

Recent Results from the TCV Tokamak

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INTRODUCTION The TCV tokamak ($B_T < 1.5$ T, $R \approx 0.89$ m, $a < 0.25$ m, $I_p < 1.2$ MA) has produced a wide variety of plasma configurations, both limited and diverted, with elongations, κ in the range $0.9 \rightarrow 2.58$ and triangularities, δ from $-0.7 \rightarrow 1.0$. A few recently produced plasma equilibria are shown in Fig.1. Three gyrotrons at 82.7 GHz and 0.5 MW each are presently installed and have been used in the second harmonic X-mode (X2) for the ECH and ECCD experiments described in this paper. These sources are capable of a pulse length of 2 s, with the microwaves being delivered to the plasma by poloidally and toroidally steerable mirror systems for flexible power deposition and current drive. The implementation of another six gyrotrons (a further three for X2 and three for X3 at 118 GHz) is in progress. The in-vessel graphite armour has recently been upgraded for high power ECH experiments, with new tiles on the central column and low-field-side wall of the vacuum vessel providing almost 90% internal surface coverage.

TOKAMAK OPERATION AT HIGH ELONGATION Elongations up to 2.2 in single null (SN) divertor configurations and up to 2.58 in limited plasmas have been obtained on TCV. The highest elongations

($\kappa > 2.2$) are only possible for $q_{95} < 3$ and require the use of fast feedback coils inside the vessel. They correspond to stability margins $m_s \geq 0.08$ (computed using a variant of the rigid current distribution model) and growth rates up to 2000 s^{-1} [1]. Crossing $q_{95} = 3$ during discharge formation is not observed to be associated with increased disruptivity provided that a modest

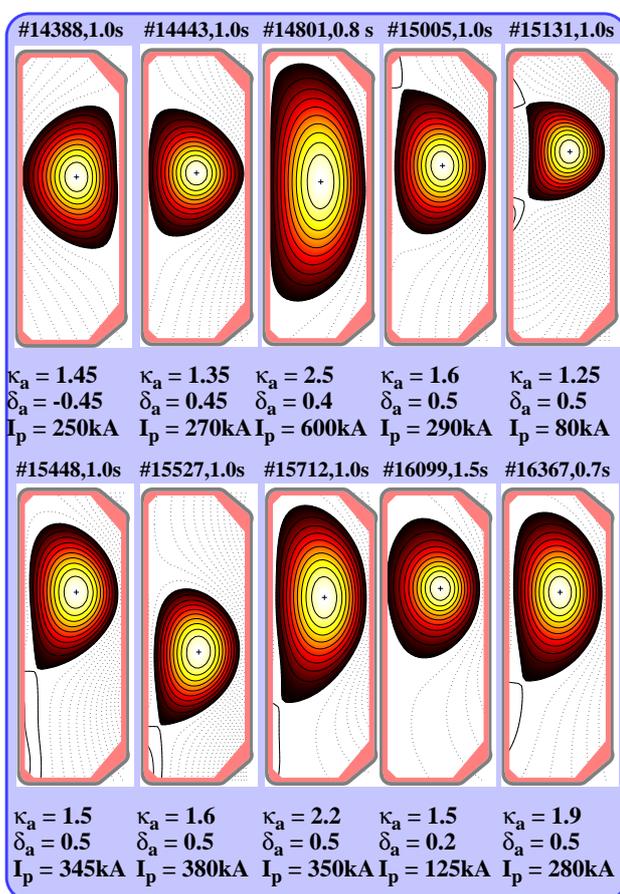


Figure 1: Illustrating the flexibility of TCV for plasma shape experiments. The equilibria above are representative of the range of shapes used in the experiments described in this paper.

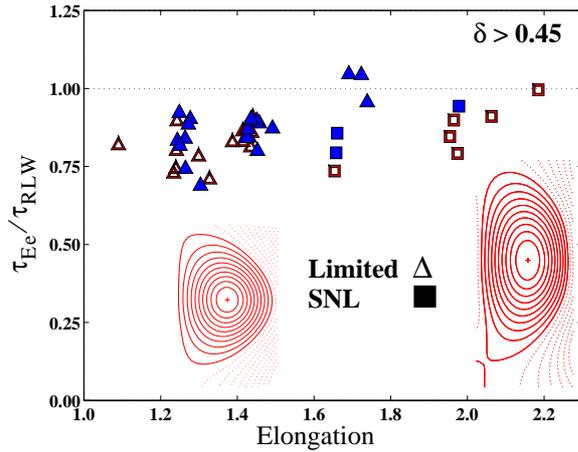


Figure 2: Electron energy confinement time normalized to RLW scaling for highly elongated SNL discharges compared with limited equilibria of similar triangularity (ohmic L-mode only). Open symbols, $q_{95} > 3$, closed symbols, $q_{95} < 3$.

amount of shaping is already present (typically $\kappa=1.4, \delta=0.3$ [2]).

A series of SN diverted discharges with $1.6 \leq \kappa \leq 2.2$, $2.5 < q_{95} < 3.5$ and $\delta > 0.45$ has been developed with the goal of assessing their confinement properties. For ohmic heating alone and sufficiently high values of plasma current and density, these discharges undergo H-mode transitions [3]. The latter are invariably followed by ELM-free H-modes (especially for favourable ion ∇B drift direction), rapidly terminated by a disruption. Confinement data in stationary conditions are therefore available only in ohmic L-mode, as shown for the electrons in Fig. 2. In comparison with limited discharges, there are clearly no major differences in confinement time at high elongation and low q_{95} in SN equilibria.

DIVERTOR DETACHMENT Despite its small size, the possibility for plasma shape variation in TCV permits the creation of magnetic equilibria allowing the detached divertor state to be accessed, even in completely open geometries [4]. Long midplane to target connection lengths, L_c , can be generated in SN configurations with the interesting feature that most of L_c appears in the poloidal distance between X-point and target and not between midplane and X-point as in more conventional geometries. Two examples are shown in Fig. 3 where, for fixed plasma current, the X-point height is varied for fixed main plasma parameters, reducing L_c near the separatrix from 20 m to 13 m, of which only ≈ 5 m is above the X-point. Detachment at the outer target is clearly seen in both cases (reduction of ion current, j_{sat}) with simultaneous increase in divertor D_α intensity. For higher L_c , detachment occurs at lower densities and the absolute particle flux is lower than for shorter connection length. In each case, the electron temperature in the divertor reaches low values (≈ 5 eV) at detachment and, at high L_c , the divertor is already in the high recycling regime, even when \bar{n}_e is low at the start of the discharge.

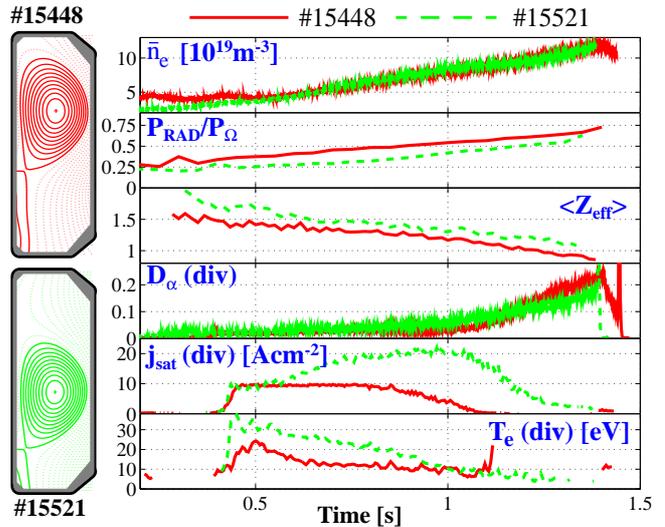


Figure 3: Identical ohmic density ramp discharges for two equilibria with varying X-point height and thus connection length. Both have radiation fractions approaching 75% and low Z_{eff} at the highest densities. $I_p = 340$ kA in each case.

H-MODE TRANSITIONS WITH ECRH Below a density of $\bar{n}_e = 3.5 \times 10^{19} \text{ m}^{-3}$ for the ion ∇B drift direction towards the X-point and elongation in the range $1.5 < \kappa \leq 2$, ohmic H-mode transitions are not obtained in TCV. Recent experiments [3] using ECRH (for which cut-off occurs at a local density of $\bar{n}_e = 4.3 \times 10^{19} \text{ m}^{-3}$) have shown that this threshold density is significantly reduced in the presence of heating. Figure 4 shows that transitions do not occur for $\bar{n}_e < 2.5 \times 10^{19} \text{ m}^{-3}$ with the 1.5 MW of power currently available. No systematic dependence of threshold power, P_{thr} , on elongation has been observed in these preliminary experiments. In ECH plasmas, P_{thr} increases sharply as the density is reduced, in contrast with

the scaling ($P_{\text{thr}} \propto \bar{n}_e^{0.7}$ approximately [5]) generally observed with heating systems other than ECRH. The decoupling of the ion population from the electrons at low density and high electron temperature may be the cause of this behaviour.

ECCD EXPERIMENTS The ability to change both the poloidal (real time) and toroidal (between discharges) angles at which ECH power is injected permits a wide variety of experiments aimed at investigating both pure ECRH and ECCD. In one such study, the toroidal launching angle, ϕ , has been varied from -35° to $+35^\circ$ with a total of 1.5 MW of power being injected near the plasma center (the 0° case corresponding to pure ECH). Figure 5 shows the ϕ dependence of the fast-electron bremsstrahlung emission from the plasma centre in the photon energy range $40 < E_{\text{ph}} < 50$ keV measured using a multichannel hard X-ray camera on loan from the Tore Supra tokamak [6]. For $\phi \approx 0^\circ$, there is no measurable suprathermal population and the photon energy spectra are consistent with a Maxwellian distribution at a temperature close to that measured by Thomson scattering. During ECCD, photon count rates increase with increasing ϕ in both co- and counter-ECCD directions. The highest values of T_e ever measured on TCV ($T_{e0} \approx 11$ keV) [7] were obtained with counter-ECCD at $\phi = -7^\circ$ and -14° , for which electron energy confinement times up to twice RLW are obtained, indicating that improved confinement related to shear modification is occurring in the plasma centre under these conditions.

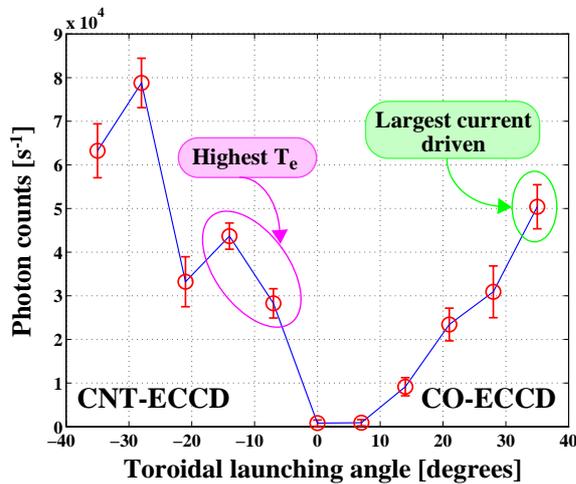


Figure 5: Toroidal angle variation of the hard X-ray emission from the plasma centre in the energy range 40-50 keV during a shot-to-shot angle scan at constant $I_p = 170$ kA, $\kappa = 1.3$, $\delta = 0.3$ and $n_{e0} = 2-2.5 \times 10^{19} \text{ m}^{-3}$.

and avoiding the generation of MHD modes. The latter are at the origin of disruptions in alternative scenarios in which on-axis co-ECCD of all three sources produces higher current drive efficiencies at the expense of very peaked profiles and subsequent rapid loss of confinement. A number of experiments have also been performed demonstrating that even in

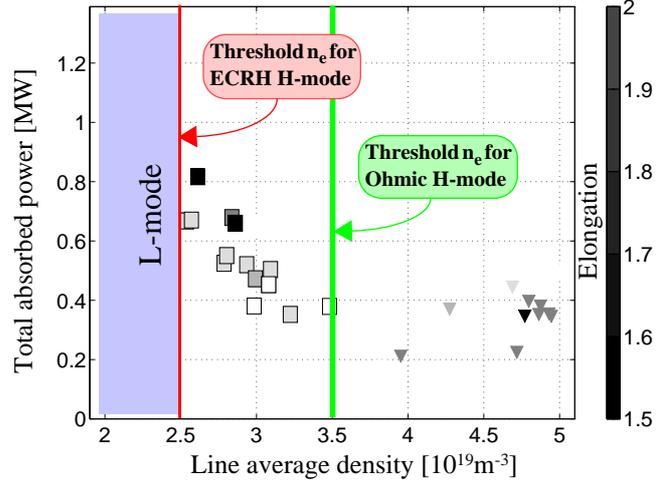


Figure 4: Power at the L-H transition for ohmic and ECR heated SN diverted plasmas of varying elongation and the ion ∇B drift towards the X-point. \blacktriangledown : Ω -H transitions, \blacksquare : L-H transitions

As also shown in Fig. 5, the highest current drive efficiencies have been measured for $\phi = +35^\circ$. Under these conditions, stationary, full current replacement has been achieved, sustaining nearly 125 kA for 1.9 s, limited only by the gyrotron pulse length [8]. Figure 6 shows how the ohmic transformer current reaches a constant value almost immediately after switch-on of 1.5 MW of co-ECCD yielding a current drive efficiency of $\gamma_{\text{CD}20} \approx 0.01 \text{ AW}^{-1} \text{ m}^{-2}$ for $n_{e0} = 1.5 \times 10^{19} \text{ m}^{-3}$, $T_{e0} = 3.5$ keV and $R = 0.88$ m. Although full non-inductive current drive occurs rapidly after the application of heating, the time variation of the plasma inductance and elongation included in Fig. 6 demonstrates that the current profile requires about 500 ms to relax. These stationary conditions are obtained only if the power deposition of the three available sources is distributed carefully over the minor radius, leading to broader current and pressure profiles

the case of pure ECH, sweeping the power deposition location off-axis can have considerable effect on MHD activity, notably sawtooth periods and amplitudes [9]. This is a result of local heat deposition and finite current drive components due to a non-zero projection of the parallel wave vector onto the local field when moving off-axis. The degree to which sawteeth behaviour is modified depends on the direction of this current drive, itself dependent on the toroidal field direction and deposition location (above or below the magnetic axis). With increasing central ECH power deposition, positive triangularity and low elongation have a stabilising effect on sawteeth leading to longer sawtooth periods and higher crash amplitudes, in qualitative agreement with the effect of triangularity on Mercier and resistive MHD stability [10]. High κ or negative δ would therefore appear to be attractive for the reduction of heat pulses and seed islands which can follow high power sawtooth crashes. There is also evidence for a marginal increase in electron energy confinement time with negative triangularity at absorbed ECH powers of up to 1.4 MW [10].

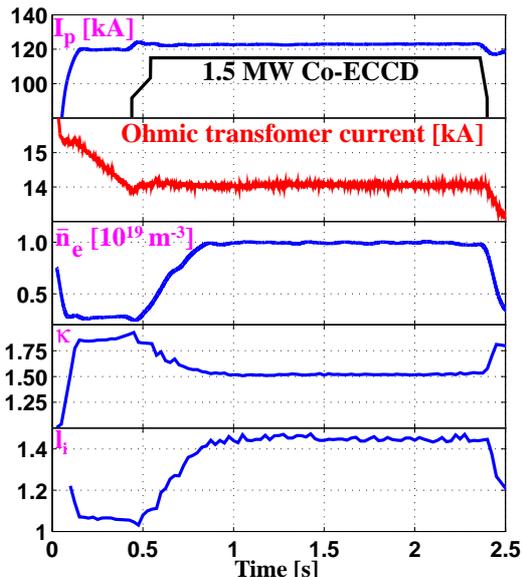


Figure 6: Steady-state, full plasma current replacement for 1.9 s with 1.5 MW of co-ECCD distributed over the minor radius in a limited plasma with $\delta=0.3$ and $I_p = 125$ kA.

CONCLUSIONS The traditional capacity of TCV for creation of a wide range of plasma shapes has led to a large database of equilibria showing that, for stability margins of current interest, there should be no difficulty with plasma control using external coils only. In addition, at least in L-mode, SN discharges with $\kappa > 2$ and low q_{95} appear to have similar confinement to limited equilibria at lower elongation. Divertor detachment is now regularly obtained in TCV and its characteristics are being studied, in particular with respect to variable and extremely open magnetic geometries. With the addition of the first third of an eventual 4.5 MW of ECH, important new ECRH and ECCD studies are now being pursued. The high degree of flexibility in toroidal and poloidal launching position and high power density has revealed interesting features in the plasma response to off-axis deposition, yielded new results regarding the characteristics of ECCD at high toroidal angles and produced the highest electron temperatures so far observed in TCV ($T_e > 10$ keV). Steady-state, full current replacement of 125 kA has been demonstrated for 1.9 s using co-ECCD distributed over the minor radius. This corresponds to more than 400 energy confinement times and 4 current diffusion times.

ACKNOWLEDGEMENT

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