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IN THE POLOIDAL NULL REGION OF A TOKAMAK
AXISYMMETRIC DIVERTOR

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ABSTRACT

Ion transport through the separatrix of a tokamak with a poloidal divertor is reconsidered, to reconcile the interpretation results of different diagnostics and understand the unexpected multiplet structure of the heat deposition on the targets.

The tokamak magnetic configurations with a poloidal divertor which should prevent the material and thermal contact of the plasma with the vessel, are presently of considerable interest because of the possibility of controlling the impurity contamination of the plasma, which is essential for reactor grade performances [1], and because of the excellent achievement of high confinement regimes (H-modes), in many recent experiments (ASDEX, PBX, DIII-D, JET) [2-5]. While a full explanation of the transition to the H-mode is still to be found, its behaviour has been associated with a favourable heat and particle flow pattern in the edge region of the plasma, due to the separatrix boundary. One of the important mechanisms advocated for the transition from the L regime to the H regime is the special feature of prompt ion heat removal, provided by the separatrix configuration, detached from the wall by a few ion banana widths.

This is supposed to force a large temperature gradient at the plasma edge, which leads to a higher energy content within the plasma [6]. Previous work [6-7] on the structure of the plasma boundary, in presence of a separatrix, has led to a general understanding of the loss regions in velocity space, which determine the shape of the electrons and ions distribution functions, and the associated particles and energy fluxes parallel and perpendicular to the magnetic surfaces.

However, the conventional geometric picture of heat convected along the open field lines in the scrape-off layer (SOL) has been shown to lead to misinterpret-

ation of experimental results, [8] when applied to the region of the vanishing poloidal field (X-point), where the grad-B drift terms dominate over the parallel flux. In several single and double X-point discharges in JET, direct observations [8,9] of the target plates (with a CCD camera and Langmuir probes) during the ohmic phase show the formation of two discrete impact zones or hot spots. With additional heating or during a transition to an H-mode in which a sharp steepening of the edge density and temperature gradients occurs a third strike zone is observed; a result which is at variance with the usual description of plasma flows in the SOL regions of the discharge, according to which the plasma flow is subsonic, along field lines connected to the target plates [10] and produces maxima of heat deposition on or very near the points of intersection of the separatrix with the plates.

The basic assumption of this work, substantiated by other experimental data [11] is that in the separatrix layer the ions are hot and collisionless while the electrons might be cold and collisional. That is, for the ions it is verified that the bounce (τ_b) and collision (τ_s) times satisfy

$$\kappa = \frac{\tau_s}{\tau_b} = \frac{10^{19} T_e^{3/2}}{n_e} \sqrt{\epsilon/2} \frac{T_i^{1/2}}{R_0 q} \gg 1$$

for $r \sim r_x$

where r_x is the (average) minor radius of the separatrix. For edge parameters of a tokamak like JET we have $\epsilon = 0.4$, $n_e = 10^{13} \text{cm}^{-3}$, $T_i = T_e = 0.1 \text{keV}$, $R_0 = 3 \text{m}$, $q = 3$, and therefore $\kappa = 7$.

The description appropriate for the cold electron flow is inadequate for the ion component for which the grad-B drifts are important. Since the ion component may dominate the heat transport in the diverted region of the discharge, the geometry of heat deposition at the plates can be expected to be modified considerably.

In this work it is definitely assumed that the heat flux in the diverted region of the plasma is predominantly through the ion channel and that the deposition of energy on the target plates is completely determined by those collisionless particle trajectories which connect starting points in the scrape-off layer, or in the plasma volume with the targets.

LOSS TRAJECTORIES

The ordering implies that the ion distribution function is nearly constant on a particle orbit. Considering the axisymmetry of the poloidal divertor configuration and neglecting the effects of an electric field E on the orbits, as allowed by the condition $T_e \ll T_i$ in the SOL [9] the guiding centre drift surfaces are conveniently identified by the canonical conjugate momentum

$$\Psi^* = \Psi(\varepsilon, \theta) - Fv\xi / \Omega \quad (1)$$

where Ψ is the poloidal flux, $F = RB$, $\Omega = eB/mc$, $\varepsilon = r/R$ is the aspect ratio, $R = R_0(1 + \varepsilon \cos\theta)$, the major radius of a generic orbit point, v the particle velocity, and $\xi = v_{||}/v$ the pitch angle variable, related to the total energy and magnetic moment μ .

An exact evaluation of the drift orbit invariants for experimental cases can be obtained using the results of the full MHD equilibrium reconstruction [9], and the experimental information on the plasma scrape-off temperature and density. However, here it is expedient to reconsider the essential ingredients of the problem, assuming a specific simple model of a single null divertor generated by filamentary current distributions, with the coordinate system described in Fig. 1. In this case, in the SOL and divertor region expression (1) can be rearranged in the dimensionless form

$$P_\phi = \xi(1 + \varepsilon \cos\theta) + \frac{\varepsilon_s}{\rho_{i0}} \ln \left\{ \varepsilon [\varepsilon^2 + \delta^2 - 2\varepsilon\delta \sin\theta]^{\lambda/2} \right\} \quad (2)$$

having defined $\rho_{i0} = \rho_{i0} / R$ the Larmor aspect ratio of the ions in the poloidal field at the (dimensionless) separatrix radius ε_s in the equatorial plane ($\theta = 0$), having taken advantage of the ordering $\varepsilon < 1$. Here $\delta = d/R$ is the (dimensionless) distance of the divertor coil from the equatorial plane, and $\lambda = (d - r_x/r_x)$ relates to the vertical position of the magnetic field stagnation point, radially located at $r = r_x$. In the plasma interior, for a uniform current distribution the orbit invariant is, in the same ordering:

$$P_\phi = \xi(1 + \varepsilon \cos\theta) + \frac{\varepsilon_s}{\rho_{i0}} \ln \left\{ [\varepsilon^2 + \delta^2 - 2\varepsilon\delta \sin\theta]^{\lambda/2} \right\} + \frac{\varepsilon^2}{2\varepsilon_s \rho_{i0}} \quad (3)$$

The type of loss orbits relevant to the problem are shown schematically in Fig. 1. These include counter-moving ($v \cdot J < 0$) particles which are initially in the SOL region or within the plasma interior and drift across the magnetic separatrix to the right of the X-point impinging on the targets on the low field side at $\theta < \pi/2$. Radially they are distributed in the range $0 < \epsilon$. The range of pitch angle is obtained as

$$\sqrt{\epsilon} < \xi < 1$$

Clearly co-moving particles from the plasma volume drift inwards and do not contribute to losses.

In a similar way, the loss regions for particles impinging on the divertor targets on the high field side $\theta > \pi/2$ are:

$$0 < \epsilon \leq \epsilon_s$$

$$\sqrt{\epsilon} < \xi < \sqrt{2\epsilon}$$

and

$$\epsilon_s < \epsilon$$

$$-1 < \xi < -\sqrt{2\epsilon}$$

The former corresponds to the counter-moving (trapped) particles which are initially deep in the plasma volume and have a turning point on the high field side, with respect to the X-point position ($\theta = \pi/2$), and are sufficiently energetic to drift out of the confinement region after reflection, hitting the target. The latter is the co-moving passing fraction of the SOL population that travel the long way round to the target plate.

The velocity $v(\xi, \epsilon, \epsilon_w, \theta)$ of the various classes of particles, starting from the equatorial plane, is obtained from Eqs. (2-3), where ϵ_w, θ are the coordinates of the intersection of the particles trajectories with the plate. Having determined the loss regions, and by assuming that the radial transport and/or Q-L loss cone diffusion in velocity space is sufficiently great that the distribution functions of the escaping particles is Maxwellian, the particles and energy fractions can be calculated by integrating over all loss trajectories. The fractions of particles and energy deposited at the target plates take the form:

$$\left\{ \begin{array}{l} N(\epsilon_w, \theta) \\ E(\epsilon_w, \theta) \end{array} \right\} = \int (1 + \epsilon) d\epsilon \int \xi d\xi \int_0^\infty v'^3 dv' \left\{ \begin{array}{l} 1 \\ \frac{1}{2} m v'^2 \end{array} \right\} f(\epsilon, v') \delta[v' - v(\xi, \epsilon, \epsilon_w, \theta)] \quad (4)$$

where the distribution function can be taken here as:

$$f(\epsilon, v) = \frac{n(\epsilon)}{2\pi v_{th}(\epsilon)^3} \exp(-v^2 / v_{th}(\epsilon)^2)$$

where $n(\epsilon)$, $v_{th}(\epsilon)$ are the particle density and thermal velocity respectively, and assume the functional form $2/[1 + \exp(\epsilon - \epsilon_s)/\Delta]$, and Δ is the scrape-off width (SOW). The integration over v' is trivial and the remaining integrations are taken over the loss regions just described. It is worth mentioning that other distribution functions could be used, such as those suggested in [6], but the use of such functions further complicates the problem and may not alter the qualitative results of this work. It should be noted that the specific results of this analysis for the single null configuration do depend on having considered also a class of trapped ions which intercept the target near the X-point which were neglected in previous work.

RESULTS AND DISCUSSION

The effect of the ion grad-B drift on the deposition of energy on the divertor target plates has been evaluated by performing the appropriate integrals appearing in Eq. (4) for a magnetic configuration based on JET confinement system during single null operation. The typical parameters considered are an elliptical vessel wall with $a = r_s + 15\text{cm}$, $b = 200\text{cm}$, a plasma current $I_p = 5\text{MA}$, and a SOW $\Delta = 1\text{cm}$ and a scrape-off temperature (SOT) = 0.1keV in the ohmic phase. The divertor current and position d are chosen to locate the poloidal field null and give a separatrix radius at the mid-plane of $r_s = 136\text{cm}$. The two limiting regimes investigated are the low edge temperature ohmic case, and the high edge temperature case typical, for instance, of the H-mode. In Fig. 2 the model temperature profiles near the plasma edge are shown, for the two cases. Using these temperature profiles the integrals over the distribution function have been evaluated, and the resulting distribution of energy at the target plates is shown in Fig. 3.

For the low temperature ($T \leq 0.1\text{keV}$), ohmic phase the fraction of particles that are initially within the plasma volume and can drift across the separatrix, entering the divertor region is not significant and the energy deposition onto the targets is dominated by the SOL population. These particles give rise to the formation of two regions of target plate heating on opposite sides of the magnetic stagnation point (line). The hot spot on the high field side is due to the impact of co-moving particles on orbits which drift inwards through the separatrix.

It has often been argued that the distance of the magnetic null point from the tokamak wall is an important parameter in determining the conditions for transition to H-modes.

The present analysis establishes the qualitative effects of the heat flux due to different separation of the plasma separatrix boundary from the wall. If the X-point is positioned on the target plate these particles give rise to the one-sided decay distribution with maximum intensity up against the separatrix, while the other on the low field side ($\theta < \pi/2$) peaks away from the separatrix. When the X-point is positioned definitely below the target plates (the vertical position of the X-point depends, of course, on the chosen ratio $\lambda = I_d/I_p$ of the divertor and plasma current), the grad-B drifts and the resulting particle trajectories in the divertor channel are increasingly determined by the local magnetic field of the divertor coil. Particle trajectories that intersect the target plates are progressively displaced away from $\theta = \pi/2$.

In the case of intense additional heating, leading to a high edge temperature ($T > 1\text{keV}$; $\epsilon < \epsilon_s$), energetic ions within the plasma volume can cross the separatrix and strike the target plates. The calculations show (Fig. 3) that there is a significant increase in loading and the distribution of heat on the low field side target plate is broadened. On the high field side the deposition of energy is modified by the flux of energetic trapped ions. This population of ions gives rise to a further concentration of heat on the target plate with peak away from the separatrix, and the distribution of energy impacting on the plates is modified considerably. The energy deposition is broader and it is to be noted that the centre of heat intensity occurs away from the separatrix. Under suitable plasma edge density and temperature conditions, or with the addition of a hot ion component, these peaks can be well separated and give rise to two distinct regions of heat intensity on the divertor plates located on the high field of the X-point, on the so-called "ion drift side".

In summary, it is expected that for high edge temperatures in a single null experiment, two hot spots on the high field side and one on the low field side, might be visible as a consequence of plasma striking the targets. Conversely, if such a pattern is observed, it supports an interpretation of edge transport dominated by the ion transport [6]. Furthermore, in view of the importance of grad-B drifts on the power and particle flows in the plasma edge region and SOL, previous studies of transport in the SOL and divertor channel in which orbit effects are neglected [12] are clearly unsatisfactory.

Finally, it is worth mentioning that in double null operation, the passing co-moving fraction of the SOL population would be swept into the lower divertor field region and the associated impact zone at the upper target plate would disappear. The distribution of energy is also modified and the heat loading on the high field side significantly reduced and restored to a single zone.

CONCLUSIONS

The effect of grad-B drifts on the spatial distribution of energy entering the X-point of a single null divertor has been investigated in the cases of ohmic and intense auxiliary heating. The interpretation of the optical images of the target plates heated by the plasma impact can be reconciled with the information on the magnetic configuration when particle orbits effects are taken into account.

The vertical position of the X-point relative to the target plates affects the spread of the hot spots on the plates. It has been shown that when the X-point is positioned on or near the target plates, and the heat flux into the divertor region is dominated by the ion component, then

- i) Two discrete impact zones are predicted, for low edge temperature ($T \sim 0.1\text{keV}$). One on the high field side, buttressed up against the magnetic separatrix, and the other on the low field side, well separated from the X-point.
- ii) For edge conditions that can be expected to occur during intense auxiliary heating, energetic ions from within the plasma volume make a significant contribution to the heat flux. The distribution of impact energy is broadened and the peak of the impact zone on the high field side occurs away from the X-point. For particular plasma edge conditions a splitting of

the high field heat deposition into two discrete impact zones is predicted, and interpreted in terms of dominant ion transport effects.

If the X-point is below the targets and the plasma edge temperature is low, the particles are convected in the "divertor" channel. The positions of maximum heat loading will then be progressively displaced away from the separatrix and the plasma centre plane.

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REFERENCES

- [1] Rebut, P.H. and the JET Team, IAEA-CN-53/A-1-2, Washington, USA, 1990.
- [1] Wagner, F. et al., Phys. Rev. Lett. 49, (1982) 1408.
- [3] Burrell, K.H., The Phys. of Fluids B 2, (1990) 1405.
- [4] Luxon, J.P., Anderson, P., Batty, F. et al., Plasma Physics and Controlled Fusion (1986) Vol 1, p 159, IAEA Vienna.
- [5] Tanga, A. et al., Nucl. Fusion 27 (1987) 1877.
- [6] Hinton, F.L., Chu, M.S., Nucl. Fusion 25 (1985) 345.
- [7] Hinton, F.L., Hazeltine, R.D., The Phys. of Fluids 17 (1974) 2236.
- [8] O'Brien, D., Kovanen, M.A., Reichle, R., Core, W.G.F., Lazzaro, E., Summers, D.D.R., Taylor, T., 17th EPS Conference on Controlled Fusion and Plasma Heating, Amsterdam (1990).
- [9] Erents, S.K. et al., 17th EPS Conference on Controlled Fusion and Plasma Heating, Amsterdam (1990).
- [10] Braams, B., 17th EPS Conference on Controlled Fusion and Plasma Heating, Amsterdam (1990).
- [11] The JET Team, Plasma Physics and Controlled Fusion 32 (1991) 949.
- [12] Simonini, R. et al., 17th EPS Conference on Controlled Fusion and Plasma Heating, Amsterdam (1990).

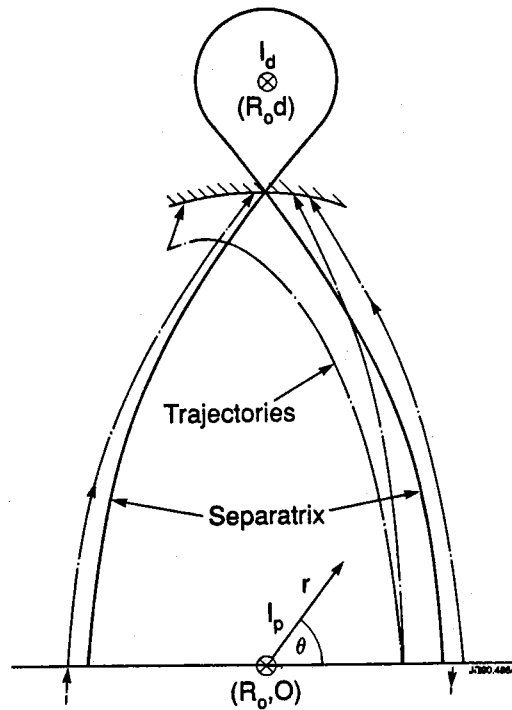


Fig. 1 The model and coordinate system. The magnetic field in the SOL is produced by the two parallel filamentary conductors $I_p(R_0, 0)$ and $I_d(R_0, d)$. Specimen trajectories over which the flux integrations are to be taken are also shown.

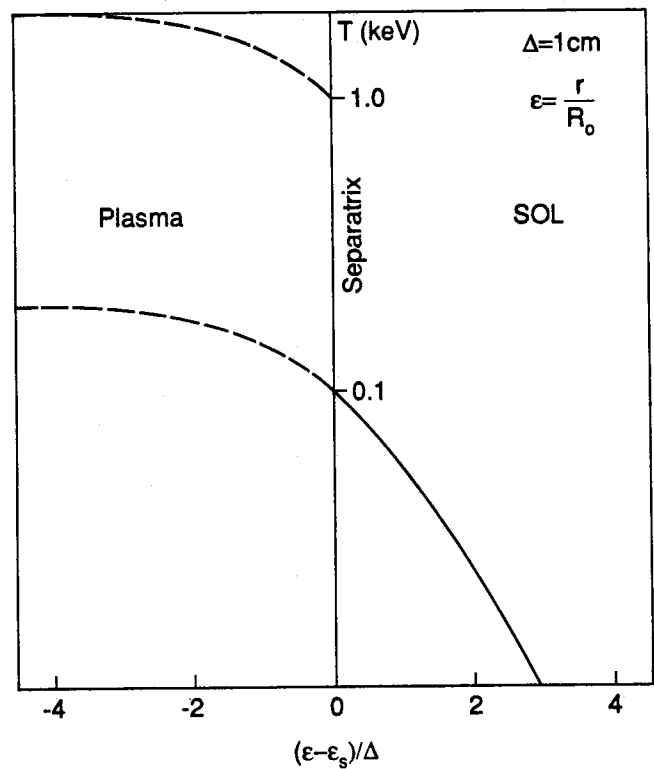


Fig. 2 The model form of the plasma density and temperature profiles at the plasma edge and in the SOL (see text). The upper broken profile models the increase in plasma edge temperature during additional heating or during a transition into a H-mode.

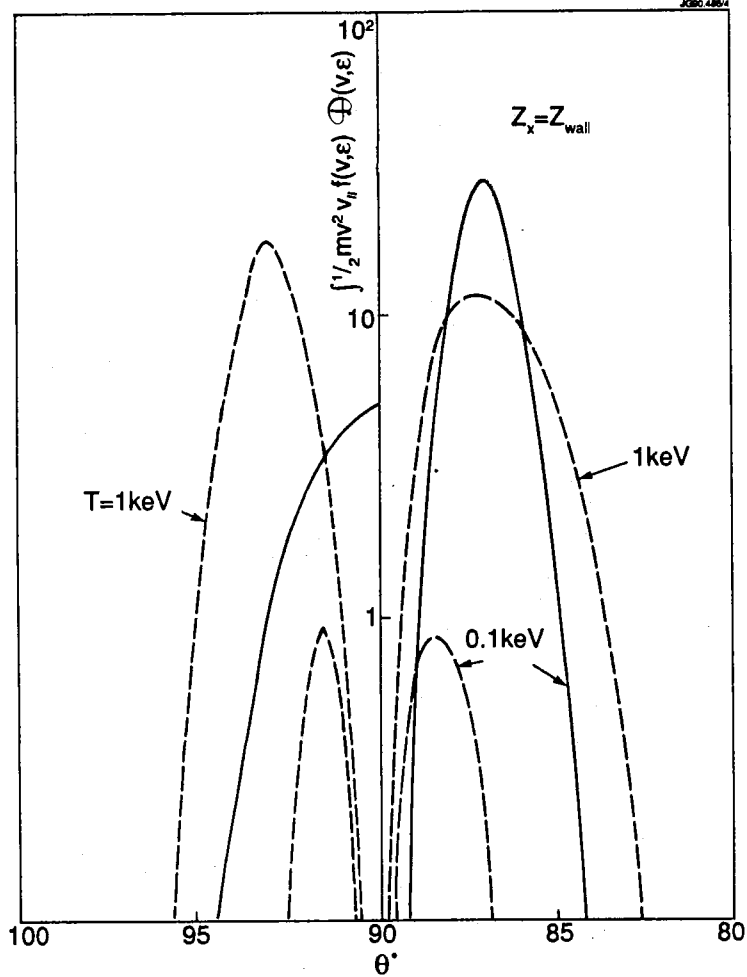


Fig. 3 The energy function

$$\int \frac{1}{2} m v^2 v_{||} f(v, \epsilon) D(v, \epsilon, \xi)$$

taken over all the trajectories intersecting the target plates is shown. The full line is the contribution due to particles initially in the SOL and the broken line is of particles initially within the plasma volume.