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Simulation of plasma flux detachment in Alcator C-Mod and ITER

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Abstract

Understanding the physics of divertor detachment is important since detached operation in ITER could reduce the target heat flux drastically, while aiding helium ash removal. In order to model detachment properly we have incorporated a parallel Navier–Stokes neutral model in UEDGE. In simulations of Alcator C-Mod we reproduce the partial detachment observed in experiments. A bifurcation to a MARFE has been found, similar to experiments. Volume recombination is a very important effect in removing the ion current to the target and we observe strong plasma flux detachment. Similar results have been found for ITER, with an order of magnitude decrease of the peak heat flux and a strong reduction of the target ion flux. Detachment has been induced with both neon and carbon.

Keywords: Alcator C-Mod; ITER; Divertor plasma; Fluid simulation; Detached plasma

1. Introduction

The design criterion for the target heat flux in ITER is 5 MW/m^2, several times less than what could be expected if the divertor configuration and operation was not well optimized [1]. Thus, divertor detachment seems like a very promising operation scenario, since it is characterized by a reduction of the target particle and heat fluxes by an order of magnitude. An other issue is that of particle control and ash exhaust—the He fraction in ITER must remain at or below 10% and Z_{eff} should be ≤ 1.6. Also for this purpose, the present ITER vertical divertor design would benefit from detached operation. In order to understand the physics of detachment better, a concerted experimental, theoretical and numerical effort is required.

2. Physics of detachment

Experimentally, detachment is observed as a strong drop in the target temperature and heat flux (thermal detachment) as well as a strong drop of the target ion saturation current (momentum detachment). In simulations, the *thermal detachment* is usually easy to obtain by impurity radiation. The next step that occurs is *pressure detachment*, i.e. the total pressure can vary strongly along a field line. A description of this requires a momentum conservation equation. The most difficult level of detachment to achieve numerically is *plasma flux detachment*, i.e. a reduction of the ion current to the target. Pressure and plasma flux detachment are often just referred to as momentum detachment, and it is a common misconception that they are equivalent. This can be seen from the pressure reduction factor

$$\gamma_p = \frac{p_{at}}{p_{det}} = \frac{n_{at}T_{at}}{n_{det}T_{det}} > 1 \qquad (1)$$

and from the current reduction factor

$$\gamma_j = \frac{j_{at}}{j_{det}} \approx \frac{n_{at}\sqrt{T_{at}}}{n_{det}\sqrt{T_{det}}} = \gamma_p\sqrt{\frac{T_{det}}{T_{at}}} < \gamma_p \qquad (2)$$

where n_{at}, n_{det}, T_{at}, T_{det} are the attached and detached plasma density and temperatures. Since the temperature always drops strongly at detachment, the current drop is

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much smaller than the pressure drop. When the temperature becomes low enough, however, the plasma starts recombining at a high rate—in this case both the pressure and plasma flux decease strongly. Volume recombination can in fact be the main current removal mechanism.

In order to simulate thermal, pressure and plasma flux detachment we have upgraded UEDGE with a three-dimensional Navier–Stokes neutral model on an orthogonal geometry [2] and a one-dimensional Navier–Stokes neutral model on a non-orthogonal multiply connected (allowing poloidal fluxes at the X-point) geometry. The one-dimensional neutral model [3] features a parallel neutral momentum equation, fully coupled to the parallel plasma momentum equation through ion–neutral collisions, ionization and recombination. This allows parallel plasma momentum to be converted into neutral momentum, which can be dispersed radially at a much higher rate than the ion momentum, due to the high neutral viscosity. The model is relevant and appropriate for high density, short mean free path conditions such as in Alcator C-Mod and ITER, and accounts for both ion–neutral and neutral–neutral collisions.

3. Simulation of partial detachment in Alcator C-Mod

The divertor geometry of C-Mod is very flexible, allowing for several different types of divertor scenarios, e.g. gas box, vertical target and flat plate. In the vertical target geometry (see [4] for a picture of the geometry used in the present simulations) detachment is always partial, i.e. it begins at the strike point and it does not extend beyond the nose of the divertor. We have simulated a vertical target diverted high density discharge which was on the limit of detachment (and partially detached for some time). We have used the following plasma parameters which provide good agreement with midplane probe measurements of T_e and the ion current: $P_{sep,i} = 250$ kW, $P_{sep,e} = 350$ kW, $n_{sep} = 10^{20}$ m^{-3}, $D_{\perp i} = 0.25$ m^2/s, $\chi_{\perp i} = \chi_{\perp e} = 0.4$ m^2/s. Here, $P_{sep,i/e}$ is the ion and electron heat flux leaving the core, n_{sep} is the plasma density at the core boundary, and $D_{\perp i}$, $\chi_{\perp i}$ and $\chi_{\perp e}$ are the anomalous perpendicular ion particle diffusivity and ion and electron heat conductivities, respectively.

At this core density the plasma is still attached; detachment is induced by adding a fixed fraction of carbon (see [5] for earlier results), with a non-coronal radiation function taking into account charge exchange between carbon and hydrogen atoms [6]. This simple impurity model provides no information on the impurity redistribution but it retains the feature that is most essential for detachment, namely a strong reduction of the heat flux through line radiation. The corresponding drop of T_e allows for volume recombination and ion–neutral interaction that finally removes the target ion flux and produces full detachment. We have found a bifurcation for $n_c/n_e = 0.5\%$, see Figs. 1 and 2. This impurity level is typical for C-Mod plasmas. The transition leads to a MARFE, characterized by the peak radiation moving from a position close to the target up into the core plasma, above the X-point. The MARFE solution agrees qualitatively with results from bolometers and H_α-measurements. A closer comparison of the absolute magnitude remains to be done. The fact that the MARFE occurs as a bifurcation, or at least as a very sharp transition, agrees nicely with the experimental observations of MARFES as very rapidly developing phenomena.

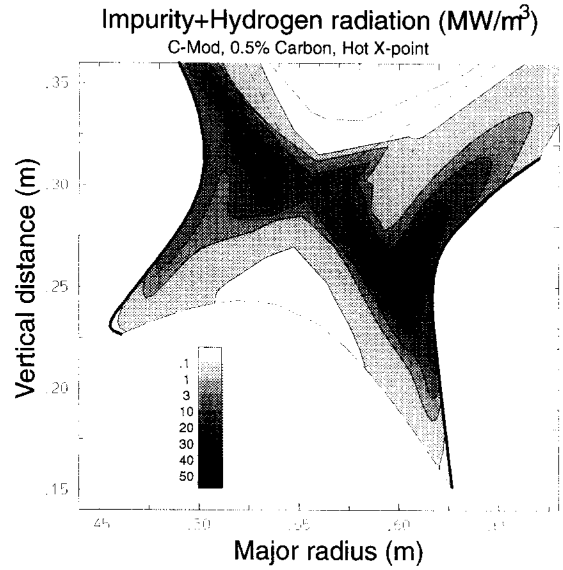

Fig. 1. Carbon + hydrogen radiation, $n_c/n_e = 0.5\%$, hot X-point.

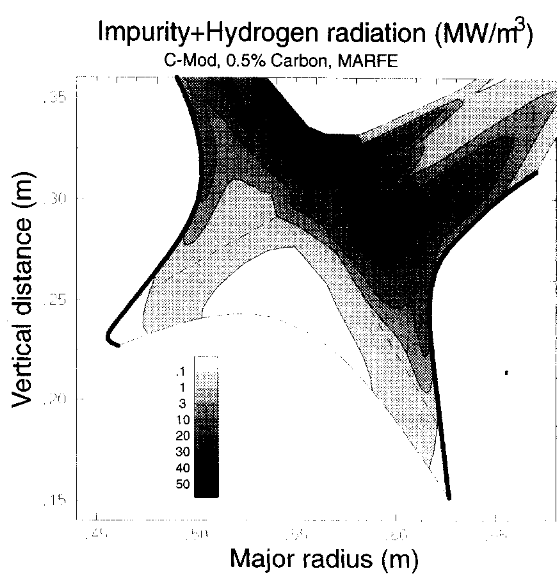

Fig. 2. Carbon + hydrogen radiation, $n_c/n_e = 0.5\%$, MARFE.

We have also induced partial detachment by adding a

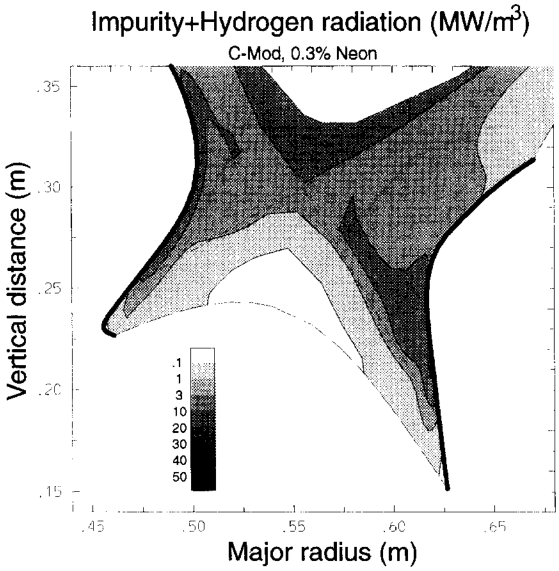

Fig. 3. Neon + hydrogen radiation, $n_{Ne}/n_e = 0.3\%$.

fixed fraction of neon, see Fig. 3. No bifurcation is observed for this case; this is probably related to the fact that neon radiates for a higher and broader range of temperatures, producing less sharp gradients.

The outer target profiles corresponding to the above detached solutions are shown below (Figs. 4 and 5), together with experimental data from a medium density (attached) and high density (partially detached) discharge [4]. We note that there is good qualitative agreement, although the simulated T_e is lower above the nose than the experimental data. We note that other recombination

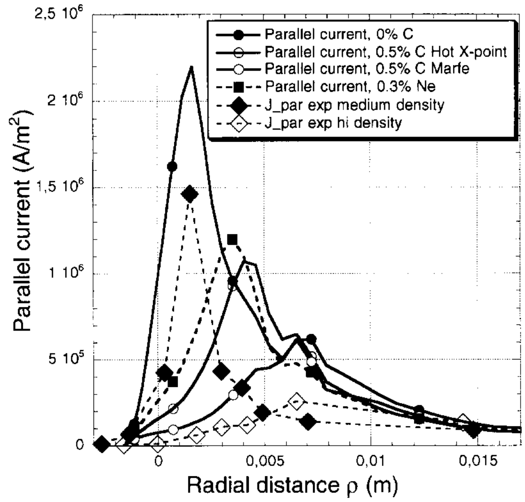

Fig. 5. As Fig. 4, but ion saturation current.

mechanisms, such as charge exchange and dissociative recombination, which can be important at higher temperatures and lower densities than conventional 3-body recombination, could give a larger current removal at higher temperatures [7].

The influence of volume recombination on plasma flux detachment is shown in Figs. 6 and 7. As detachment is induced, the parallel ion flux peaks further and further off the plate (Fig. 6). The ion flux is fed by the strong ionization source, but it is recombined before it reaches the target (Fig. 7). The flow near the target is rather stagnant at detachment, giving the ions more time to recombine. Globally we have found that the volume integrated ionization, i.e. roughly the number of ions that would flow to the

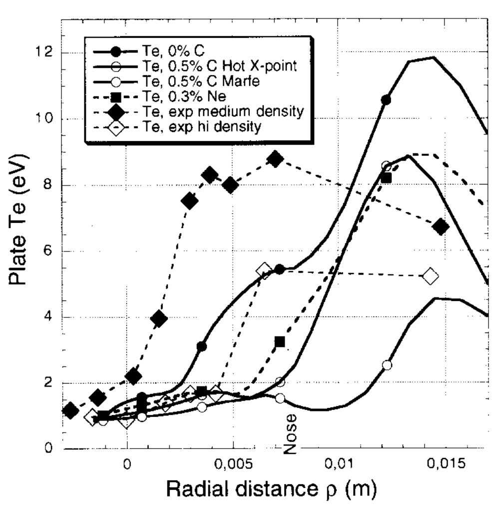

Fig. 4. Electron temperature along the outer target for different simulated impurity fractions. Experimental profiles for a medium (attached) and high (detached) density discharge [4]. The radial distance is mapped to the midplane.

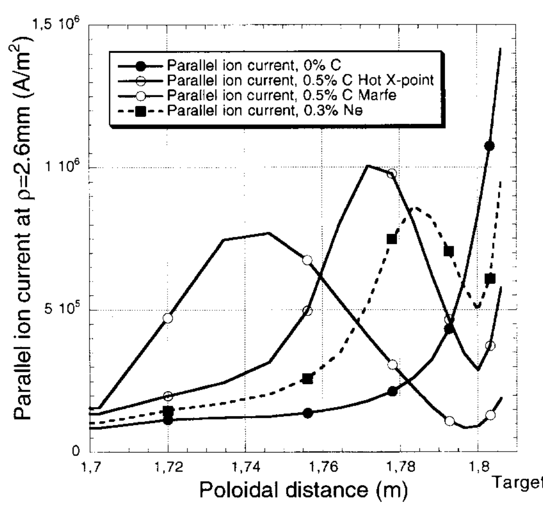

Fig. 6. Parallel ion flux along a field line for $n_c/n_e = 0.5\%$ (hot X-point), 0.5% (MARFE) and for $n_{Ne}/n_e = 0.3\%$, peaking further from the plate as detachment proceeds.

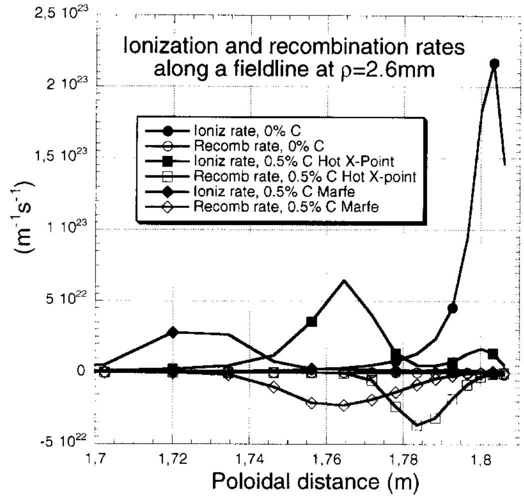

Fig. 7. Ionization and volume recombination rates along the same field line as in Fig. 6, showing how the ionized neutrals at detachment recombine before they reach the target.

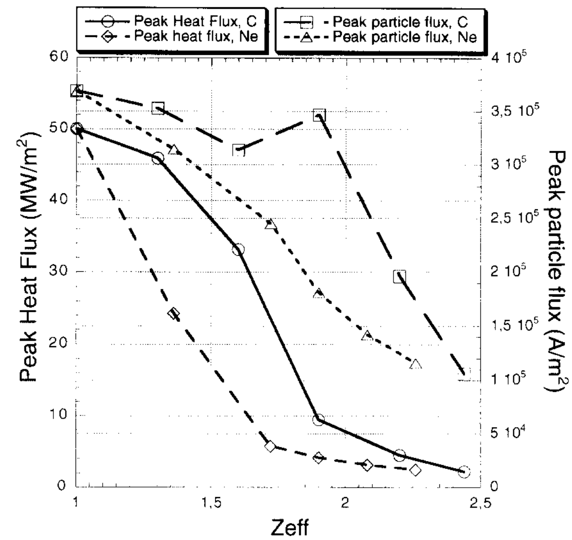

Fig. 8. Peak heat and particle flux to the outer divertor plate as a function of Z_{eff} for neon and carbon.

target in the absence of recombination, is canceled by recombination to 55% in the MARFE solution.

4. Simulation of detachment in ITER

The progress with respect to simulation of thermal and plasma flux detachment in C-Mod puts some confidence in advancing the simulations to ITER dimensions. In order to resolve structures such as ionization fronts, which may have the same physical dimensions in ITER as in e.g. C-Mod, we have chosen to simulate only the outer half of the ITER SOL, using 174 × 24 grid points (see [3,8] for more information on the geometry). The divertor plates are orthogonal to the poloidal field, P_{sep} = 100 MW (into the outer half), $n_{sep} = 4.10^{19}$ m^{-3} and $D_{\perp i} = \chi_{\perp i} = \chi_{\perp e} = 1$ m^2/s.

Without impurities the plasma is fully attached, with a peak heat flux of 50 MW/m^2. We again induce detachment by adding a fixed fraction of impurities; neon or carbon. The carbon simulations [3], were the first to show such a large drop of the ion saturation current. Carbon will however only be an intrinsic impurity in ITER, and neon or argon are more realistic for inducing detachment. The present simulations confirm the advantage of neon over carbon, as seen in other simulations and experiments. Particularly the heat flux is reduced faster; for a given Z_{eff}, see Fig. 8. This is natural, since carbon is a poor radiator at the high temperatures of a nearly attached ITER (for C-Mod on the other hand, with its much lower temperatures, there was no advantage of neon over carbon, see Figs. 4–6). A Z_{eff} of 1.7 due to neon causes almost as strong detachment as $Z_{eff} = 2.2$ due to carbon; both radiate 78 MW of impurity radiation and the peak target electron temperature is 1.2 eV. Note that $Z_{eff} = 1.7$ due to neon ($n_{Ne}/n_e = 0.8\%$) is unnecessarily conservative however, since the radiated power in the whole SOL (2 × 78 MW) may be more than necessary if we also take into account core bremsstrahlung and radiation from the mantle [8]. Also, just the geometric effect of tilting the target will reduce the heat flux by about a factor of 3. A simulation with less neon and higher density is reported in Ref. [8].

In this simulation we observe strong momentum detachment, except in a narrow layer outside the separatrix (cf. Fig. 9). The peak pressure at the target detaches faster than the plasma flux, by a factor of 3, in qualitative agreement with Eq. (2). Away from the current peak, volume recombination is very effective, with the plasma

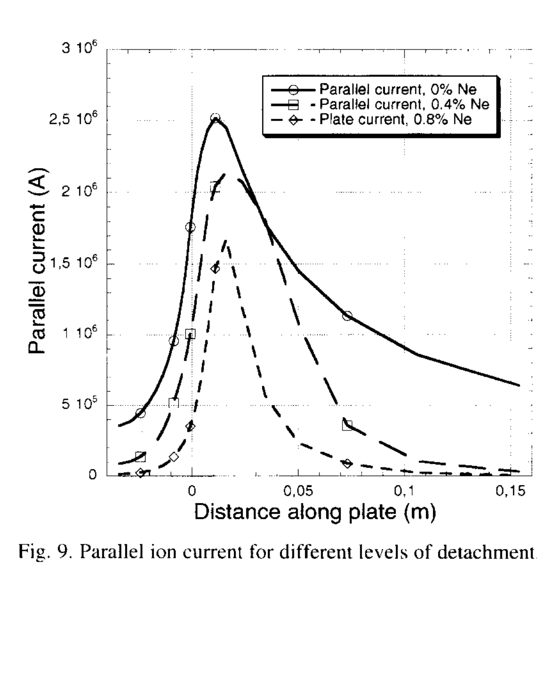

Fig. 9. Parallel ion current for different levels of detachment.

flux reduced by an order of magnitude and more, and with the plasma density 1–2 orders of magnitude smaller than the neutral density. The remaining current peak corresponds very nicely to the net ionization source along a field line (the number of ionization events subtracted by the number of recombination events) [3]. The volume integrated total recombination versus ionization ranges from 60% for $Z_{\rm eff}(\rm neon) = 1.7$ to 80% for $Z_{\rm eff}(\rm carbon) = 2.4$. Similar results are also observed in B2-EIRENE for JET [9] and ITER [10], and there is a growing consensus that volume recombination can play a dominant role in plasma flux detachment.

The strong reduction in pressure and current far out in the SOL observed in the ITER simulation (Fig. 9) differs from the C-Mod simulation (Fig. 5), where partial detachment is initiated at the separatrix and the plasma remains attached above the nose (farther out in the SOL). Since effective current removal in our simulations is equivalent to strong volume recombination, low temperatures are required for detachment. This is obtained predominantly by impurity radiation (which is roughly proportional to the square of the plasma density) and not by transverse power losses due to e.g. CX-neutrals. Plotting the quantity $P_{\rm in}/\int n_i^2\,{\rm d}V$ (where $P_{\rm in}$ is the poloidal heat flux incident into a flux surface from above the X-point, and the volume integral is taken over the part of the flux surface with temperatures around and below the maximum of the impurity emissivity function), we get an indication of which field lines have the smallest capacity to dissipate the incident heat flux and thus are most difficult to detach. For the ITER simulation this gives a strong peak about 2 cm outside the separatrix, while the C-Mod case has a peak at $\rho = 14$ mm (well above the divertor nose), explaining qualitatively the difference between the two simulations. The onset of partial detachment at the separatrix is thus a result of the reduced poloidal heat flux (resulting from the field line pitch) and the high radiative capacity (resulting from the high density and the flux expansion). Far from the separatrix detachment is determined mainly by the density scrape-off length.

5. Conclusions

Simulations of detached divertors have improved in the last two years. We have adopted a 1D Navier–Stokes neutral model in UEDGE, featuring neutral–neutral collisions and full coupling to the plasma ions. The code has been applied to the vertical target divertor configuration of Alcator C-Mod. Partial detachment, including the strong reduction of the ion saturation current all the way out to the nose, has been reproduced. A bifurcation to a radiating MARFE has been found, similar to experiments. Volume recombination has been found to be the most important effect in producing plasma flux detachment, even for usual 3-body recombination. Taking into account dissociative and charge exchange recombination would facilitate the current removal even further, possibly allowing plasma flux detachment at higher temperatures.

The progress with modelling Alcator C-Mod, which has several unique ITER relevant features, such as high density and short neutral mean free paths, is a basis for extending the calculations to ITER size geometries. We report on simulations of ITER detachment, induced by carbon or neon radiation. The resulting target heat flux and ion current is reduced strongly, particularly with neon. The results have been obtained with a simple fixed fraction impurity model, which provides the radiation energy sink necessary for detachment. In order to make more detailed comparisons with e.g. radiation patterns in C-Mod, or to obtain the core impurity influx in ITER, more detailed multi-charge state simulations are required. Such calculations, including the Navier–Stokes neutrals and FMOMBAL multi-charge state impurities, are currently under way with UEDGE.

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