A Model for Detached Scrape-Off Layer Plasmas in a Tokamak Divertor

K Borrass, P C Stangeby[1]

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA.
[1] Permanent Affiliation: Institute for Aerospace Studies, University of Toronto, North York, Ontario, Canada.

A MODEL FOR DETACHED SCRAPE-OFF LAYER PLASMAS IN A TOKAMAK DIVERTOR

K. Borrass and P. C. Stangeby[†]
JET Joint Undertaking, Abingdon, Oxfordshire, United Kingdom
[†] Permanent affiliation: Institute for Aerospace Studies, University of Toronto, North York, Ontario, Canada

1. INTRODUCTION

In JET, X-point discharges with divertor temperatures of $\leq 5\ eV$, often show a substantial decrease in both plasma pressure and the particle flux density I^+_{sat}, while the upstream plasma conditions in the SOL remain relatively unchanged (detachment). Detachment is observed in both low power ohmic discharges and high power, high density discharges ("gas target" discharges [1]). Analysis has been focussed on the "gas target" discharges. They show strong divertor radiation and total radiative fractions of about 90% without marfing and are of potential interest for the problem of power exhaust in next-generation devices.

2. CONDITIONS FOR THE EXISTENCE OF A NEUTRAL CUSHION

In a differentially-pumped, linear magnetic plasma simulator, Hsu [2] demonstrated an externally sustained gas target, where plasma contact with the solid target was prevented by increasing the neutral hydrogen density to sufficiently high levels that ion-neutral ($i-n$) collisions formed a "neutral cushion". In Ref. [3], the criteria were considered for a self-sustained gas target to form in a tokamak divertor, based on the $i-n$ collisions associated with the natural recycling flux at the target (see Fig. 1). (The recycling flux is assumed to be large compared with any external fueling rate.) One criterion is that T_e be sufficiently low ($T_e \leq 5\ eV$) that there can be many $i-n$ collisions before the recycling neutral is ionized. A further criterion is that the $i-n$ collisions be effective at removing the plasma momentum, which requires $\lambda_{n-i} \geq \Delta$ (λ_{n-i} the neutral mean free path, Δ the SOL width) to hold, so that in general each $i-n$ collision is followed by a neutral-wall collision. In this situation the $i-n$ collisions can be expected to have three principal effects on the edge plasma:

(a) In the collisional region (CR) $i-n$ collisions transfer momentum to the neutrals which then transfer it kinetically to the solid surface. As a result the plasma pressure will drop along B.

(b) In the CR, because of the favourable mass ratio, also ion energy is effectively transferred to neutrals and thus to the solid surfaces, and the ion temperature decays over a distance of about λ_{i-n}

(c) Assuming that the plasma flow velocity at the target sheath is sonic, the effect of $i-n$ collisions is to reduce the plasma Mach number M_C at the entrance to the CR and $M_C << 1$ holds for sufficient $i-n$ collisionality [3]. Since, by definition, there is no ionization source in the CR, also the plasma outflux rate to the target (thus the ion saturation current I^+_{sat} to target-mounted Langmuir Probes) will decrease for given upstream plasma conditions.

At the entrance of the CR, because of the low Mach number, convective energy at the modelling of discharges where the total radiation from the SOL is known from measurements. In that case one conveniently introduces $q_{\perp,rad} = \frac{2}{7}\frac{\Delta}{L}\int_0^L dz Q_{rad}$, so that

$$\frac{2}{7}\frac{\Delta}{L}(q_\perp - q_{\perp,rad}) = \gamma n_X T_X c_s(T_X) \qquad (6)$$

Note that $q_\perp^{rad} = P_{rad}^{div}/(4\pi^2 Ra\sqrt{s})$, where P_{rad}^{div} is total SOL radiation power and s the plasma elongation. Manipulating Eq. (6) by analogy with Refs [4, 5], one gets

$$n_S = C\left(\frac{f}{\gamma T_X^{1/2}}\right)^{11/16} \frac{(q_\perp - q_{\perp,rad})^{11/16} B_t^{5/16}}{q_\perp^{1/16} L^{1/16}} \left(1 - \left(\frac{T_X}{T_S}\right)^{7/2}\right)^{3/8} \qquad (7)$$

Equations (2) to (4) and (7) now alternatively describe attached or detached SOLs if the following specifications/differences are taken into account:

- In the attached case ($X \equiv D$) one has $f = 2$ (because of $M = 1$ at the sheath entrance [6]), $\gamma \simeq 8$ and the divertor temperature is a variable while $L = const$.
- In the detached case ($X \equiv C$) one has $f = 1$ (because of $M << 1$ at the entrance of the CR), $\gamma = 1$ (as outlined above) and the "effective" connection length L_C (see Fig. 1) is now a variable while $T_C = const$ ($\simeq 5\ eV$).

Hence in both cases we have four equations for seven quantities n_S, T_S, n_D, Δ, $q_\perp$, $q_{\perp,rad}$ and T_D/L_C.

From Eq (7) one concludes that in the detached case n_S depends on power essentially through $q_\perp - q_{\perp,rad} \propto P_{heat} - P_{rad}^{bulk} - P_{rad}^{div}$, i.e., the power flux into the CR. ($(1-(T_X/T_S)^{7/2})^{3/8} \simeq 1$). Hence, for comparison with empirical data specific knowledge about the splitting of radiation into its bulk and divertor fractions is not required.

It is illuminating to compare the detached version of Eq. (7) ($T_X \equiv T_C \simeq 5\ eV$, $\gamma \simeq 1$, $f = 1$) with the version of an attached SOL with a divertor temperature close to the threshold where ion-neutral collisions become effective (marginally attached case, $T_D \simeq 5\ eV$, $\gamma \simeq 8$, $f = 2$). Comparing Eq. (7) for these two cases one concludes that marginally attached cases and detached cases differ considerably in the external parameters (n_S, P_{heat}, P_{rad}^{bulk}, P_{rad}^{div}) that control the discharge. In particular, transition into the detached state requires finite changes of these external control parameters. In JET discharges, in general, these parameters evolve slowly (as compared to the characteristic time scales of the SOL) [1]. Hence transition into detachment is a gradual process in these discharges.

Model validation requires measurements of at least four of the basic variables of Eqs (2) to (4) and (7). The JET database provides $P_{heat} - P_{rad}^{bulk}$ ($q_\perp$), P_{rad}^{div} ($q_{\perp,rad}$) and n_S from bolometer and Lidar measurements. The dependence on L_C is so weak in Eq. (7) that one can take $L_C \simeq L$. With this approximation Eq. (7) provides n_S from $q_\perp$ and $q_{\perp,rad}$ which can be compared with the measured values. (Note that, though Eq. (7) is basically freestanding, its derivation involves Eqs (2) to (4).)

This is done in Fig. 2 for shot 26839, which is detached after formation of the X-point ($t \simeq 12\ s$), then shortly attaches when the heating power is ramped up and detaches again when in the later stage P_{rad}^{bulk} and P_{rad}^{div} increase with increasing n_S. Figure 2 illustrates the difference n_S shows in attached and detached cases for the same power flux into the CR. It also gives an example for the gradual transition.

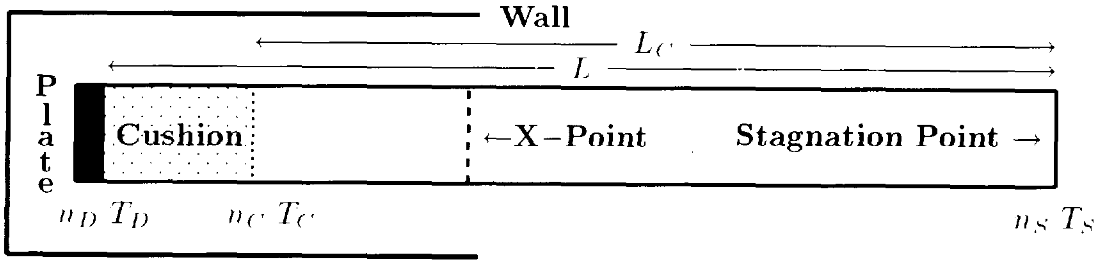

FIG. 1. *Schematic view of the setup considered.* $(L - L_S)/L << 1$

transport is small. Heat conduction is dominated by $i-n$ induced ion heat conductivity and approximately given by (z is the coordinate along B)

$$q_{\parallel,C} = -\kappa_{i-n} n_C \frac{\partial T_C}{\partial z} \simeq v_t \lambda_{i-n} n_C \frac{T_C}{\lambda_{i-n}} \simeq n_C T_C c_s(T_C) \quad (1)$$

where $_C$ denotes values at the entrance of the CR and c_s is the sound speed at this point. (Note that $T_e \simeq T_i \simeq T$ may be a good approximation <u>outside</u> the CR.) Equation (1) is reminiscent of the usual sheath condition with the transmission factor $\gamma = 8$ replaced by $\gamma = 1$.

3. MODELLING OF DETACHED SOL PLASMAS

In the upstream region, i.e., between stagnation point and entrance of the CR, the physics basically does not differ from that in an attached SOL. Modelling of this part is achieved by applying a standard 1-D, two point SOL model with the usual sheath boundary condition of the attached case replaced by proper boundary conditions at the entrance of the CR.

A version of the basic equations of a two point model are given in Refs [4, 5] for the case of Bohm-like perpendicular heat transport ($_S$, $_X$ denote stagnation point and downstream quantities, respectively)

$$n_X = \frac{n_S T_S}{f T_X} \quad (2)$$

$$\Delta = \frac{5}{32} \frac{c}{e} \frac{n_S T_S^2}{q_\perp B_t} \quad (3)$$

$$T_S = \left(\frac{49}{4\kappa} \frac{q_\perp L^2}{\Delta} \right)^{2/7} \left(1 - \left(\frac{T_X}{T_S} \right)^{7/2} \right)^{-2/7} \quad (4)$$

$$\frac{7}{2} \frac{L q_\perp}{\Delta} = \int_0^L dz Q_{rad} + \gamma T_X c_s(T_X) n_X \quad (5)$$

Here Δ is the temperature SOL thicknesses and $q_\perp$ the mean power flux across the separatrix. f reflects a possible pressure drop along the field lines. Otherwise the notation is conventional. For a detailed discussion of Eqs (2) to (5) see Ref. [4, 5].

Equation (5), which is basically the global energy balance in the SOL, can be in various ways brought into a more tractable form. In the present study we are aiming

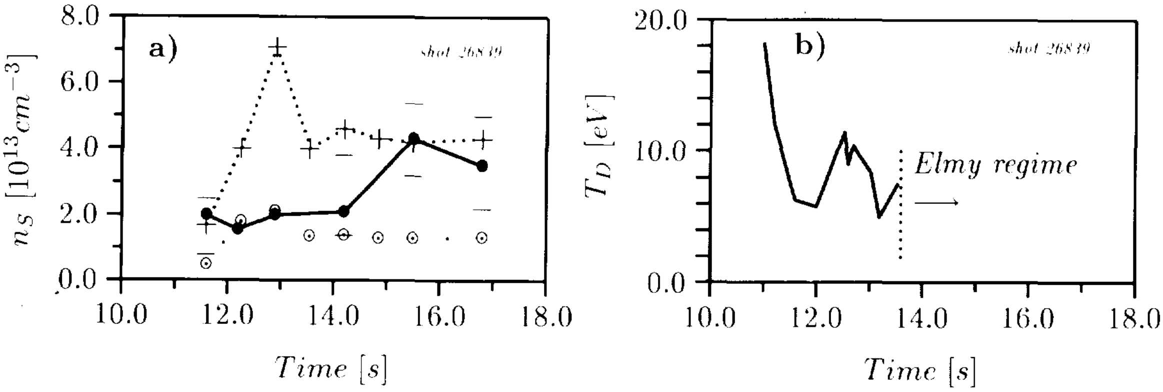

FIG. 2. *(a) Time evolution of n_S for shot 26839. • denotes measured points. + denotes detached model results. ○ denotes attached model results [4]. (b) Time evolution of T_D from a probe close to the inner separatrix. The increase of T_D above 5 eV indicates intermediate attachment which occurs during the power ramp up.*

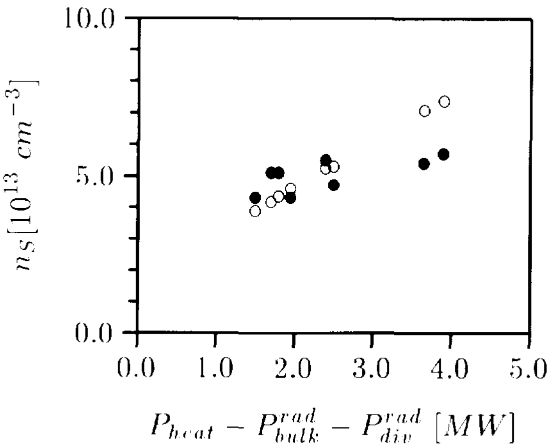

FIG. 3. *n_S versus $P_{heat} - P_{rad}^{bulk} - P_{rad}^{div}$ for a variety of "gas target" discharges. • denotes measured values. ○ denotes calculated values. Ranges of variation: $5\ MW \le P_{heat} - P_{rad}^{bulk} \le 11.5\ MW$, $3.5\ MW \le P_{rad}^{div} \le 9\ MW$.*

In Fig. 3 the special power dependence according to Eq. (7) is checked by comparing measured and calculated n_S values for a variety of detached discharges with different input and radiation powers.

One has to be aware of the rather poor accuracy of the Lidar and bolometer measurements, since otherwise the good agreement as shown in Figs 1 and 2 might be somewhat misleading. Also most gas target discharges show transition into a poor H-mode. This seems to have little effect on the SOL properties, but that remains to be confirmed by an analysis of transition free discharges.

[1] JANESCHITZ, G., CLEMENT, S., GOTTARDI, N., et al., in Controlled Fusion and Plasma Heating (Proc. 19th Eur. Conf. Innsbruck, 1992), Vol. 16C, Part II, European Physical Society (1992) 727.

[2] Hsu, W. L., Yamada, M., Barret, P. J., Phys. Rev. Lett. **49** (1982) 1001.

[3] STANGEBY, P. C., Report JET-P(93)13, JET Joint Undertaking, Abingdon, Oxfordhire (1993), submitted to Nuclear Fusion.

[4] BORRASS, K., Nucl. Fusion **31** (1991) 1035.

[5] BORRASS, K., CAMPBELL, D. J., CLEMENT, S., VLASES, G. C., Nucl. Fusion **33** (1993) 63.

[6] HARRISON, M. F. A., HARBOUR, P. J., HOTSTON, E. S., Nucl. Technol./Fusion **3** (1983) 432.