency of 82.7 GHz and the maximal nominal magnetic field of 1.43T, however, the EC resonance is located off-axis on the high field side at mid normalised radius. At the highest injected EC powers, discharges show spontaneous oscillating transitions in confinement, best revealed by changes in the the central soft X-ray emission. Drops in the central soft X-ray emission are associated with a flattening of the density profile reconstructed from the fifteen interferometer channels, presumably triggered by changes in the q-profile with off-axis heating [8].

These transitions raise the issue of the role of high power localised ECH heating in confinement experiments, which can change shear and gradient profiles relative to the ohmic target plasma. Thus, the use of highly localised on-axis heating in these experiments may result in a radial deposition profile very different from its Ohmic counterpart, particularly for highly shaped plasmas, e.g. for strong negative triangularities or high elongations. In negative triangularity discharges, the ohmic power is relatively reduced [1]. The effect of localised/distributed heating needs in fact to be determined experimentally. In the case of counter-ECCD discharges with central deposition, confinement about twice the Rebut-Lallia-Watkins scaling has been measured.

Sawteeth Stability and Plasma Shape   The effect of power on the sawtooth period and amplitude was studied in a triangularity scan ($-0.3<\delta<0.5$, $q_{eng}\sim2$, $P_{EC}/P_{OH}\leq3$) and an elongation scan ($1.1<\kappa<2$, $q_{eng}\sim2$) while keeping deposition well inside the inversion radius. In these shape scans at constant q_{eng}, the normalised inversion radius measured from soft X-ray tomography varies by less than 5%.
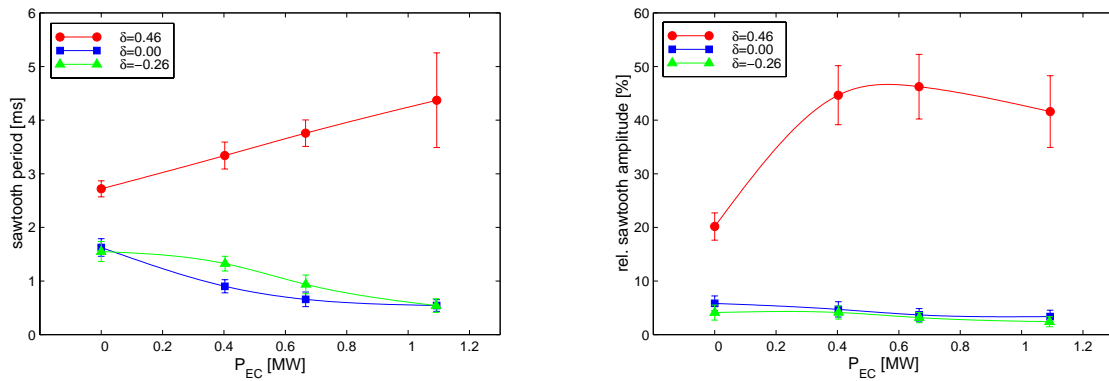

Fig. 4. Sawtooth period (4a) and relative crash amplitude (4b) stabilisation/destabilisation with increasing central power deposition for different triangular plasma shapes ($-0.26<\delta<0.46$, $\kappa=1.5\pm0.05$, $q_{eng}\sim2$).

For $\delta>0.2$, the sawtooth period and crash amplitude increase with increasing heating power, whereas for $\delta<0.2$ the sawtooth period decreases with increasing heating power, with a smaller relative crash amplitude, see **Fig. 4a, b**. Therefore, for positive triangularity $\delta>0.2$, heating power shows a sawtooth stabilisation effect, associated however with large crash amplitudes; on the contrary, increasing the power in negative triangularity discharges induces sawtooth destabilisation and relative smaller crash amplitudes. This has two advantages: first of

all, negative triangularity discharges reduce the amplitude of the sawtooth heat pulse and can help to reduce the amplitude of a possible seed island.

The effect of increasing the plasma elongation appears very similar to the effect of increasing negative triangularities: when increasing the power for elongations above κ=1.5, sawteeth are also destabilised, sawtooth periods becoming shorter and of smaller amplitude.

The stabilisation effect of positive triangularity and high elongation seen in the experiment is in qualitative accord with the effect of triangularity and elongation on the Mercier stability of the ideal internal kink mode or on the resistive MHD stability of the m=1 mode, both stabilised by positive triangularity and ellipticity (and destabilised at negative triangularity and high elongation [9].

Conclusions   The dependence of the electron energy confinement time is studied by varying the density, power, triangularity, elongation and current. The electron energy confinement time is found to increase with a combination of elongation and plasma current, two quantities which are still strongly correlated in the present study. The beneficial effect of triangularity, previously observed in Ohmic discharges, continues to be seen at the power levels used here. However, the benefit of low or slightly negative triangularity on confinement is most effective at low total power and decreases, without disappearing, at the highest powers used so far. The specific power scaling law obtained by regression on the TCV data for constant triangularity very closely fits the Rebut-Lallia-Watkins scaling and, over the parameter range studied, is similar to the ITER-98-L scaling when neglecting the ion contribution. Using these two scaling representations, the beneficial effects of negative triangularity appear clearly.

Sawtooth stability is improved at positive triangularity and at low elongation, producing large sawtooth crashes. High elongation or negative triangularity appear therefore attractive to reduce the amplitude of heat pulses and seed islands which can follow large sawtooth crashes in high power experiments. The strong effect of plasma shape on the sawteeth characteristics and (de-)stabilisation with power could also play a role in the present confinement experiments, since sawteeth are one of the major loss channels in the plasma core of these centrally heated discharges.

The addition of the second cluster of ECRH power sources will be important to determine more clearly the triangularity dependence at high power and will allow the study of confinement in higher elongation discharges at a higher P_{EC}/P_{OH} ratio.

References
[1]   J-M Moret, et al., Phys. Rev. Lett. **79** (1997) 2057 and Weisen H. et al., Nucl. Fus. **37** (1997) 1741.
[2]   A Pochelon et al., Proc. of Joint ICPP 1998 and 25th EPS Conf. on Contr. Fusion and Plasma Physics, Praha 1998, ECA Vol. **22C** (1998) 1324.
[3]   A Pochelon et al., 17th IAEA Fusion Energy Conf. 1998, CN-69/EX8/3, to appear in Nuclear Fusion, Yokohama Special Issue (1999).
[4]   A Pochelon et al., 2nd Eur. Top. Conf. on RF Heating and Current Drive, Brussels, **22A**, (1998) 253.
[5]   ZA Pietrzyk. et al., Nuclear Fusion, **39** (1999) 587.
[6]   H Weisen et al., Plasma Phys. Control. Fusion **40** (1998) 1803.
[7]   K Thomsen et al., 17th IAEA Fusion Energy Conf. 1998, CN-69/ITER/3-ITERP1/07.
[8]   KA Razumova et al., Peculiarity of Plasma Behav. in the Vicinity of rat. q Value, this Conf., Or 20.
[9]   H Lütjens, A Bondeson and G Vlad, Nuclear Fusion **32** (1992) 1625.