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Controlled detachment and particle transport in the divertor plasma in TdeV

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Abstract

At high densities, the plasma detaches from the outboard divertor plates in TdeV. The signatures are a reduction of the ion flux to the divertor plate, movement of the radiating zone from the plate toward the X-point, a pressure gradient between an ionization front and the target plate, and strong cross-field transport in the divertor. A toroidally-viewing TV imaging system allows us to observe local interactions between the divertor plasma and the different divertor plates. As the plasma detaches, the gas pressure in the divertor continues to rise, and there is evidence for molecular processes in the cold plasma near the divertor plates. Auxiliary heating increases the power and particle flow across the separatrix; our results suggest that detachment depends on the energy transported per particle. Simulations using the B2/EIRENE and DIVIMP codes give reasonable agreement with the measurements for the attached phase.

Keywords: TdeV; Poloidal divertor; Detached plasma; Divertor plasma; Atomic physics

1. Introduction

It is considered essential to establish a plasma pressure gradient within the divertor to allow increased radiation losses from the divertor and reduce power flow to the divertor plates [1]. In this paper, we present detailed measurements on the detachment of the plasma from the divertor plates in TdeV. As the central density is raised, the radiating zone in the divertor moves away from the neutralization plates toward the X-point. For central densities above 5×10^{19} m^{-3}, while the ion flux through the divertor throat continues to increase, there is a decrease of the ion flux to the horizontal plate. At the same time, there is a considerable broadening of the plasma within the divertor, resulting in a redistribution of the power onto the divertor plates. A strongly radiating region near the divertor plate which forms upon detachment indicates that molecular processes play an important role in the reduction of the ion flux.

2. Experiment

TdeV is a medium-size tokamak with an outer closed divertor, and an open inner divertor [2]. All the results presented in this paper concern measurements taken in the closed divertor, with the plasma operated in the single null (top) configuration. The central plasma density is measured with a 7-channel laser interferometer [3], while the electron density profile near the separatrix is measured by probes and by a Li-ablation technique [4]. The Li is injected near the divertor throat. The power deposited on the divertor plates is measured by thermocouples and an IR camera, while the power radiated from the main plasma

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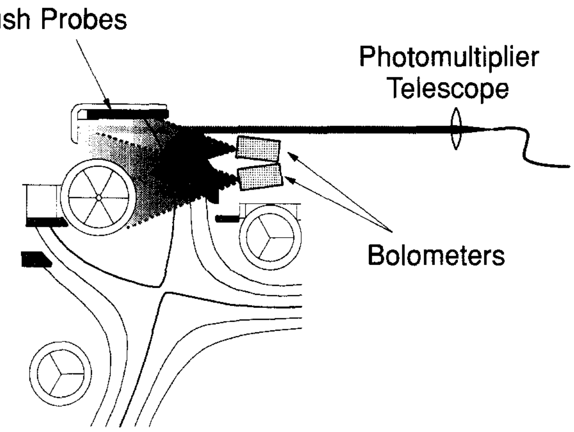

Fig. 1. Upper closed divertor showing relevantdiagnostics.

and from the divertor is measured by a system of bolometers. Of special interest is a pair of bolometers which measure the radiation from two vertically adjacent regions in the divertor, as shown in Fig. 1. There is an array of 16 flush-mounted probes in the top divertor plates [5], and two TV cameras mounted on a toroidally-viewing periscope give images of the divertor plasma at two wavelengths simultaneously. Interference filters allow the observation of spectral lines from *DI* (D_α, D_β), *C*II, *C*III, and HeI. These same lines are measured by a radial chord 15 mm below the horizontal target plate (see Fig. 1). The He emission comes from the residual gas used for discharge cleaning. In addition to the Ohmic power, the plasma can be heated by a lower hybrid system which is capable of delivering up to 1 MW to the plasma [6].

3. Results and discussion

As the central line-average density $\bar{n}_e$ is raised, the edge density $n_e(a)$ measured by the interferometer, by probes, and by Li ablation continues to increase (Fig. 2),

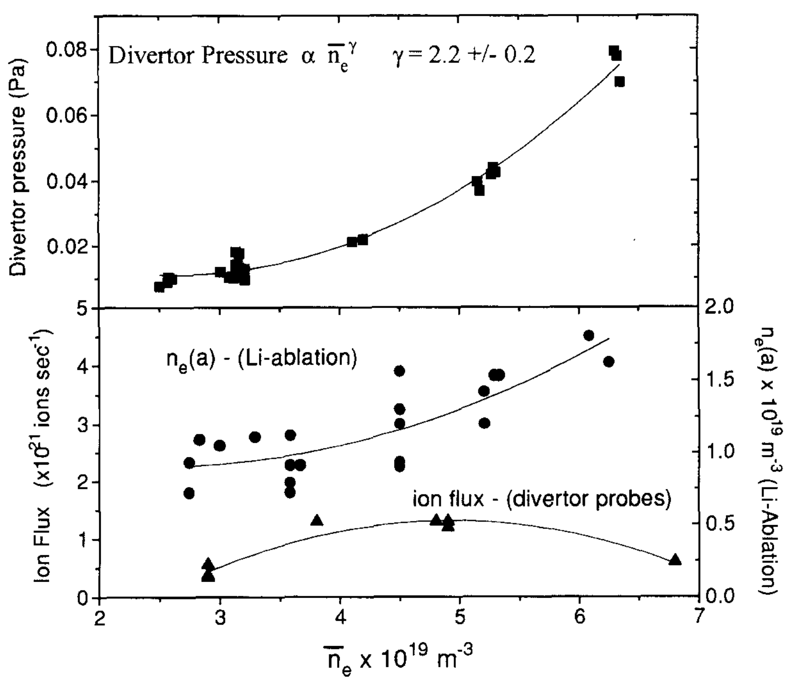

Fig. 2. (a) Variation of the divertor gas pressure and (b) variation of the edge density and the ion flux to the divertor plate as a function of the central line-average density.

while the edge electron temperature decreases slowly. Measurements of the particle confinement time using D_α emission and a gas-puffing technique show that it has a shallow maximum at low densities but is relatively constant; thus the particle flux from the main plasma continues to rise as we raise $\bar{n}_e$. At the same time, the gas pressure in the divertor continues to increase (see Fig. 2), indicating that the particle flux into the closed divertor continually increases.

At low central density the majority of the divertor radiation comes from a region close to the horizontal target plate. At higher densities, the power radiated from a zone upstream from the target plate increases, and at the highest densities the most intense radiation zone has moved to the X-point. The TV camera system can follow this evolution in some detail: it shows the expected transition from a high-recycling configuration at low density to a 'detached' configuration at high density. The fact that the radiation zone moves away from the target plate is not, in itself, sufficient to show that the plasma is detached. The standard definition of detachment requires a reduction of the particle flux at the plate, and a drop of the plasma pressure between the upstream plasma and the divertor plate [7]. The ion flux onto the horizontal divertor plate is obtained by integrating the ion current profile measured by the flush-mounted probes. Fig. 2 shows an increase at low density, a maximum for densities of about 5×10^{19} m^{-3}, and a decrease for higher densities. Thus, although the particle flux from the main plasma continues to increase, the ion flux to the divertor plate decreases at high density.

The TV camera system is used to estimate the divertor plasma parameters from the ratios of HeI lines [8] and of DI (D_α and D_β) lines [9]. The ratio of the D_α and D_β lines is sensitive to the electron density over the density range observed in the divertor, and only weakly dependent on the electron temperature, thus serving as an indicator of the electron density distribution in the divertor (as long as T_e is not below about 10 eV). In Fig. 3 we show the D_α emission and the line intensity ratio as a function of distance below the (upper) divertor plate for an attached plasma and near detachment threshold. At low density, the ratio increases toward the plate, typical of the classical high-recycling regime. At high density, however, the position where the ratio is maximum moves away from the plate, indicating a decrease of the density between an ionization front and the plate. Under fully detached conditions, the DI line intensity ratios are more difficult to interpret since the excited atoms are being produced by completely different processes. Although the radiation zone has moved near to the X-point, the region of maximum density remains within the divertor; this is confirmed by measurements made with a scanning probe. We note that the radiating zone is generally upstream of the region of decreasing density, indicating that radiation losses are important for establishing the conditions necessary for detachment.

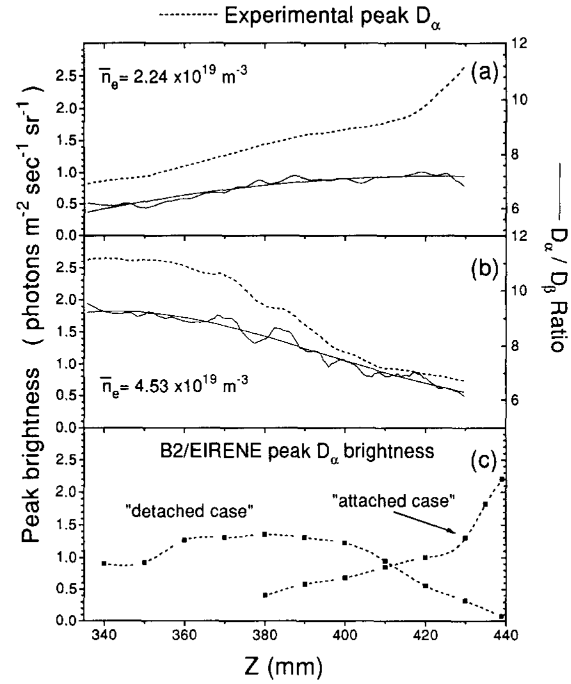

Fig. 3. Measured peak D_α brightness (dashed) and the D_α / D_β ratio (solid) as a function of height in the divertor (a) for an attached plasma (b) near detachment threshold. (c) calculated D_α brightness from B2/EIRENE simulations for attached and marginally detached plasmas.

Whereas the electron temperature obtained from the characteristics of the flush-mounted probes does not go below about 10 eV, estimates of T_e derived from the ratio of line-integrated HeI line intensities show a drop to values below 5 eV for central densities of about 5×10^{19} m^{-3}. It should be noted that the equilibration distance for excited He atoms coming from the wall is much less than the width of the plasma. This discrepancy in the measurement of T_e suggests that the calculation of temperature from probe characteristics is not reliable in the low temperature detached regime. Such an effect is expected in a plasma with a temperature gradient, since probes measure an effective temperature, representative of a position about a mean-free path upstream [10], i.e. near the ionization front, which is significantly higher than that within the detached region. Mach probe measurements in the divertor show an upstream temperature which is higher than the downstream temperature, supporting the interpretation that there is a significant temperature gradient. On the other hand, estimates of the electron densities calculated from the spectroscopic data are compatible with those measured by the probe, decreasing above the detachment threshold.

The TV imaging system gives us a unique opportunity to observe in some detail the interaction between the plasma and the surrounding surfaces in the divertor. At low densities, the D_α emission layer just below the hori-

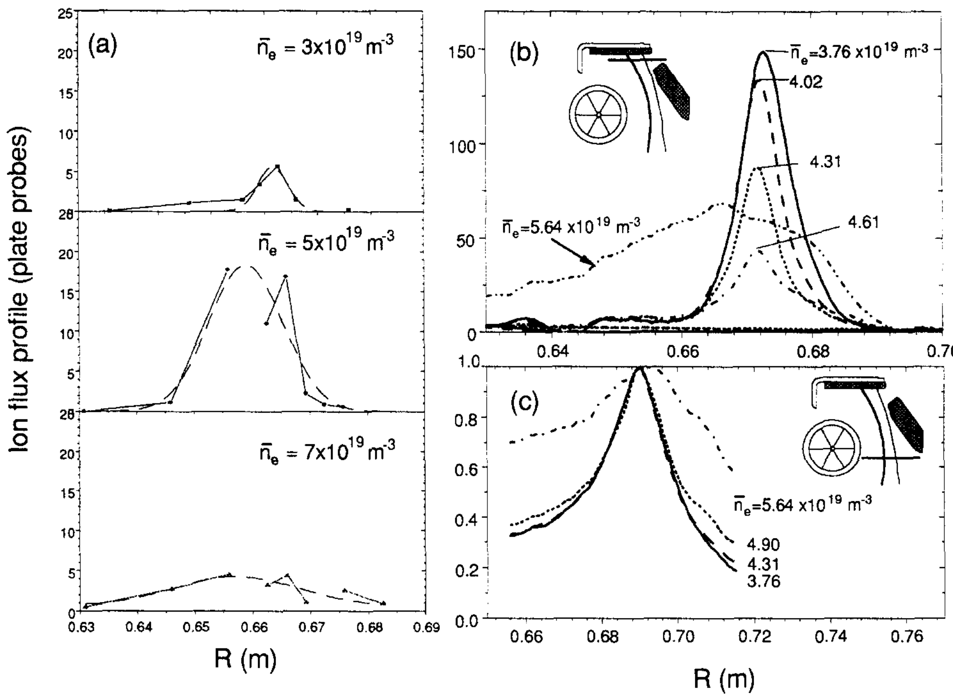

Fig. 4. Radial profiles in the divertor for attached and detached plasmas (a) ion flux to the plate (10^{21} m^{-2} s^{-1}) (b) inverted D_α emission (10^{20} photons m^{-3} s^{-1}) just below the horizontal plate (c) normalized and integrated D_α emission just inside the divertor throat.

zontal plate is relatively narrow, and collapses, mostly from the outside, as $\bar{n}_e$ is raised (see Fig. 4b), ultimately being extinguished prior to detachment. The emission layer just inside the throat (Fig. 4c) shows evidence of an ionization zone on the outer edge. For densities above detachment ($\bar{n}_e \geq 5 \times 10^{19}$ m^{-3}), when the radiating zone has moved near to the X-point, we see the reestablishment of a broad, strong D_α (and D_β) emission zone near the horizontal plate, which expands upstream to fill the divertor at the highest densities (Fig. 5). The profiles of both the emission layer and the particle flux to the horizontal divertor plate show that the plasma fan is significantly broader under these detached conditions (see Fig. 4). In addition to the reduction of the flux to the horizontal

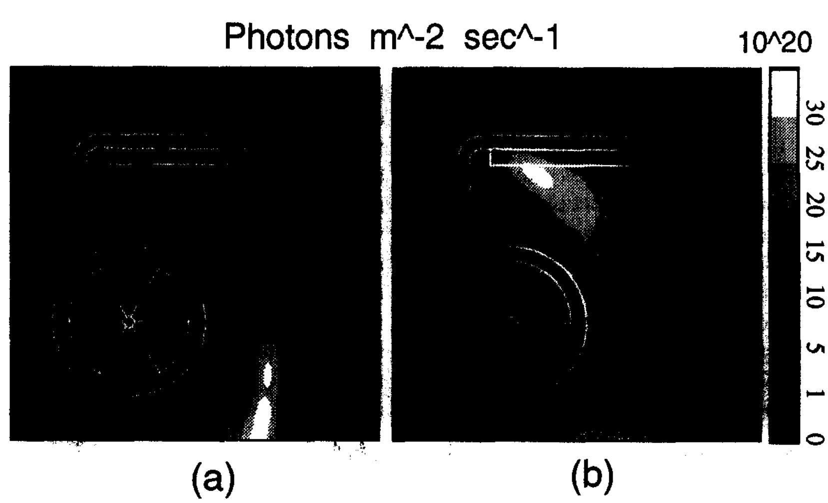

Fig. 5. Image (uninverted) of D_α radiation in the divertor (a) just before detachment ($\bar{n}_e = 4.8 \times 10^{19}$ m^{-3}) (b) well beyond detachment ($\bar{n}_e = 6.1 \times 10^{19}$ m^{-3}), showing the appearance of a broad region of visible radiation which expands upstream from the divertor plate.

divertor plate, there is thus strong evidence for increased radial transport, consistent with an increasing fraction of the divertor power flowing to the inclined plates. On the other hand, density profiles outside the divertor throat obtained with the laser ablation diagnostic show that the SOL profile is not significantly broader under detached conditions. There must then be significant cross-field transport within the divertor, carrying the incoming ions both inward into the private flux region and outward onto the inclined plates, resulting in increased recycling from these surfaces. The recycling neutrals result in an ionization source, cooling the edge of the plasma. In addition to this radial transport, we must consider the possibility of recombination leading to a reduction of the total ion flux to the horizontal plate.

Although the enhanced radiation zone indicates a strong source of atoms and visible radiation near the divertor plate under these detached conditions, the total power measured by the bolometers is not appreciable, and the radiation from carbon near the plate is much reduced; the power deposited by neutrals could now become important. The proximity of the radiation region to the horizontal divertor plate, the high emissivity, and its correlation with the reduction of the ion flux to the plate lead us to propose that molecular processes are responsible for these phenomena. Rate coefficients of about 1×10^{-14} m^3 s^{-1} would be required, suggesting that recombination involving dissociative attachment [11] or ion conversion [12], which invoke excited molecules coming from the surface, plays a major role.

The B2/EIRENE codes have been used to model the experiment under both attached and marginally-detached conditions. The adjustable parameters in the simulation are: (1) the conditions for density and temperature imposed at the boundary with the center, and (2) the anomalous diffusion coefficients. These are selected so as to reproduce the measured power fluxes into the SOL and to the divertor plates. Fig. 3 shows a comparison between experimental and calculated D_α profiles characteristic of an attached ($\bar{n}_e \sim 2 \times 10^{19}$ m^{-3}) and a mildly detached ($\bar{n}_e \sim 5 \times 10^{19}$ m^{-3}) plasma. For the lower density, the agreement is good both qualitatively and quantitatively. For the higher density, the fact that the region of maximum emissivity is farther away from the horizontal plate than obtained from the simulation is attributed to the fuelling via the divertor and recycling from the inclined plate, which are not treated correctly in the simulations. The fully detached configuration, specifically the broadening of the density profile and the recombination region, has not yet been simulated.

At low central densities, the poloidal distribution of the carbon and deuterium radiation obtained from the TV images shows the influence of local interactions, especially with the oblique plate. This confirms that the divertor geometry affects the distribution of the impurity sources, even though at detachment the radiation zone is located near the X-point. Simulations with the DIVIMP code [13] show the necessity to include the chemical sputtering of carbon to obtain a good quantitative agreement with the 2D TV images. The parameters of the background plasma are taken from flush-mounted probe results [5].

Finally, when the Lower Hybrid heating system was used to increase the power flow across the separatrix P_{SOL} (= input power minus radiated power) from 100 to 500 kW,

the central density at which the plasma detached from the horizontal plate was only slightly increased. There is only a slight increase of the edge electron temperature, but it is the edge density $n_e(a)$ and the flux of particles into the SOL which increase significantly, due to a degradation of the particle confinement. Detachment depends on the energy per particle: when $P_{SOL}/n_e(a) \leq 4 \times 10^{-14}$ W m^{-3}, the plasma detaches from the plate.

4. Conclusions

In TdeV, the plasma detaches from the horizontal divertor plate when the line-average density exceeds about 5×10^{19} m^{-3}, as shown by a reduction of the particle flux to the plate and a strong reduction of the electron temperature and the electron density in the divertor plasma. The electron temperature deduced from the flush-mounted probes does not show this drop at detachment; this is felt to be due to the inability of the probes to measure the local T_e correctly in a strong temperature gradient. At the density where detachment occurs, the radiation zone is seen to move away from the divertor plate toward the X-point, always being upstream of the ionization front, the position where the density begins to decrease. The plasma interacts strongly with the inclined plates in the divertor, suggesting that the process of detachment could be significantly modified by a closed divertor geometry. Beyond detachment, the plasma in the divertor is considerably broader, due to strong cross-field transport in the divertor. There are indications that recombination involving molecular processes is important for reducing the ion flux in the detached phase. Simulations with the B2/EIRENE and DIVIMP codes give good agreement with the experimental measurements. With auxiliary heating, the line-average density at which the plasma detaches increases only slightly; the increased power flow is counterbalanced by an increase of the edge density and the particle flux into the SOL.

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References

[1] K. Borrass and G. Janeschitz, Nucl. Fusion 34 (1994) 1203.
[2] R. Décoste, J.-L. Lachambre, G. Abel et al., Phys. Plasmas 1 (1994) 1497.
[3] J.-L. Lachambre and M. Gagné, Rev. Sci. Instrum. 65 (1994) 3428.
[4] D. Michaud, G.G. Ross, E. Haddad et al., Rev. Sci. Instrum. 63 (1992) 5698.
[5] J.P. Gunn, C. Boucher, B.L. Stansfield and S. Savoie, Rev. Sci. Instrum. 66 (1995) 154.
[6] A. Côté et al., Proc. of the 22nd European Conference on Controlled Fusion and Plasma Physics 19C (1995) II-361.
[7] G. Matthews, J. Nucl. Mater. 220–222 (1995) 104.
[8] B. Schweer, G. Mank, A. Pospieszczyk et al., J. Nucl. Mater. 196–198 (1992) 174.
[9] T. Fujimoto, S. Miyachi and K. Sawada, Nucl. Fusion 28 (1988) 1255.
[10] Q. Yu and J.A. Wesson (1995) JET report JET-P(95)81.
[11] D. Post, R. Hulse and D. Stotler, Contrib. Plasma Phys. 34 (1994) 300.
[12] S.I. Krasheninnikov, A.Yu. Pigarov and D.J. Sigmar (1995) MIT report PFC/JA-95-37.
[13] P.C. Stangeby and J.D. Elder, J. Nucl. Mater. 196–198 (1992) 258.