Detachment in Variable Divertor Geometry on TCV

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Abstract. Although the requirement of shape flexibility in TCV precludes the use of fixed baffle or optimised divertor target structures, it does allow for the investigation of diverted equilibria not possible in more conventional tokamaks. One such single null configuration is simultaneously characterised by a very short inboard poloidal depth from X-point to strike point on a vertical target and an extremely long poloidal depth to a horizontal target on the outboard side. Density ramp discharges leave the inboard target plasma attached even at the highest densities, whilst clear partial detachment is observed at the outboard target. Modeling of this configuration using the B2-Eirene code package shows that the outboard divertor achieves high recycling at very low densities, with the rollover to detachment occurring near the outer strike point very soon after the density ramp begins. An important result of the modeling effort is that, due to the low apparent densities in the TCV outboard divertor, the code cannot quantitatively reproduce the absolute level of observed detachment without artificially increasing fivefold the charged particle sink due to three-body and radiative recombination.

1. Introduction

An interesting aspect of certain diverted equilibria possible on the TCV tokamak is the geometrical contrast between inner and outer strike zones. This permits the influence of horizontal and vertical targets and short and long divertor poloidal depths to be investigated simultaneously with regard to their effects on the divertor plasma and in particular on detachment [1]. In addition, the relatively unconventional (with regard to most operating tokamaks) nature of these configurations makes them an interesting subject for code modeling. This has been performed for TCV data using the coupled B2-Eirene package [2] and some results are presented here along with experimental data.

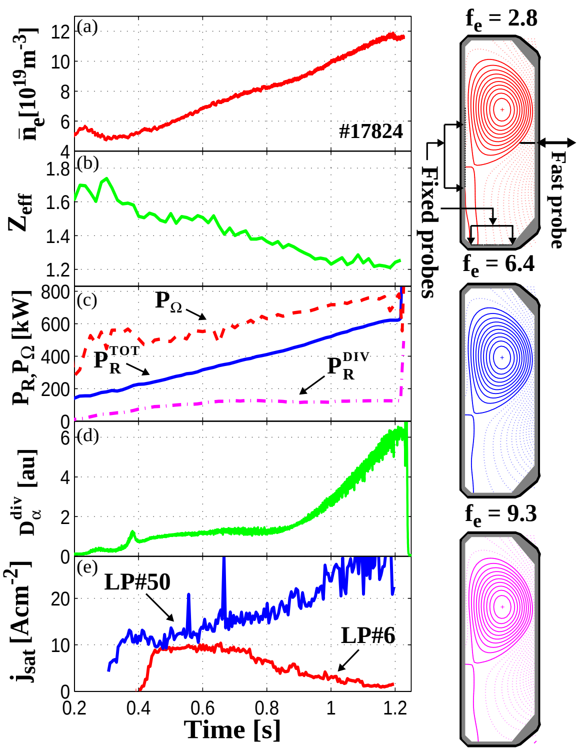

Fig. 1 Illustrating the time dependence of some relevant plasma sigals for a typical density ramp discharge for detachment studies.

2. Experiment

A typical density ramp discharge is summarised in Fig.1, along with three of the equilibria studied. All have κ_{95} = 1.6, δ_{95} = 0.35 and fixed height (57 cm) from outer target to X-point. In each case, I_p = 345 kA (q_{95} =

2.9), with fixed flux expansion (≈ 4) at the inner target but variable at the outer strike zone in the range f_e = 2.5 → 10. In what follows, f_e is taken to refer to this outer target flux expansion the variation of which can be clearly seen in the equilibria of Fig.1. All cases discussed here have unfavourable ∇B drift direction and are deuterium fueled density ramp discharges, leading invariably to an X-point MARFE but not necessarily to disruption ($\bar{n}_e \approx$ 65% of the Greenwald limit at maximum). One may note the very low Z_{eff} (Fig. 1b) and the low level of divertor radiation (Fig. 1c), taken here to mean all radiation found below the X-point. Most of the former originates at the X-point since, even at the lowest densities in the ramp, the outer divertor is too cold for carbon (the dominant impurity in TCV) to radiate efficiently.

3. Results and Comparison with B2-Eirene Code Modeling

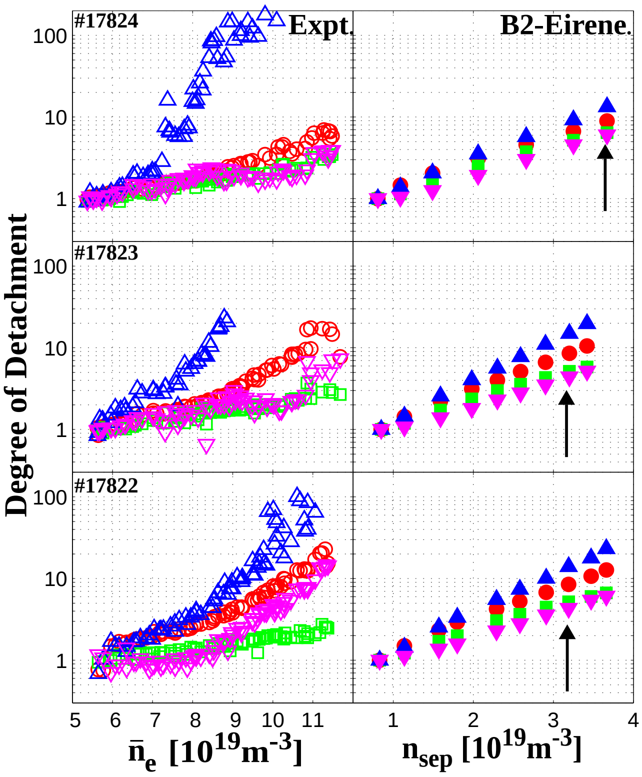

Fig. 2 Strike point and integral ion flux DOD's from experiment and B2-Eirene simulations as a function of density (main or separatrix) and outer target f_e. ❍: Outer divertor, integral current, ❑: Inner divertor, integral current, Δ: Outer divertor, separatrix current density, ∇: Inner divertor, separatrix current density. The vertical arrows indicate the B2-Eirene run numbers corresponding to the D_α distributions of Fig. 5.

In what follows, code results are presented along with experimental data to facilitate comparison. In the former, the power crossing the separatrix, P_{SOL}, the chemical sputtering yield, Y_{chem} and the transport coefficients, $D_\perp$, $\chi_\perp$ have been fixed at 0.36 MW, 3.5% and 0.2 m^2s^{-1}, 0.9 m^2s^{-1} respectively for all densities and equilibria. These parameters are chosen so as to approximately match upstream profiles and target ion fluxes at the lowest densities in the ramp.

In Fig.1e the parallel ion flux densities measured by target Langmuir probes at the inner (probe 50) and outer (probe 6) strike points show that the inner target remains attached throughout the density ramp, whilst at the outer target a plateau value is already attained at divertor formation followed by a rollover to detachment at around $\bar{n}_e \approx 8\times10^{19} m^{-3}$. This suggests that the outer divertor plasma rapidly accesses the high recycling regime and is close to detachment at the beginning of the density ramp. With increasing f_e, although a plateau region is always attained, detachment at the strike point occurs at progressively lower densities. This can be seen clearly in Fig.2 which compiles experimental and theoretical values of the Degree of Detachment [3], defined as DOD = $C\bar{n}_e^2/I_{sat}^{div}$ with I_{sat}^{div} the probe ion saturation current to the divertor target, expressed either as a peak value at the separatrix or an integral value across the target. The DOD's describe the extent to which the 2-point model [4] scaling $\Gamma \propto \bar{n}_e^2$ is obeyed, with DOD » 1 indicating detachment. As f_e increases, the outer target integral DOD progressively increases for given $\bar{n}_e$ indicating detachment right across the target. Except at the highest f_e and highest $\bar{n}_e$, the inner target remains largely attached everywhere. With the exception of the outer target separatrix DOD's, there is excellent agreement between the B2-Eirene predictions and experiment both in absolute magnitude and relative ordering amongst the individual DOD's. However, and this is one important outcome of the code modeling effort, with the chosen run parameters, B2-Eirene is unable to match experiment in this way *without artificially increasing the rate coefficients for three body and radiative recombination by a factor of 5*. These pathways to recombination: $e+D^+ \rightarrow D_o+h\nu$ (radiative) and $e+e+D^+ \rightarrow D_o+e$ (3-body) are assumed to be the most important electron-ion recombination channels in operation for temperatures and densities common to most tokamak divertor plasmas [5]. Without increasing these reaction rates, insufficient recombination occurs for the observed degree of detachment to be reproduced. Even with this artificial modification, the code fails to reproduce the strong strike point detachment seen experimentally.

Experiment and theory are again compared in Fig.3, on this occasion in terms of scrape-off layer (SOL) and divertor profiles of T_e, n_e and electron pressure, p_e, measured with target probes and a fast reciprocating probe entering the edge plasma at the tokamak midplane (Fig.1). All profiles are mapped to the outer midplane at the magnetic axis of the equilibrium. In the very low density case, to the left of Fig.3, the experimental data indicate the divertor plasma to be in the low recycling regime with roughly equal upstream and downstream T_e and p_e. Agreement with code results is reasonable given that run parameters where not optimised

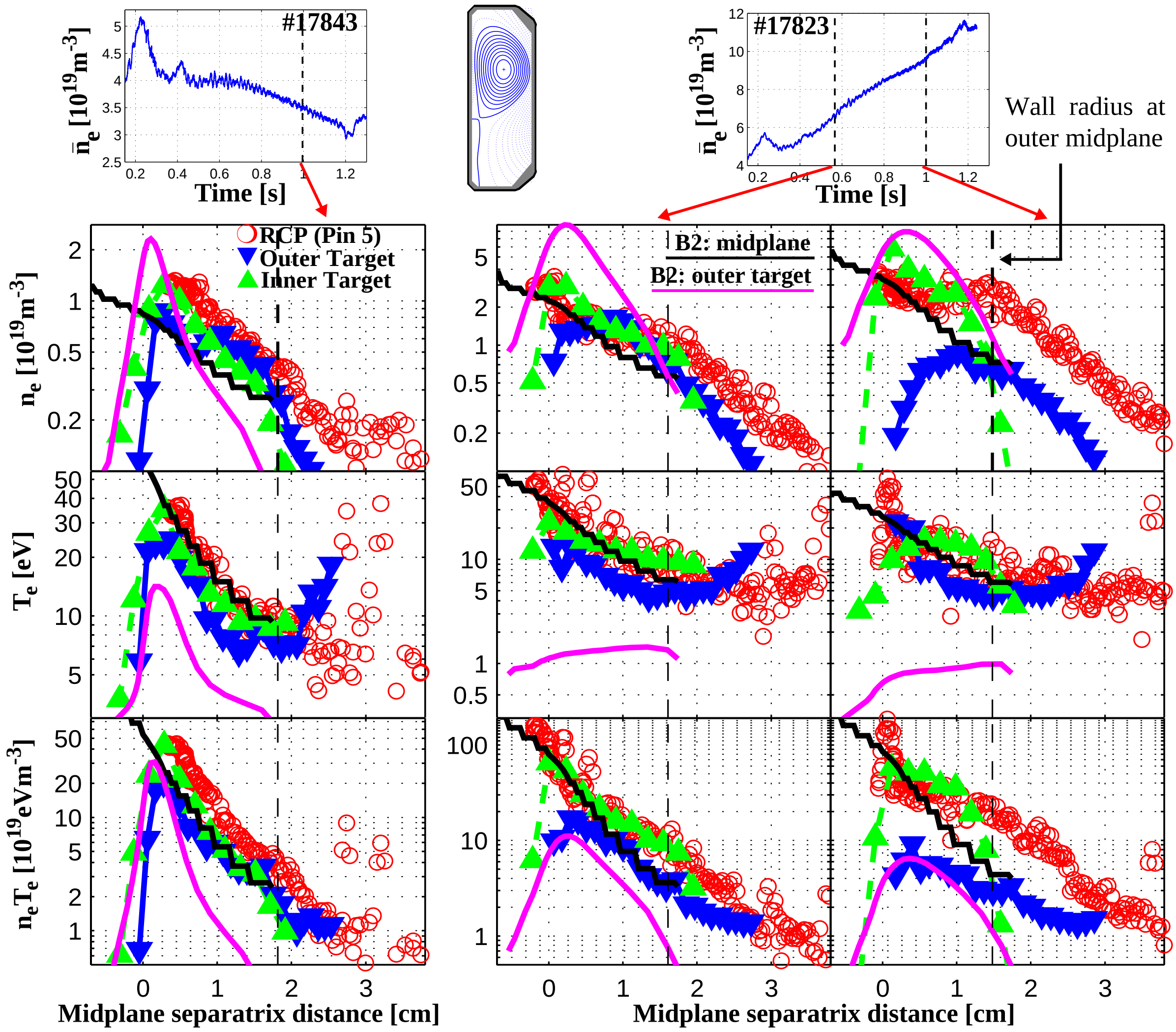

Fig. 3 Compilation of fast reciprocating and divertor target probe profiles mapped to the magnetic midplane for a very low density case (TCV #17843, left) and during a high density ramp discharge (TCV #17823, right). In both cases f_e = 6.4. B2-Eirene profiles for the outer target only are also included from runs approximately matching the observed midplane profiles.

for this case. At the beginning of the density ramp, when upstream profiles are approximately matched, one notes the large discrepancy in the values of simulated and measured outer target T_e. This is preserved at higher densities and in turn leads to large differences in density at the target when comparing theory and experiment. By coincidence, agreement is rather good with regard to p_e in the divertor. That the Langmuir probe measured T_e can be an overestimate of the true value is nothing new [6] and there are strong arguments for the case of the TCV divertor in support of significant deviations of the measured T_e from the real value local to the outer target under high recycling and detached conditions [7].

For the case of lowest flux expansion, Fig.4 illustrates the comparison between measured and simulated outer target perpendicular ion flux profiles (at low f_e, field line impact angles are sufficiently high as to avoid problems associated with probe shadowing by adjacent tiles leading to erroneous measured fluxes [1]). Whilst profile shapes are evidently less well matched, absolute values of maximum ion flux are in good agreement. With increasing separatrix density, the simulated ion flux increases and then begins to decrease, corresponding to a certain degree of separatrix detachment. But, as mentioned above, a charged particle sink sufficiently high for any significant detachment to occur (a maximum of 30% of the ion flux for the highest density B2 case in Fig.4) can only be obtained if recombination rate coefficients are artificially increased. Even this level of recombination is far from sufficient to reproduce the level of separatrix detachment seen in Figs.4 and 2 at the highest densities.

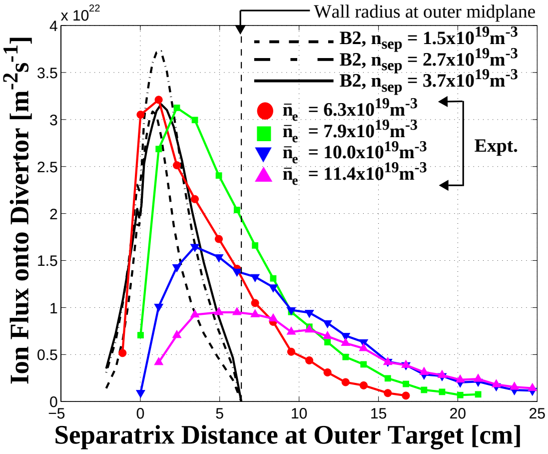

Fig. 4 Experimental divertor ion flux profiles at the outer target for low f_e (#17824) and four values of plasma density compared with B2-Eirene predictions at three values of model separatrix density.

As a further example of the comparison between experiment and simulation, Fig.5 compiles model predictions, at each value of f_e, of the 2-D distribution of D_α emission in the divertor and inverted emissivities from tangential CCD camera measurements of the same emission. The latter originates both from excitation and recombination processes. In the case of the experimental data, distributions are compared at discharge times (or, equivalently, values of $\bar{n}_e$) having approximately the same outer target integral DOD (Fig.2), whilst the model cases correspond to runs for which the level of total recombination is similar. Agreement is satisfactory with regard to the differences when passing from low to high flux expansion in the vertical extent of the emission. The indications are this is likely due to more uniform distribution of momentum losses further up the outer leg owing to the greater neutral transparency of a laterally "thinner" divertor. Code and experiment differ, however, with respect to the localisation of D_α emission at the target. Whilst the simulation places the highest intensity at the strike point and even into the private region, experiment shows the emission to be localized further out in the divertor fan, especially at high f_e. This behaviour is not currently understood but is most likely strongly linked to the inability of the code to reproduce the high degree of strike point detachment. One may also note in Fig.5 how the two extreme flux expansions are very similar from the point of view of code results. This is also reflected in other aspects of code output, particularly in the levels of recombination achieved at a given density.

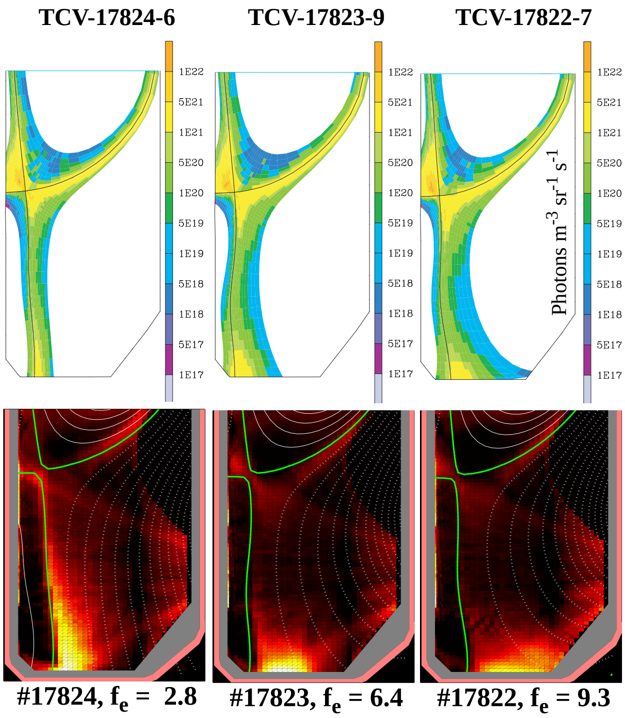

Fig. 5 Comparing visible CCD camera inversions of D_α emissivity (bottom) with B2-Eirene simulations (top) for the three values of outer target f_e. All experimental data are plotted on the same, arbitrary, intensity scale. For the model distributions, the cases correspond to the vertical arrows in Fig. 2

Concerning the essential differences between the results of experiment and simulation, the problem lies with the low apparent densities in the TCV divertor. Although outer target detachment is readily observed experimentally, it can only be obtained theoretically without adjustment of recombination rates if the upstream density is fixed at values significantly higher than measured experimentally. This in turn yields target ion fluxes incompatible with observed values. The modelling strategy has therefore been to reduce P_{SOL} such that upstream densities stay low enough when detachment occurs and to increase the carbon chemical sputtering yield such that radiation balance is achieved at the relatively low divertor (and hence neutral) densities implied by the low ion fluxes seen experimentally. Whilst this approach leads naturally to the low divertor T_e (Fig. 3) required for recombination to occur, the effective (3-body and radiative) rate coefficient at these temperatures is strongly density dependent and is too low for recombination to play a role, at least if the rate coefficients are not artificially increased. An alternative mechanism for charged particle removal, the action of a cold plasma buffer just in front of the target [5], is unimportant in TCV as a consequence of the low densities and hence low neutral-neutral collision rate. Of course, by fixing input parameters in the way described here, one does not realistically simulate all experimental aspects (in particular P_{SOL} varies rather strongly with increasing density). However, given the CPU intensive nature of these simulations, this kind of systematic approach serves at least to highlight those areas where discrepancies are largest. In the case of TCV, it would appear that an alternative recombination pathway must be sought to explain the level of observed detachment. Such processes might involve molecular recombination pathways involving both deuterium [5] and/or hydrocarbons [8].

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