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Study of recombining gas targets

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Abstract

JET high-density discharges, when approaching detachment, typically show a gradual drop of the ion saturation current $J_{\rm sat}$ (rollover), an increase of the D_α signal and an increase of the divertor neutral density as the main plasma density is ramped up, even in cases with constant net input power. This has been found difficult to explain by ion–neutral collisions alone. This problem has been studied with a view to the potential role of volume recombination using the B2-Eirene scrape-off layer simulation code package. The main conclusion is that volume recombination indeed plays a role in the parameter range under consideration and is essential to explain the experimental findings.

Keywords: JET; Detached plasma; Fluid simulation

1. Introduction

Experimentally, detachment is usually approached by ramping up the density at otherwise fixed discharge parameters. In virtually all devices detachment is manifested as a drop of the particle flux (or ion saturation current $J_{\rm sat}$) onto the plate, an increase of the D_α signal, an increase of the neutral pressure $P_{0,\rm D}$ in the divertor and a drop of the plasma density $n_{\rm D}$ and plasma pressure $P_{\rm D}$ at the plate. Divertor temperatures are found to be in the few eV range and the upstream separatrix (and line-average) densities typically show a moderate increase.

A central element of the present paper is the understanding of the drop of the particle flux to the plate. It depends in a complex way on a number of physical effects, as is illustrated by the global SOL energy balance

$$\gamma\Gamma_{\rm D}T_{\rm D}(1+M_{\rm D}^2)+\frac{\Gamma_{\rm D}\xi}{1-f_{\rm rec}}=\frac{q_\perp L_S}{\Delta}(1-f_{\rm rad}^{\rm div})(1-\tilde{f}), \tag{1}$$

where $\Gamma_{\rm D}$ is the parallel particle flux at the target, $q_\perp = P_{\rm in}/O_{\rm p}$ is the mean energy flux density across the separa-

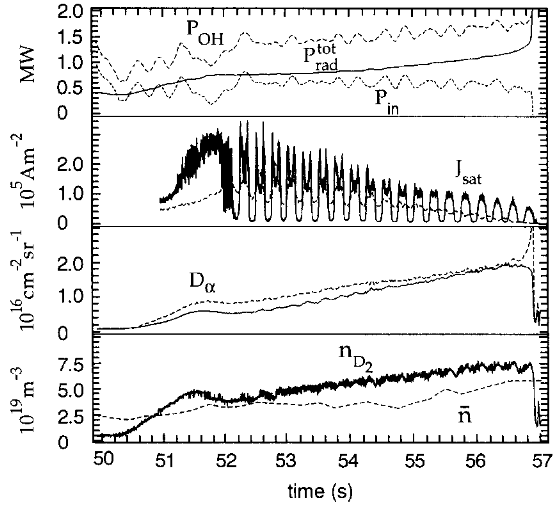

Fig. 1. Traces of various parameters for the detaching JET discharge 30829: (a) traces of the heating power $P_{\rm OH}$ (upper dashed line), total radiation power $P_{\rm rad}^{\rm tot}$ (solid line) and net input power $P_{\rm OH} - P_{\rm rad}^{\rm tot}$ (lower dashed line) (b) $J_{\rm sat}$ for two near-separatrix inboard (dashed line) and outboard (solid line) probes (c) the D_α signals for an inboard (dashed line) and outboard (dotted line) channel. (d) neutral density in the private flux region n_{D_2} (solid line) and line-averaged (dashed line) density $\bar{n}$. The oscillations are due to X-point sweeping.

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trix ($P_{\mathrm{in}} = P_{\mathrm{heat}} - P_{\mathrm{rad}}^{\mathrm{bulk}}$ the power across the separatrix, O_{p} the plasma surface area), L_{S} the connection length between the stagnation point and X-point, $f_{\mathrm{rad}}^{\mathrm{div}} = P_{\mathrm{rad}}^{\mathrm{div}}/P_{\mathrm{in}}$ the divertor radiative fraction, $\tilde{f}$ the fraction of energy entering the gas target which is lost due to i–n interaction and f_{rec} the ratio of the number of volume recombination events to the number of ionization events per second. M_{D} and T_{D} are, respectively, the Mach number and temperature at the target and Δ is the energy decay length. ξ is the energy per ionization event and γ is the heat transmission coefficient. This results in the expression

$$\Gamma_{\mathrm{D}} = \frac{L_{\mathrm{S}}\left(1 - f_{\mathrm{rad}}^{\mathrm{div}}\right)\left(1 - \tilde{f}\right)}{\Delta} \times \frac{q_{\perp}}{\left(\xi/\left(1 - f_{\mathrm{rec}}\right)\right) + \gamma T_{\mathrm{D}}\left(1 + M_{\mathrm{D}}^{2}\right)} \qquad (2)$$

Of course, Eq. (2) provides merely a necessary condition for the parameters $q_{\perp}$, $f_{\mathrm{rad}}^{\mathrm{div}}$, $\tilde{f}$, f_{rec}, T_{D}, etc., which, in principle, have to be determined selfconsistently to draw any conclusion. However, JET has given clear evidence of a drop of Γ_{D} even at constant net input power ($q_{\perp}(1 - f_{\mathrm{rad}}^{\mathrm{div}}) \simeq$ const, see Fig. 1). A drop of Γ_{D} must then solely result from the combined variations of $\tilde{f}$, T_{D} and, possibly, f_{rec}. When approaching detachment, T_{D} typically decreases and i–n induced energy losses increase (increase of $\tilde{f}$). Assuming that $f_{\mathrm{rec}} = 0$, the question then is, whether $\tilde{f}$ increases sufficiently with decreasing T_{D} to provide a drop of Γ_{D}. Modelling studies consistently show that this effect is sufficient to provide saturation of Γ_{D}, but is too small to provide a drop. This suggests that volume recombination must play a role.

Another challenge is the observed increase of the D_{α} signal despite a drastic reduction of Γ_{D}. In the absence of volume recombination this implies reduction of recycling, i.e., of the number of ionizations per second. One might argue that the photon production per ionization event may increase in the parameter range prevailing in gas targets.

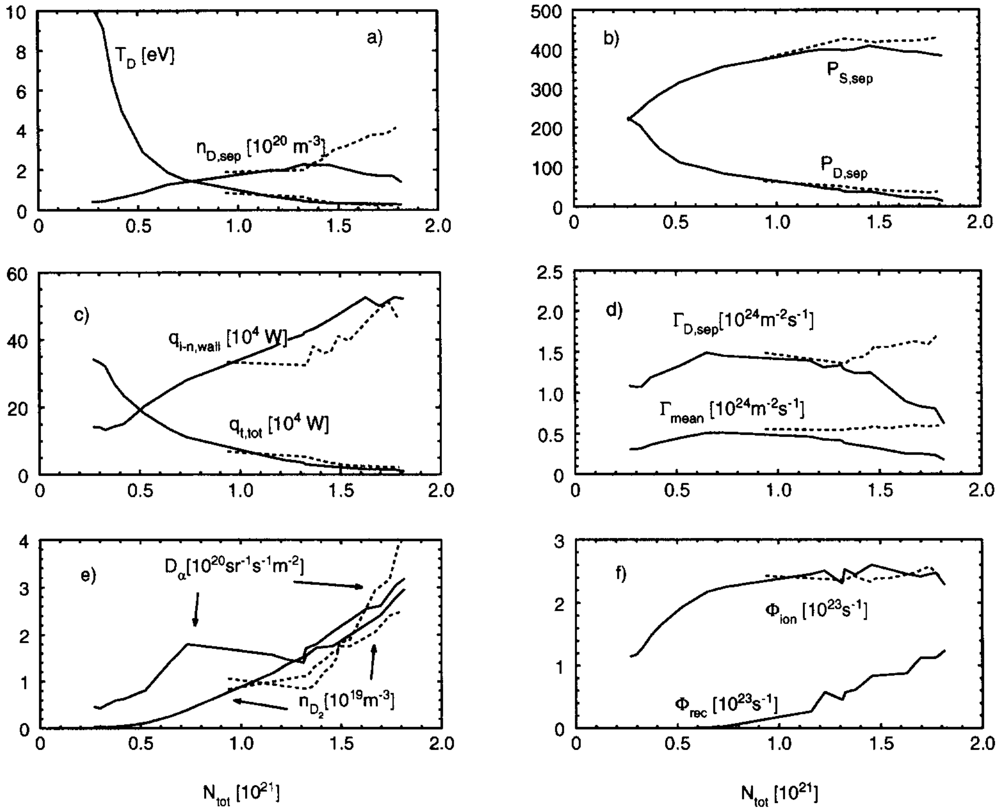

Fig. 2. Summary of N_{tot} traces for a variety of inboard SOL quantities with (solid lines) and without recombination (dotted lines). N_{tot} is the total number of particles (ions and neutrals). n_{D}, T_{D} and P_{D} are, respectively, the separatrix plasma density, electron temperature and plasma pressure at the plate. Subscript S denotes upstream quantities. n_{D_2} is the neutral density in the private flux region. $q_{\mathrm{i-n,wall}}$ is the energy flux carried by neutrals to the surrounding walls and $q_{\mathrm{t,tot}}$ is the total energy flux to the target. $\Gamma_{\mathrm{D,sep}}$ and $\Gamma_{\mathrm{D,mean}}$ are, respectively, the separatrix and mean parallel particle flux densities at the plate. Φ_{ion} and Φ_{rec} are the total ionization and recombination rates. For $T_{\mathrm{D}} \geq 1.5$ eV volume recombination becomes insignificant, and, apart from the Monte Carlo noise, the dashed and solid lines would coincide.

However, this effect has to be rather large in order to overcompensate the observed reduction of Γ_D.

In this study we assess the importance of volume recombination in detachment by modelling a density ramp-up scenario with and without recombination. The main result of this paper is that recombination may indeed play a significant role in the parameter range under consideration and seems to be essential to reproduce the full set of detachment characteristics as described above. Though the present study does not aim at detailed modelling, the relevance of the results is demonstrated by producing qualitative and broad quantitative agreement with actual JET discharges.

2. Description of computational set-up

JET discharge 30829, which particularly clearly shows the drop of J_{sat} at constant net input power [1], is adopted as the study point (see Fig. 1). The original magnetic configuration and, except for gaps, the MARK-I divertor and first wall shapes are used in the simulation. In this study our main interest is in gas target physics. Therefore, in order to avoid the complication of varying impurity radiative fractions, we confine ourselves to a pure hydrogen case. An input power of 1.8 MW is adopted, corresponding roughly to the net input power of discharge 30829. The incoming power is evenly distributed between electrons and ions. 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. The simulation includes, in addition to the SOL region, part of the bulk plasma, defined by some interior flux surface. The particle content is controlled by the plasma density at the control surface. Details of refuelling should have little impact on the questions we are addressing, since the recycling rate is large in comparison. The present version of B2-Eirene includes radiative and three body recombination based on data from Ref. [2].

3. Summary of results and discussion

The results of such an N_{tot} scan are summarized in Fig. 2. At the highest N_{tot}, about 60% of the ionized neutrals recombine through volume recombination ($f_{rec} \simeq 0.6$). The complete experimental detachment signature is reproduced:

(1) The particle flux to the plate first increases and then shows the typical rollover behavior. There is no significant difference between the mean and separatrix values, consistent with what is seen experimentally in this discharge. However, an enhanced drop near the separatrix has been observed in other JET discharges [3].

(2) The divertor density shows similar behavior.

(3) The number of ionization events per second saturates during rollover, while the number of recombination events continuously increases to a level where volume recombination dominates over recombination at the plate. Thus, while the photon emission from ionization remains basically unchanged (ionization occurs predominantly at about 6–7 eV), an additional contribution from recombination arises, implying the overall increase of the D_α signal.

(4) The neutral density in the divertor increases.

Also shown in Fig. 2 are the results for the same series of runs, but with recombination artificially turned off (dotted lines). Interestingly, there is practically no difference, except for the particle flux to the plate and the divertor density (and, of course, Φ_{rec}). Of the three quantities T_D, $\tilde{f}$ and f_{rec}, which according to Eq. (2) control Γ_D, the first two are basically unaffected by volume recombination (see Fig. 2a, c), so that the drop of Γ_D must be entirely due to the increase of f_{rec}.

When rollover starts, most of the power into the gas target is removed by i–n induced losses (see Fig. 2c). Only a small fraction of the incoming power reaches the target through heat conduction or convection. (However, the actual target heat load will be larger due to the energy carried by neutrals.)

In Fig. 3 the poloidal distance of the tip of the 6.5 eV contour (ionization front) to the plate is plotted versus N_{tot}. The ionization front moves upwards and is close to the X-point when complete detachment is achieved.

In Fig. 4 more detailed information about the spatial shape is given for a well-detached case ($N_{tot} = 1.7 \times 10^{21}$). The density peaks near the plate, but, unlike in the standard high-recycling regime, the peak does not coincide with the peak of the ionization source but with the maximum of recombination. Recombination occurs in a narrow layer close to the plate and reaches its maximum somewhat off-axis. As expected, significant D_α contributions arise in the recombination zone. At full detachment the

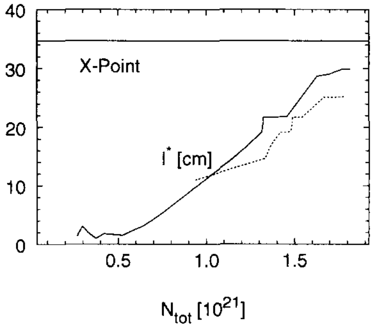

Fig. 3. Poloidal distance l^* of the inboard tip of the 6.5 eV contour (ionization front) from the plate versus N_{tot} for the cases with recombination (solid line) and without recombination (dotted line).

molecular density reaches values where neutral–neutral collisions are no longer negligible in some remote parts of the chamber and this might impact on the results [4].

The solutions found here are similar to the recombining cases described in Refs. [5,6], except that, because of the lower input power, we find much lower neutral and peak ion densities.

The temperature drops to values well below 1 eV, while experimental values based on Langmuir probes typically lie in the few eV range. This discrepancy is systematically observed in simulations. However, recent Thomson scattering measurements in different machines resulted in temperatures in the 1–2 eV range. Also refinements of the standard probe theory suggest lower T_e values [7]. This problem requires further investigation and at present it would be premature to rule out alternative concepts [8]. Otherwise, the predicted values are quantitatively consistent with experimental findings as shown in Fig. 1.

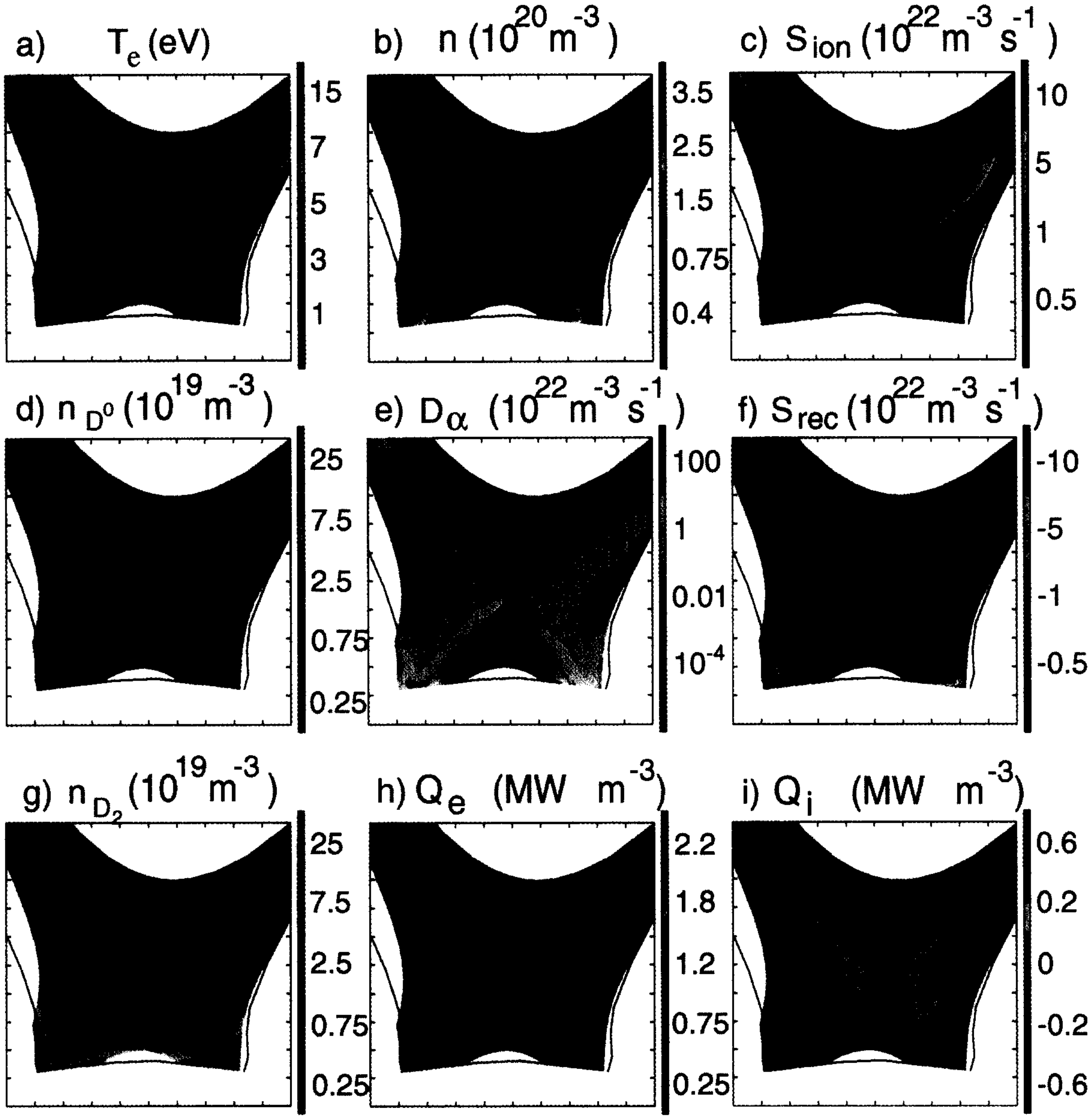

Fig. 4. Spatial distribution of relevant parameters for $N_{tot} = 1.4 \times 10^{21}$ (a) electron temperature (b) plasma density (c) ionization source strength (d) atom density (e) D_α emissivity (f) recombination source (g) molecule density (h) total electron energy losses (i) total ion energy losses.

The shapes of the curves in Figs. 1 and 2 are not directly comparable. In experiments, the density is ramped up by continuous gas puffing, typically at a constant rate. Though N_{tot} will increase in time under these conditions, the dependence is certainly weaker than linear. In fact, most of the incoming gas is pumped by the walls [9] and the pumped fraction will increase with increasing neutral density (see Fig. 2e). Within the present computational set up, where a constant wall pumping efficiency is assumed, we are unable to establish the exact relation between the gas rate and N_{tot}.

A study along similar lines, recently performed for Alcator C-mod conditions, has lead to similar conclusions about the importance of volume recombination for detachment [10].

4. Conclusions

Detachment has been studied with a view to the role of volume recombination in getting a consistent description of the observed detachment characteristics. This includes modelling of the drop of J_{sat}, the increase of the D_{α} signal and increase of the divertor neutral density during a density ramp-up, even at constant net SOL input power. A JET discharge which exhibits this behavior particularly clearly is taken as study point.

The main result is that in the parameter range under consideration, recombination plays a role and is essential to reproduce the full set of detachment characteristics. A comparison of cases with and without volume recombination reveals that volume recombination basically affects the particle balance in the vicinity of the plate while the solutions are otherwise virtually unchanged.

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References

[1] L.D. Horton and JET Team, in: Plasma Physics and Controlled Nuclear Fusion Research 1994, Proc. 15th Int. Conf., Seville (1994), paper IAEA-CN-60/A4-I-5.
[2] R.K. Janev et al., Elementary Processes in Hydrogen–Helium Plasmas (Springer-Verlag, Berlin, 1987).
[3] A. Loarte, JET Joint Undertaking, Abingdon, Oxfordshire, United Kingdom (1996), personal communication.
[4] D.A. Knoll and P.R. McHugh, Phys. Plasmas 3 (1996) 293.
[5] M. Petravic, Phys. Plasmas 1 (1994) 2207.
[6] M. Petravic et al., Contrib. Plasma Phys. 34 (1994) 380.
[7] K. Günther, in: Controlled Fusion and Plasma Physics, Proc. 22th Eur. Conf. Bournemouth 1995, Vol. 19C(1) (European Physical Society, Geneva, 1995) p. 433.
[8] P. Ghendrih et al., J. Nucl. Mater. 220–222 (1995) 305.
[9] G. Haas et al., J. Nucl. Mater. 162–164 (1989) 509.
[10] F. Wising et al., Contrib. Plasma Phys. 36 (1996) 136.