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Preliminary Confinement Studies during ECRH in TCV

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Introduction - Following extensive Ohmic heating confinement studies on various plasma shapes [Moret 97], ECRH heated experiments were started on small, low elongation plasmas in the TCV tokamak with positive and negative triangularities. For these studies, an EC power of up to 1 MW at 82.7 GHz (second harmonic X2) was injected, representing for such discharges up to 14 times the Ohmic power during EC [Pochelon 97]. When complete, the ECW system will provide 3 MW second harmonic and 1.5 MW third harmonic at pulse lengths of 2 seconds [Goodman 97]. For TCV ($R = 0.89$ m, $a = 0.25$ m, $I_p < 1.2$MA), the nominal field of $B = 1.44$ T and the frequency of 82.7 GHz place the resonance slightly on the high-field side (HFS) of the magnetic axis ($\Delta\rho$=-0.16 to -0.2). The effects of different heating localisations on confinement and MHD were studied using *1)* the mobility of the launcher mirrors (in particular for poloidal angle θ sweeps), *2)* the large vertical room for displacing the plasma in the TCV vessel and *3)* the radial displacement of the cyclotron resonance with magnetic field. Initial studies of heating and confinement have con-centrated on close-to-circular plasmas to study power absorption in a large variety of beam-plasma geometries and to compare with earlier results of other machines - a necessary first step before investigating more strongly shaped plasmas.

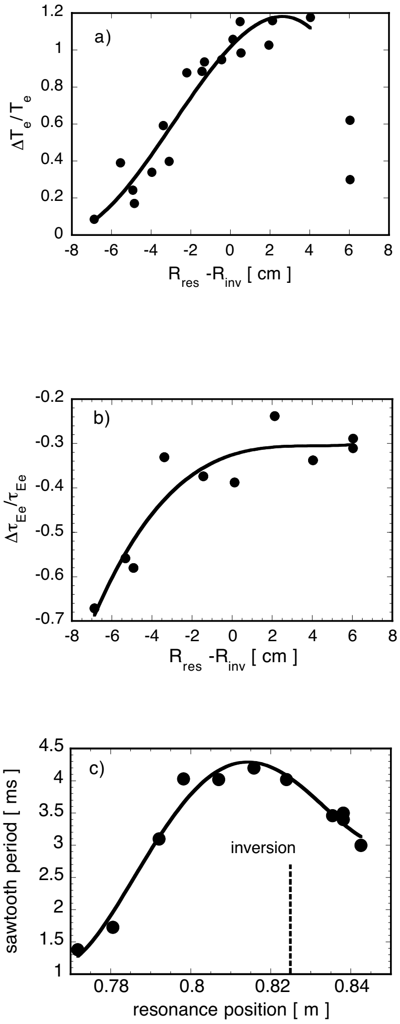

Fig. 1 Radial deposition scan relative to q=1 surface by varying B:
a) Relative T_{eo} increase, 2<q<6
b) Relative global τ_{Ee} degradation
c) Sawtooth period, q=1 position indicated
(κ=1.32, q=5, n_{eo}=2 10^{19}[m^{-3}], P_{EC}=360kW)

Confinement - To study basic confinement dependencies (B, q, n_e, P), second harmonic EC power was launched on a small target plasma placed in front of the launcher with quasi-horizontal launch in order to minimise refraction effects at high density ($\theta=18^o$, z=38, κ=1.31,

$\delta=0.15$). Scan domains were: $1.32<B<1.45$T, representing a 20% plasma radius displacement of the resonance around q=1; $1.5\times10^{19}\mathrm{m}^{-3} < n_{eo} <$ over-dense (X2 cut-off density is $4.25\times10^{19}\mathrm{m}^{-3}$, TORAY guaranteed full absorption up to $4.0\times10^{19}\mathrm{m}^{-3}$); $2.2<q<6$; $P_{EC}\leq1$MW. In the q-scan, ratios of P_{tot}/P_{OH} from 3 to 14 were obtained during ECRH for 1MW power injection.

The effects of *localisation* are very important during ECRH. As an example, in a B-field scan at moderate power (0.5MW), the temperature response depends strongly on the location of power deposition relative to the inversion surface obtained from soft X-ray tomography (often assumed equal to the q=1 surface). The *central electron temperature* T_{eo} is maximum for a power deposition close to the q=1 surface (Fig. 1a); although some low q~2.5 discharges may show some increase for very central heating. The *global electron confinement time* τ_{Ee} (Fig 1b) is relatively independent of resonance position when heating inside q=1 and drops from about a/10 outside the inversion surface, meaning that efficient heating requires deposition roughly inside q=1. Data in Fig. 1 a,b) cover a large range of q values: $2.3<q<6.7$. Some low-q high-power shots may indicate a τ_{Ee} maximum (as with T_{eo}) for q~1 deposition. It is however not yet completely clear whether deposition at the magnetic axis is less efficient than heating at the q=1 surface. Nevertheless, the *sawtooth period* is maximum for q~1 deposition (Fig. 1c), which yields a dependence similar to the central electron temperature response [Pietrzyk 98].

As a function of the *safety factor q*, the confinement time τ_{Ee} increases with q, maximising at q~5 and dropping beyond (Fig. 2). In the high q shots of this scan (P_{EC}=500kW, $0.77<R_{res}<0.84$ m), the power was deposited significantly outside the q=1 surface when increasing q. The drop at high q can probably be explained by analogy to the drop observed in the radial B-field scan (Fig. 1b) when heating outside q=1. Figure 2 also contains the corresponding ohmic-confinement-time q dependence, which saturates at q>5. Even though confinement exhibits the Neo-Alcator q scaling as in ohmic plasmas [Weisen 97, Moret 97], confinement improvement with q is not as high as for ohmic heating and confinement power degradation appears stronger at high q. It is likely that higher additional power will further degrade the favourable scaling with q. In the present heating experiments, however, this beneficial ohmic scaling feature still holds for ECRH power ratios $P_{ECRH} / P_{OH} > 9$.

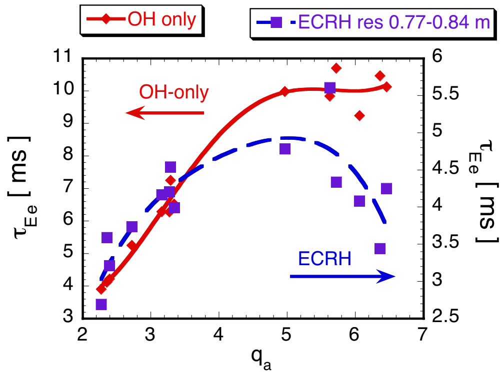

Fig. 2 τ_{Ee} versus q, for different deposition radii in a Bφ scan in ECRH, and ohmic plasmas.

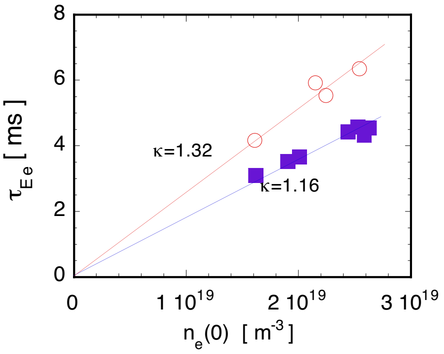

Fig. 3 τ_{Ee} as a function of n_{eo} for two elongations ($\kappa=1.16, 1.32$; $\delta=0.07, 0.16$, $q=4.7, 5.2$)

The dependence of τ_{Ee} as a function of the *density* on axis is shown in Fig. 3. Low elongation plasmas ($\kappa=1.16$ and 1.32) with $q\approx5$, located in front of the launcher to minimise refraction effects at high density, were chosen, for this scan. Heating just below cut-off density appeared operationally difficult due to the ECRH-induced density pump-out, which explains the absence of data close to cut-off. The confinement time scales nearly linearly with density, as in previous low density EC experiments [e.g. Alikaev 85]. The two elongations covered indicate the favourable effect of elongation.

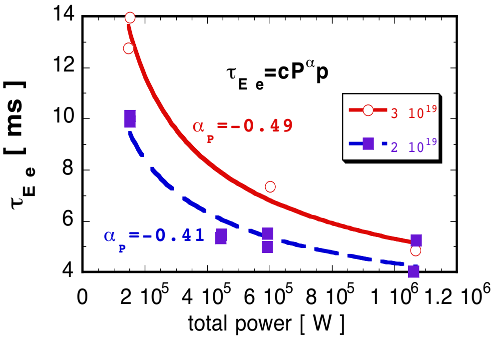

Fig. 4 τ_{Ee} power degradation for two densities, q=5

Power-induced confinement degradation was studied with 1MW of additional power. Heating results with P_{EC}>500kW contain an ECCD component since one of the launchers was placed with a non-zero toroidal angle. This should, however, have a limited effect on confinement, since power degradation in ECCD was observed to be similar to ECRH [Esipchuk 95]. The power-induced degradation exponent α_P, (τ_{Ee}~P^{α_P}), measured for q=5 at n_{eo}=2 and $3\times10^{19}m^{-3}$ (see Fig. 4), and at q=2.5 for a density close to $2\times10^{19}m^{-3}$, is as expected: α_P ~ -0.5, or possibly somewhat lower. Note that this confinement degradation may have been influenced by the effect of slightly off-axis heating on profiles and MHD-activity. In particular, the sawtooth period is lengthened for a deposition close to q=1, and sawtooth activity is observed to disappear at the higher.

Summarising, this yields density and power exponents comparable to the ones obtained in T-10 electron cyclotron heating experiments: α_n ~ 1, α_P ~ -0.5 [see Alikaev 85].

The study of confinement with triangularity was done with medium q=3.5 at 500kW. The power was deposited at the q=1 surface. Both ECRH and ohmic cases are shown in Fig 5a. As with ohmic heating, confinement improves with increasing negative triangularity during ECRH. Note that the improvement of confinement with ECRH is less than with purely ohmic heating, as shown in Fig. 5b.

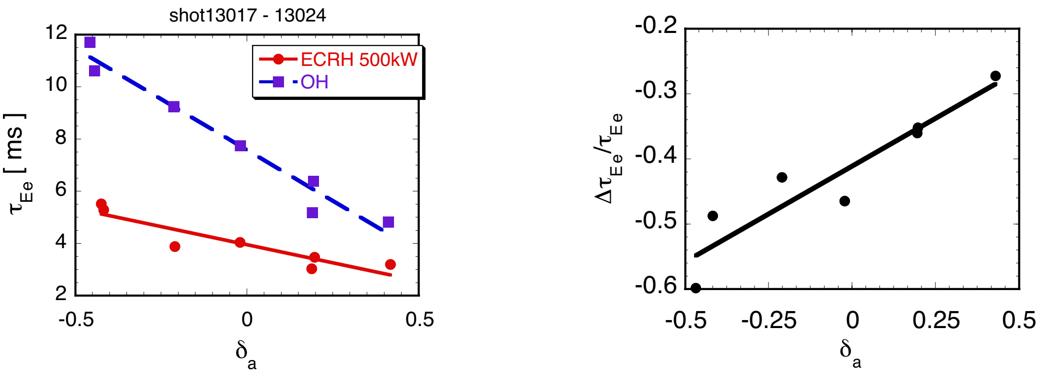

Fig. 5

a) τ_{Ee} as a function of δ, ohmic and ECRH data. (P_{EC}=500 kW, κ=1.32, q=3.5, n_{eo}=2 10^{19} [m^{-3}]).

b) Relative τ_{Ee} power degradation as a function of δ (same data as in Fig. 5a).

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Power coupling to the plasma - ECRH heated discharges have been simulated using the *ASTRA transport code*. The T-10 transport model [Dnestrovskij 93] in the ASTRA code was used without any change of transport model or coefficients and is found to reproduce the central temperature evolution of ohmic TCV discharges. In the ohmic regime, the measured TCV temperature profiles $T_e(r)$ are also well described (accuracy ±10%) by the T-10 model (i.e. similar electron transport and confinement laws can be used). To simulate correctly the measured central temperature during ECRH, it was necessary to use an absorption efficiency factor k~0.65 (where $P_{ab} = k\ P_{input}$ or more correctly, $P_{ab} = k\ P_{ab}{}^{TORAY}$), as in other ECRH experiments [Alikaev 85]. The T-10 model then correctly describes not only values and profiles of $T_e(r)$ and $n_e(r)$ but also the temperature responses for different power deposition profiles. Simulated discharges had sawteeth, q=3.1, κ=1.26, and oblique beam incidence angles on the resonance: $15^o<\theta<45^o$. For a non-sawtoothing discharge with high q~6, κ=1.32, $n_{eo}=2\times10^{19}m^{-3}$ in quasi-horizontal launch ($\theta=18^o$), where T_{eo}=3keV was obtained with 0.5MW, a higher k-factor, close to unity was appropriate.

The derivative of the stored energy deduced from the *diamagnetic probe* yields power coupling efficiencies similar to those from transport calculations, i.e. ranging approximately from 65 to 85%. Note that when transport calculations give good coupling, so do the diamagnetic probe measurements. The observation that the k-factor changes with the experimental configuration, while the calculated absorption from ray tracing remains constant (100%) indicates a violation of the assumptions made either in TORAY or ASTRA codes, as well as the diamagnetic loop method of determining the absorbed power.

Conclusions - Heating effects, MHD-activity and confinement depend strongly on the localisation of the EC power deposition. Sawteeth are stabilised for power deposition on q=1 and mode activity is destabilised for power deposition slightly inside the q=1 surface with corresponding effects on electron temperature: dramatic changes in central temperatures occur when heating is close to q=1 or towards the magnetic axis.

Within the range of plasma shapes and plasma currents investigated, the electron confinement time, τ_{Ee}, increases with density, elongation and negative triangularity ($0.4>\delta>-0.4$), similar to Ohmic heating. In addition, τ_{Ee} increases with q_a up to q_a~5 after which it decreases. There is little dependence of τ_{Ee} on the heating location provided it is inside the q=1 surface. As the heating location is moved outside the q=1 surface, τ_{Ee} decreases. This may be the explanation of the observed decrease in τ_{Ee} at high q_a.

The power-induced degradation exponent ($\tau_{Ee}\sim P^{\alpha_P}$) is generally as expected: $\alpha_P\sim -0.5$. However, there are some indications that the power degradation may be dependent on q_a and δ_a. In particular the power degradation may be stronger at negative triangularity.

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