NUMERICAL STUDY OF THE IMPACT OF DIVERTOR CLOSURE ON DETACHMENT

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Abstract: The impact of divertor closure on detachment is studied with the B2-EIRENE code package. Main focus is the observation that detachment seems to occur at unexpectedly low core densities in closed divertors. JET MARK-I and II horizontal plate configurations are adopted as study points. Effects of the observed magnitude are reproduced. While the increase of $i-n$ interactivity, expected for closed configurations, is found in the simulations, the main impact on the upstream density required for detachment is due to volume recombination which is significantly enhanced as a consequence of plate inclination and divertor chamber shape.

1. INTRODUCTION

Closed divertors have gained particular interest, owing to their potential to produce easier access to the detached regime and to reduce main chamber sputtering. In the JET MARK-II divertor, which was designed along this line of thinking, low power L-mode discharges show an onset of detachment (rollover of J_{sat}) and complete detachment at significantly lower core densities than in the less closed MARK-I divertor [1]. Since it has become obvious that complete detachment coincides with the achievement of the density limit [2], this raises concerns for ITER, where the required operation density seems to be in conflict with the Greenwald limit [3].

In this paper the impact of divertor geometry on detachment, particularly on the required upstream density n_S, is studied by simulating density ramp-up scenarios for two configurations with different divertor closure. Though the paper does not aim at detailed modelling, we adopt the MARK-I and II configurations as study points, in order to provide additional relevance of the results by producing qualitative and broad quantitative agreement with actual JET discharges.

The majority of mechanisms that determine the upstream density n_S are well described by a simple 2-P expression for n_S $(\chi_\perp, D_\perp = const)$ [4, 5, 6]

$$n_S \propto \frac{P_{heat}^{5/7}(1-f_{rad}^{tot})^{5/7}(q_\psi R)^{1/14}}{(1-f_{rad}^{div})^{1/14}} \left[\frac{1-f_E}{f_P}\,\frac{T_D^{1/2}}{\frac{\xi}{1-f_{rec}}+\gamma T_D}\right]^{9/14} \qquad (1)$$

where T_D $(T_e = T_i)$ is the divertor temperature, f_{rad}^{tot} the total radiative fraction, f_{rad}^{div} the fraction of P_{SOL} that is radiated, f_P the pressure drop along B, f_E the fraction of power into the recycling region that is lost due to $i-n$ interactions (and possibly volume recombination) and f_{rec} the ratio of the total recombination and ionization rates.

In JET the reduction of n_S is observed in discharges with virtually identical f_{rad}^{tot}, excluding different total radiative fractions as a possible cause. Eq. (1) also indicates that a change in the split between core and SOL radiation should have little impact. This suggests that the main cause for the observed difference is due to gas target physics as described by f_P, f_E and f_{rec}. These coefficients are directly relating to loss channels in, respectively, the momentum, energy and particle balances of a gas target. Since they can be easily determined from code output they provide a convenient frame to relate the differences between the two configurations to basic gas target processes.

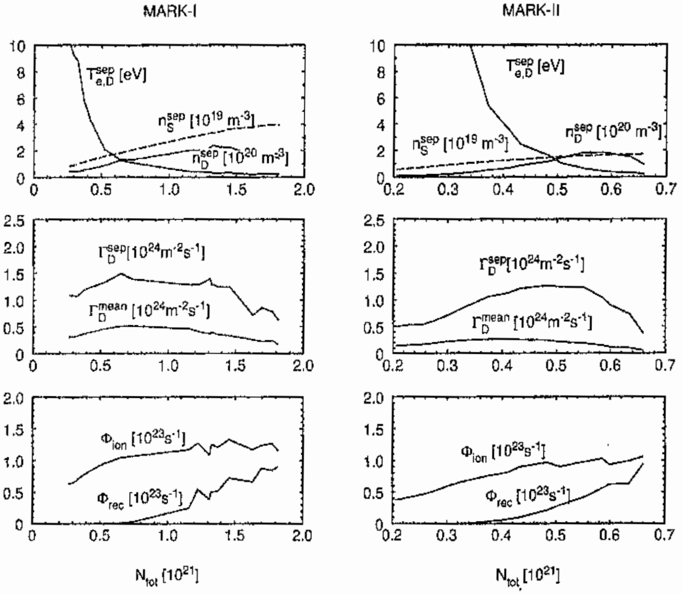

FIG. 1. *N_{tot} traces, where N_{tot} is the total number of ions, for a variety of inboard SOL quantities. n_D^{sep} and $T_{e,D}^{sep}$ are, respectively, the separatrix plasma density and electron temperature at the plate. Subscript S denotes upstream quantities. Γ_D^{sep} and Γ_D^{mean} are the separatrix and mean parallel particle flux densities at the plate. Φ_{ion} and Φ_{rec} are the total inboard ionization and recombination rates.*

The effect of f_{rec} in Eq. (1) is to increase the energy cost for ionization per ion hitting the plate through the additional internal recycling channel. Volume recombination also contributes to the energy and momentum losses in the gas target (f_P, f_E), but its impact is negligible as compared with that of $i-n$ interactions in the regime under consideration.

2. DESCRIPTION OF COMPUTATIONAL SET-UP

A detailed numerical study of detachment in a MARK-I horizontal plate configuration has been reported in Ref. [6]. To isolate the configurational aspects we adopt for MARK-II an identical set-up, except for the magnetic configuration (a so called standard fat, low triangularity configuration in this case) and the divertor geometry. Since our main interest is in gas target physics, we confine ourselves to a pure deuterium case, in order to avoid the complication of varying impurity radiative fractions. An input power of 1.8 MW is adopted, corresponding roughly to the net input power of a typical ohmic discharge. The incoming power is evenly distributed between electrons and ions. The simulation includes, in addition to the SOL region, part of the bulk plasma, defined by some interior flux surface. We simulate a typical density ramp-up scenario by performing a sequence of B2-EIRENE runs to steady state, successively increasing the particle content N_{tot} with otherwise constant input parameters. (Since different core fractions are covered in the simulations of MARK-I and II, the N_{tot} values are not directly comparable.)

3. SUMMARY OF RESULTS AND DISCUSSION

We start the discussion with Fig. 1, where a number of quantities are plotted versus N_{tot} for the two configurations under consideration. By comparing the corresponding curves one observes: (i) The values of n_S at $T_{e,D}^{sep} \simeq 5$eV, i.e., when $i-n$ collisions start to

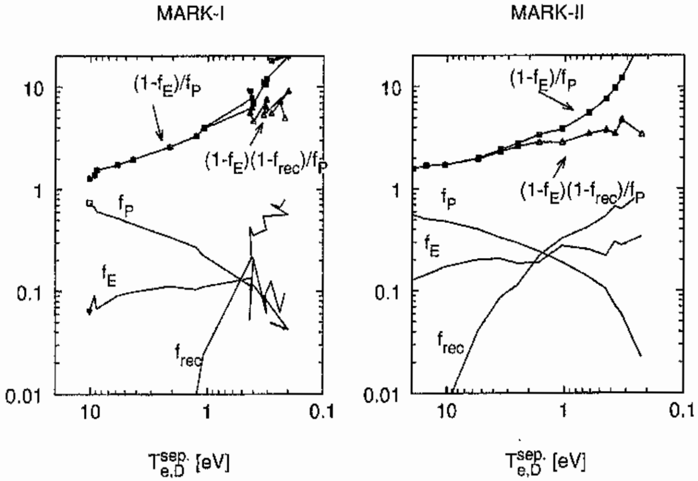

FIG. 2. f_P, f_E and f_{rec} versus $T^{sep}_{e,D}$. According to Eq. (1) $(1-f_E)/f_P$ measures the effect of $i-n$ interactions, while $(1-f_E)(1-f_{rec})/f_P$, in addition, takes into account the impact of volume recombination.

become effective, are equal in both cases, while n_S is systematically lower by an amount consistent with experimental findings in MARK-II at lower T_D values. (ii) In both cases the rollover of Γ_D^{mean} coincides with the onset of volume recombination. (iii) In the MARK-II case volume recombination starts at much higher divertor separatrix temperatures ($\simeq$ 5eV instead of $\simeq$ 1eV) and consequently rollover occurs at lower upstream density.

The situation is further clarified when discussed in terms of Eq. (1). In Fig. 2 the parameters f_P, f_E and f_{rec} as well as the combinations $(1-f_E)/f_P$ and $(1-f_{rec})(1-f_E)/f_P$ which describe the effects of $i-n$ interactions alone and the combined effect of $i-n$ interactions and volume recombination, respectively, are plotted versus $T^{sep}_{e,D}$. $T^{sep}_{e,D}$ is a better label than N_{tot} since it is more directly related to the elementary processes that determine f_P, f_E and f_{rec}. While f_P is not much affected by closure, f_E almost doubles in Mark-II. However, f_E remains too small to affect $(1-f_E)/f_P$. We thus conclude that, though closure enhances the effects of $i-n$ interaction, this is not the main cause for the decrease of n_S. On the other hand $(1-f_E)(1-f_{rec})/f_P$ is considerably lower in Mark-II and the decrease of n_S resulting from Eq. (1) agrees with the numerical results (see Fig. 1). This is entirely due to the considerably larger f_{rec}.

The increase of volume recombination and its onset at unexpectedly high separatrix electron temperatures in MARK-II ($\simeq$ 5eV) were the most surprising result of this study. The underlying mechanism can be understood with the help of Fig. 3. Fig. 3 illustrates a "thought experiment" where we start with a plate in position AO and plasma conditions where volume recombination just starts. (Since volume recombination depends much more strongly on temperature than density, this always occurs in off-separatrix regions.) If the target plate is moved into position BO, the plasma conditions upstream to the old target position are basically unchanged [2], while T_e drops drops towards the new plate position. Thus a cold, dense plasma region is formed which favours strong

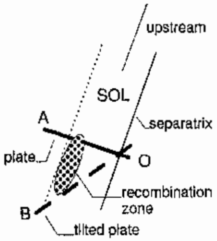

FIG. 3. *Schematic illustration of the impact of the plate inclination on volume recombination.*

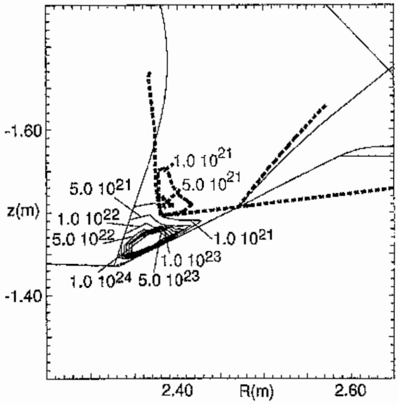

FIG. 4. *B2-EIRENE contour plot of the volume recombination rate in the divertor regions of MARK-I (solid lines) and MARK-II (dotted lines) at* $T_{e,D}^{sep} \simeq 1.5eV$*. The two graphs are merged into one such that the separatrix strike points coincide. Significant volume recombination occurs in MARK-II in areas which are cut-off by target plate and divertor chamber in MARK-I.*

volume recombination. This picture is supported by 2-D results as is demonstrated by Fig. 4, where for both configurations the recombination rate is plotted at $T_{e,D}^{sep} \simeq 1.5$, characteristic of the onset of volume recombination in MARK-I (see Fig. 1).

An immediate consequence of the proposed picture would be an atypical start of detachment in off-separatrix regions and a strong increase of D_α light from the inboard divertor corner. Both effects are seen in experiment [7].

In MARK-II the drop of n_S relative to MARK-I is found to be similar in horizontal and vertical plate discharges. It is not obvious whether the explanation proposed here for the horizontal plate configuration applies for vertical targets as well. This aspect will be addressed in a separate study.

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