

Manipulating transport barriers in RTP

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1. Introduction

At the Rijnhuizen Tokamak Project (RTP, $R_0 = 0.72$ m, $a = 0.164$ m, $B_T \leq 2.4$ T, $I_p \leq 150$ kA, pulse duration ≤ 600 ms) it was found that the plasma in RTP has a layered structure [1, 2]. Regions of high electron heat conductivity (χ_e) alternate with regions of low χ_e . The latter are called *transport barriers*. These barriers are located near low order rational values of the safety factor q .

RTP is equipped with strong additional power by means of second harmonic Electron Cyclotron Resonance Heating (ECH, $P_{ECH} \simeq 300$ kW $\sim 7 \cdot P_\Omega$). The ECH power deposition is very localized ($w_{dep}/a < 0.1$); the power deposition radius (ρ_{dep}) can be scanned through the plasma by changing B_T .

Injecting the EC waves under a toroidal angle $\phi_{launch} \neq 0$ gives rise to a noninductive current (I_{CD}) [3]. I_{CD} can have the same or the opposite direction as the inductively driven plasma current (co- or counter-drive). The strict coupling between the profiles of electron temperature (T_e) and q , which normally exists in equilibrium, can be broken with ECCD. This provides means to further scrutinize the concept of transport barriers linked to low order rational values of q .

This paper reports on experiments which were performed in RTP to investigate the effects of ECCD on location and thickness of the barriers. The main diagnostics used are a 20-channel heterodyne ECE radiometer and a high resolution, double pulse Thomson scattering system (TS).

2. Modelling

It was observed that the loss of a barrier is always accompanied by the loss of a low rational q -surface. Therefore, it is assumed that the transport barriers are located near these q surfaces ($q = 1, 4/3, 3/2, 2, 5/2, 3, \dots$). For simplicity it is assumed that χ_e is a function of q only. With a fixed χ_e , i.e. a fixed strength of the barriers, it turned out to be possible to reproduce all data from a complete dataset, in which ρ_{dep} was varied from 0 to 0.6, and the T_e profiles changed from peaked for central ECH to hollow with far off-axis ECH [1, 2]. Fig.1 shows χ_e as function of q , which reproduced standard RTP discharges at $I_p = 80$ kA, $n_e(0) \simeq 5 \cdot 10^{19} \text{m}^{-3}$ (left), and the q and χ_e profiles for a typical discharge with central ECH.

3. Dynamic Scans of ρ_{dep}

In a first series of experiments ρ_{dep} was scanned during a single plasma discharges (by sweeping B_T). When ρ_{dep} crosses a low rational q -surface, the corresponding barrier is lost, the heat is less well confined and a sudden drop in T_e is observed. These dynamic scans of ρ_{dep} were done for different CD efficiencies both in co- and counter-direction. The injection angle ϕ_{launch} was varied between -20 and $+20^\circ$. According to ray tracing calculations with TORAY [4] this corresponds, at the observed T_e and n_e , to values of I_{CD}

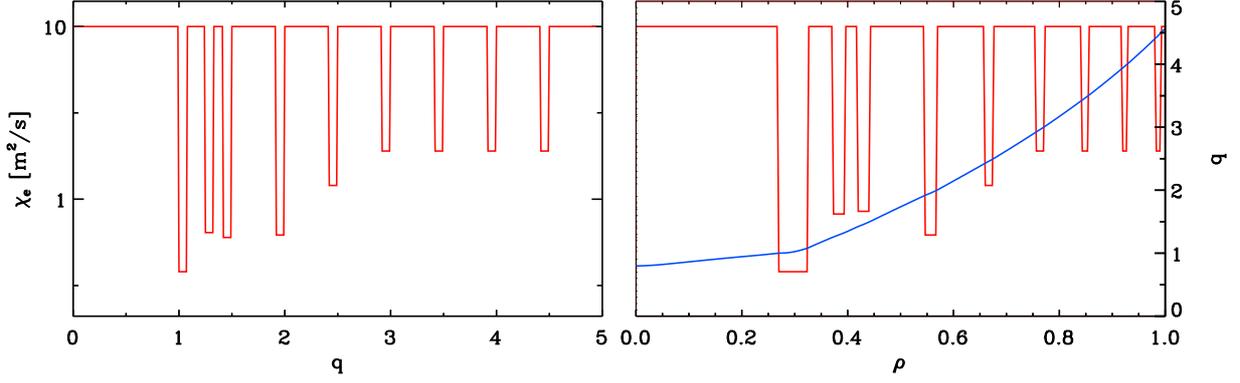


Figure 1: *a*: χ_e as function of q , as used in the modelling of standard RTP discharges ($I_p = 80$ kA, $n_e(0) \simeq 5 \cdot 10^{19} \text{m}^{-3}$). All barriers have been given the same width in q . *b*: q (blue) and χ_e (red) profiles for a typical discharge with central ECH. Note that, due to the low magnetic shear near $q = 1$, the first barrier is much wider than the others.

from -8 to +8 kA for $\rho_{dep} \simeq 0$, rapidly reducing when ECCD shifts off-axis.

When the range of the B_T sweep is sufficiently large, several sudden T_e drops can be observed. The CD efficiency does, however, rapidly decrease when ρ_{dep} moves off-axis. Therefore, the present scan concentrates on the innermost barrier, i.e. the one near $q = 1$.

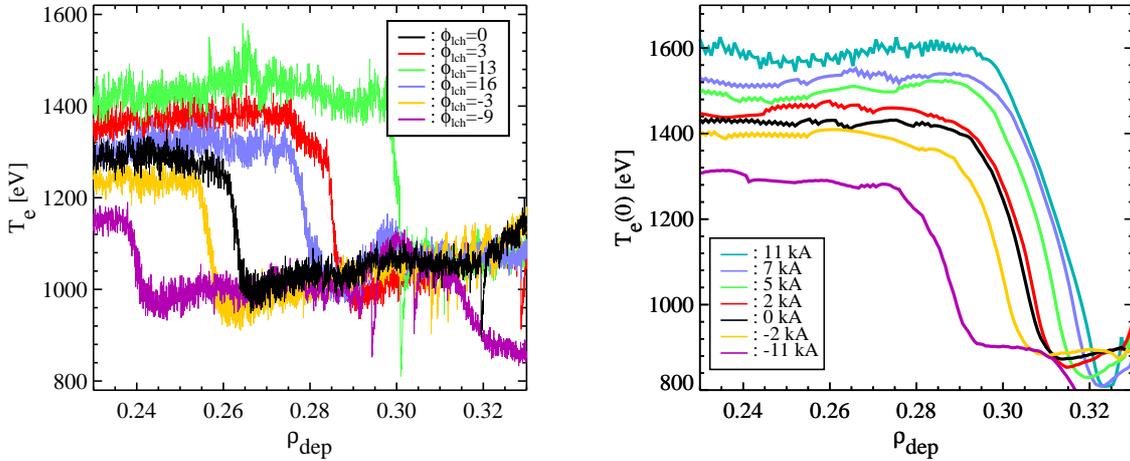


Figure 2: *a*: time traces of $T_e(0)$ from ECE for discharges in which ρ_{dep} was swept, for several values of ϕ_{launch} . Under the conditions at hand, this range of ϕ_{launch} corresponds to $I_{CD} = -8$ to $+8$ kA. *b*: simulations of $T_e(0)$ under the same conditions.

Figure 2a gives time traces of $T_e(0)$ around the time when $q = 1$ is lost, for several injection angles. It is observed that $T_e(0)$ before the transition increases with ϕ_{launch} and is highest for $\phi_{launch} = 13^\circ$. Also, the value of ρ_{dep} for which the barrier is lost, $\rho_{dep,crit}$, is largest for $\phi_{launch} = 13^\circ$. From this it can be concluded that the confinement inside the barrier (for $\rho < \rho_{dep,crit}$) is enhanced with co-driving. The roll-over past $\phi_{launch} = 13^\circ$ might be caused by a deteriorating CD efficiency at large injection angles.

Figure 2b shows simulations with the model described before. The sharp drop in $T_e(0)$ when losing a barrier is also observed here. For both the co and counter-drive case, a shift in $\rho_{dep,crit}$ with CD is seen, as well as a change in $T_e(0)$ before the loss of the barrier. Furthermore, a saturation of this effect for $I_{CD} \approx +5$ kA is observed. This closely resembles the experimental data, although quantitative similarity is not yet established.

4. Static Scans of ρ_{dep}

In another type of experiment, ρ_{dep} was scanned on a shot-to-shot basis. During each discharge ρ_{dep} was kept constant in order to reach steady state. $T_e(0)$ was determined for a series of these discharges. In the pictures obtained this way sharp drops in $T_e(0)$ at certain values of ρ_{dep} are observed (see Fig.3a). As in the dynamic scan case, these drops are the result of losing a barrier.

In these “static scan” experiments attempts were made to obtain the same results as in case of the dynamical scan; shifting and broadening of the barriers by applying ECCD. It can, however, be seen from the data in Fig.3 (left), that with both co and counter drive $\rho_{dep,crit}$ shifts *inwards*. Also the reached central temperatures are lower than without current drive. It can be concluded that the improvement of confinement in the dynamic case is only a transient effect; it can not be reproduced in a steady state situation.

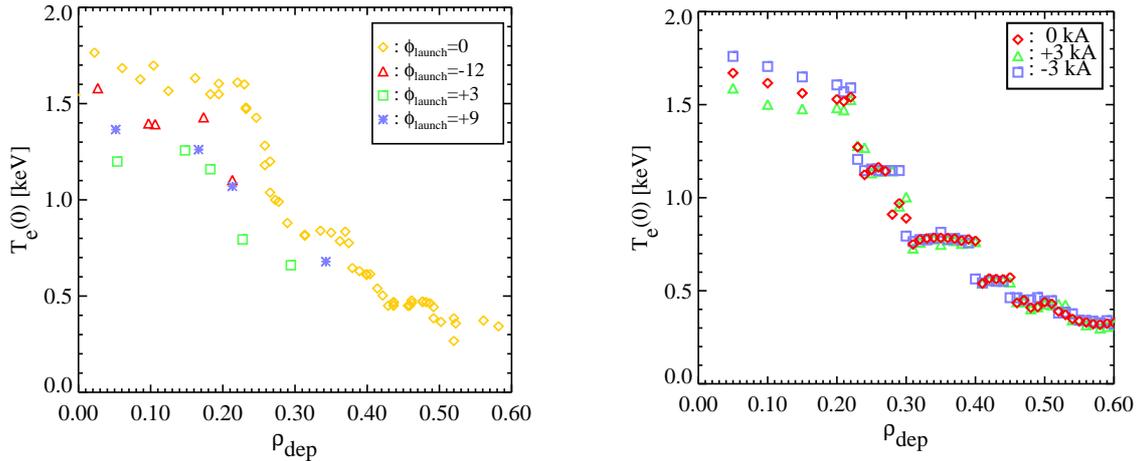


Figure 3: *Left: shot to shot scan of ρ_{dep} in a series of similar discharges ($I_p = 80$ kA, $n_e(0) \simeq 5 \cdot 10^{19} \text{m}^{-3}$), for various values of ϕ_{launch} , corresponding to I_{CD} between -7 and $+7$ kA for $\rho_{dep} \simeq 0$, reducing to less than 1 kA for $\rho_{dep} \geq 0.3$, $T_e < 1 \text{keV}$. Right: simulations under the same conditions.*

The static scan was simulated with the parameters which gave a good reproduction of the on- and off-axis heated discharges without ECCD, and various positive and negative values of I_{CD} added. As can be seen from Fig.3b, the model did neither predict the decrease of $\rho_{dep,crit}$ with co- and counter-drive, nor the dependence of $T_e(0)$ on ECCD.

5. Fine tuning of q profile

In a final series of experiments attempts were made to create a low shear region around $q = 1$. It was hoped that this would create a wide barrier, and hence enhanced T_e inside $q = 1$. This was attempted by increasing q_0 by means of central counter current drive in discharges with $q_a = 3.5 - 4.5$.

The experiments were partially successful. Indeed, very high $T_e(0)$ was observed, see

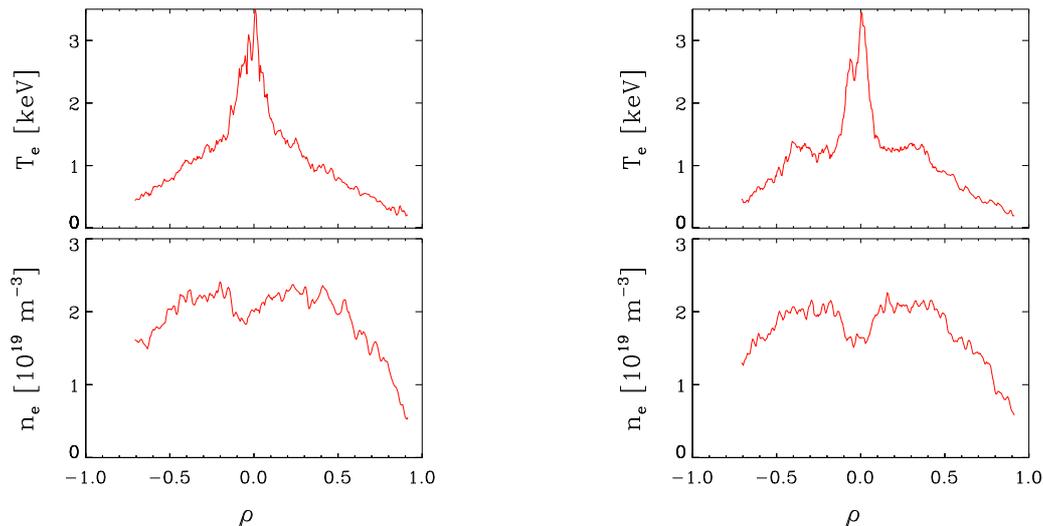


Figure 4: T_e profiles as measured with TS for discharges with $I_p = 110$ kA ($q_a = 3.5$), with central $I_{CD} \simeq -20$ kA ($\phi_{\text{launch}} = 12^\circ$). The counter CD reduces j_0 such that q_0 is above 1, and there are two $q = 1$ surfaces present. Note the hollow n_e profile. Often off-axis sawteeth are observed between the two $q = 1$ surfaces; the data in the right plots were taken just after such an event.

Fig.4; however, the area of high T_e was much smaller than without CD. Interestingly, often off-axis sawtooth activity is observed in the region just outside the steep gradient region; these events leave the hot core unaffected. This is interpreted as the signature of a *double* $q = 1$ surface in the plasma. I.e., the central CD lifts q_0 to a value above 1, and q has an off-axis minimum just below 1. Off-axis sawteeth are often observed at higher q values, with $q_{\text{min}} \simeq 3/2, 2, 5/2$ or 3 in off-axis heated RTP discharges [5].

6. Conclusions

We have shown that on RTP the electron thermal barriers can be manipulated by ECCD. With co drive it is possible to enhance the confinement of heat transiently and push the barrier region outward in a dynamic situation. This could, however, not be reproduced in steady state. With modest counter-drive in low q_a discharges a double $q = 1$ surface was created, with a very hot, but small, core.

These experimental observations provide further evidence that electron thermal transport barriers are linked to low rational values of the q profile. However, not all observations could be modelled successfully yet.

Acknowledgements

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