ELSEVIER

Journal of Nuclear Materials 241–243 (1997) 396–401

journal of nuclear materials

Interpretation of ion flux and electron temperature profiles at the JET divertor target during high recycling and detached discharges

R.D. Monk [a,*], A. Loarte [a], A. Chankin [a], S. Clement [a], S.J. Davies [a], J.K. Ehrenberg [a], H.Y. Guo [a], J. Lingertat [a], G.F. Matthews [a], M.F. Stamp [a], P.C. Stangeby [a,b]

[a] *JET Joint Undertaking, Abingdon, Oxfordshire OX14 3EA, UK*
[b] *University of Toronto, Institute for Aerospace Studies, Toronto, Canada*

Abstract

Detailed experiments have been carried out with the JET Mark I pumped divertor to characterise high recycling and detached plasma regimes. This paper presents new measurements of high resolution divertor ion flux profiles that identify the growth of additional peaks during high recycling discharges. These ion flux profiles are used in conjunction with Dα and neutral flux measurements to examine the physics of divertor detachment and compare against simple analytic models. Finally, problems are highlighted with conventional methods of single and triple probe interpretation under high recycling conditions. By assuming that the single probe behaves as an asymmetric double probe the whole characteristic may be fitted and significantly lower electron temperatures may be derived when the electron to ion saturation current ratio is reduced. The results from the asymmetric double probe fit are shown to be consistent with independent diagnostic measurements.

Keywords: JET; Divertor plasma; Detached plasma; Langmuir probe

1. Introduction

Given the large power exhaust expected from a reactor plasma (such as ITER) it is evident that the divertor target will not survive without some additional means to dissipate a significant fraction of the power. By creating a cold and dense plasma in the divertor it is possible to access the detached regime whereby atomic physics loss mechanisms reduce the particle and power fluxes to the target plates. During the 1994–95 JET Mark I divertor campaign, detailed experiments have been carried out to characterize high density discharges with intrinsic impurities. Improved and new diagnostic systems have allowed the detailed study of the ion flux, electron temperature, Dα photon flux and neutral flux in the divertor region during the transition from the high recycling regime through to divertor detachment. This paper reports upon the interpretation of these measurements to study the physics of plasma detachment. In addition, problems are highlighted with conventional methods of Langmuir single and triple probe interpretation. An alternative interpretation method is described which provides results which are more consistent with independent diagnostic measurements.

2. Experimental details

An extensive array of single and triple Langmuir probes have been installed in the divertor target to provide localised measurements of the ion flux and electron temperature. During discharges with 4 Hz strike point sweeping, the triple probes provide radial profiles with high spatial resolution (~ 2 mm) across the target [1]. Spectroscopic measurements of the divertor Dα, CIII and BeII photon fluxes are integrated across the inner and outer strike zones as shown in Fig. 1. Ionisation gauges are used to measure the neutral particle flux in the subdivertor volume [2] and

* Corresponding author. Tel.: +44-1235 465087; fax: +44-1235 464766; e-mail: raymond.monk@jet.uk.

PII S0022-3115(96)00536-3

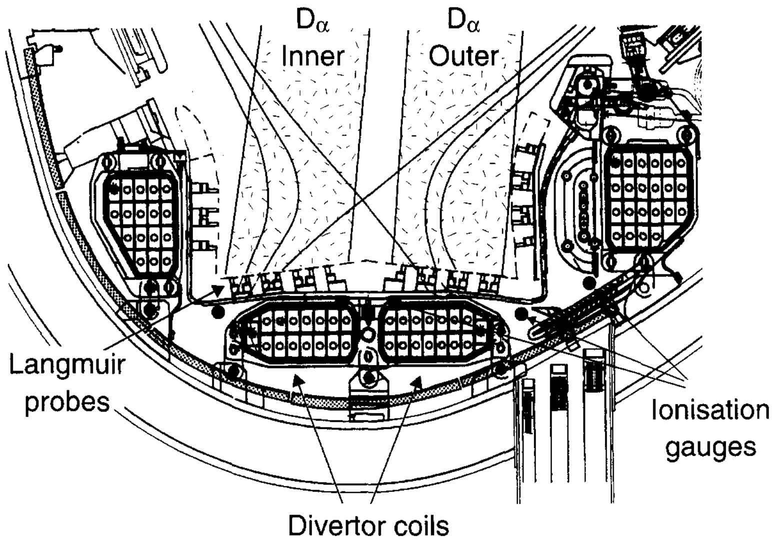

Fig. 1. Cross-section of the JET Mark I pumped divertor showing the location of relevant diagnostic systems.

infra-red thermography of the divertor target surface is used to evaluate the deposited power at the inner and outer strike zones [3].

3. Observations during the approach to divertor detachment

During discharges in which the density is increased by gas fuelling, the ion flux measured by the divertor probes is observed to increase quadratically with the main plasma density as expected for the high recycling regime. However, as the main plasma density is increased further, the divertor ion flux eventually begins to decrease while the divertor Dα photon flux and neutral pressure continue to increase indicating the onset of divertor plasma detachment [4]. In the following subsections, these observations will be discussed in more detail and compared with simple models of detachment.

3.1. Behaviour of the divertor ion flux

During high recycling discharges, the outer divertor ion flux profiles often exhibit an additional peak which grows with the fourth power of the main plasma density to produce strongly peaked non-exponential profiles (Fig. 2). The features are often observed by spectroscopic CCD cameras. The profiles are observed to be toroidally symmetric and therefore cannot be attributed to locked modes. Such profile effects are poorly understood and are not reproduced by 2D fluid edge codes [5].

Upon the transition to plasma detachment, it is observed that the peak divertor ion flux may decrease by an order of magnitude on both the inner and outer strike zones. However, to evaluate the *degree of detachment* it is more meaningful to examine the behaviour of the integrated ion flux at each strike zone. The integrated ion flux may be determined from the triple probe measurements during 4 Hz strike point sweeping and is shown in Fig. 3 as a function of main plasma density for a 2 MA, 2.8 T ohmic discharge with the ion ∇B drift directed towards the divertor target. On the inner divertor it is observed that both the peak and integrated ion flux decrease by over an order of magnitude indicating complete detachment. In contrast, the integrated ion flux to the outer divertor falls by less than a factor of two due to broadening of the profile and indicates partial detachment. The reduction in

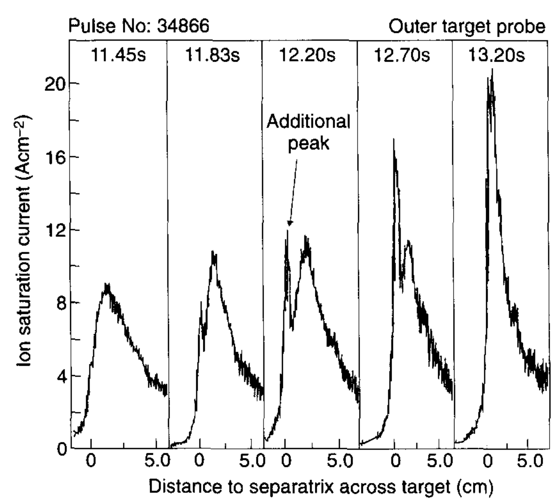

Fig. 2. Ion flux profiles at the outer divertor showing the growth of the additional peak as the density is increased during an ohmic discharge.

the peak ion flux at the outer divertor during detachment is primarily due to the decay of the non-exponential peak highlighted above. Similar behaviour of the ion fluxes have been observed for additionally heated discharges [1]. Measurements from probes mounted in the vertical plates of the divertor may be used to show that the radial ion fluxes increase only slightly during detachment. Therefore, anomalous perpendicular diffusion alone cannot account for the observed decrease in the parallel ion flux particularly at the inner divertor.

3.2. Behaviour of the divertor Dα photon flux

While the divertor ion fluxes decrease during plasma detachment, the divertor Dα photon flux is observed to continue increasing. Such behaviour may be understood by an increase in the number of photons per ionisation as the divertor electron temperature decreases. An average number of ionisations per photon may be directly determined by dividing the integrated ion flux to the target with the line-integrated divertor Dα photon flux. Using the separatrix temperature and density derived from the divertor single probes, the equivalent S/XB ratio is derived from the ADAS database [6] where S is the ionisation rate, X the excitation rate and B the branching ratio. The results are plotted for comparison in Fig. 4. During divertor detachment the number of ionisations per photon decreases from 25 at both divertors during the low recycling phase to ~ 0.1 at the inner and ~ 5 at the outer. On the inner divertor the large decrease in the number of ionisations per photon is not reproduced by the S/XB calculation unlike the outer divertor. This suggests that the electron temperature at the inner divertor may be underestimated by the probes (see Section 4). However, the decrease in the number of ionisations per photon of over two orders of magnitude also indicates very low divertor temperatures and volume recombination.

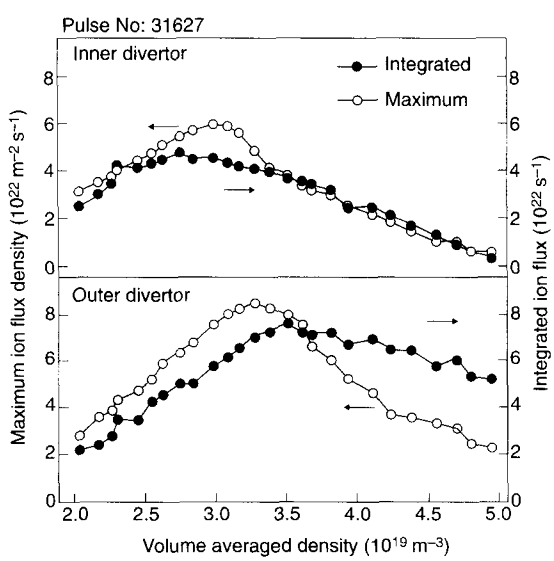

Fig. 3. Peak and integrated ion fluxes to the divertor strike zones as a function of main plasma density.

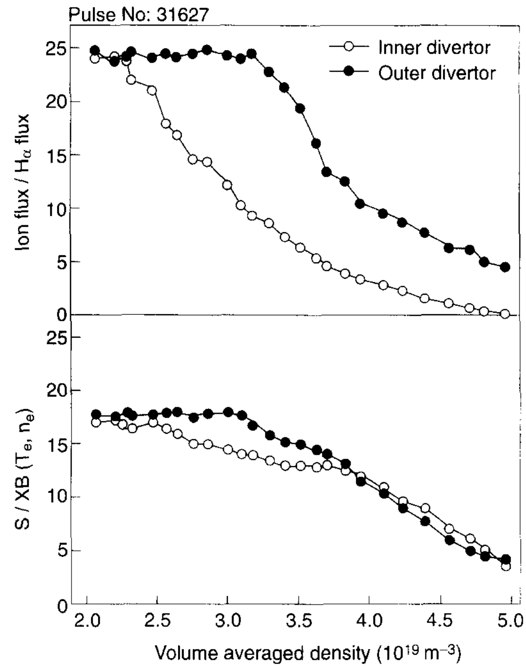

Fig. 4. Behaviour of the number of ionisations per photon derived directly from the ion flux divided by the Dα photon flux compared with the S/XB from the ADAS database using the temperature and density from the divertor probes.

3.3. Behaviour of the divertor neutral flux

In the model of self-sustained divertor detachment proposed by Stangeby [7], the reduction of the parallel ion flux may be caused by elastic and charge-exchange collisions of ions with recycled neutrals which subsequently transfer momentum back to the divertor plate. To significantly reduce the parallel ion flux, there must be a large number of effective elastic/charge-exchange collisions that each recycling neutral undergoes before being ionised ($N_{\rm eff}$). The resulting neutral flux to the divertor may be approximated by

$$\phi_n \approx N_{\rm eff}\left(\frac{I_{\rm sat}}{e}\right)\left(\frac{B_\theta}{B}\right)\left(\frac{A_p}{A_n}\right) \tag{1}$$

where $I_{\rm sat}$ is the ion saturation current measured by the probes, A_p and A_n are the areas of the divertor target over which the plasma and neutrals are distributed and B_θ/B is used to determine the component of the ion flux that is arriving normal to the surface. By extrapolating the inte-

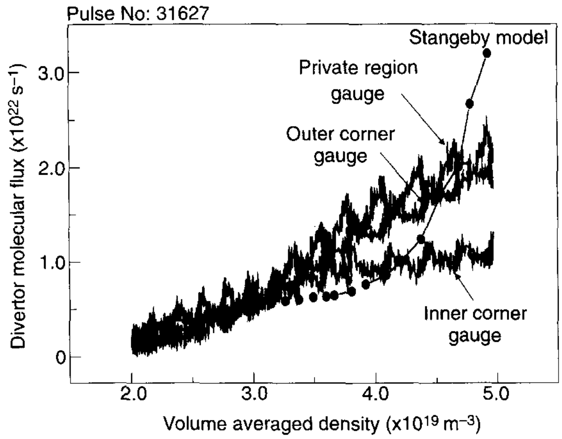

Fig. 5. Comparison of the measured neutral flux in the sub-divertor volume with calculations using the Stangeby model during detachment.

grated ion flux from the high recycling regime through to detachment, the reduction factor ($I_{sat}/I_{sat}^{attached}$) can be determined and used to directly calculate N_{eff}. In this way, it is assumed that the extrapolated ion flux is that which would be measured in the absence of the momentum removing collisions associated with detachment. By normalizing the calculated ϕ_n to the ion flux at low density using $A_p/A_n \approx 0.1$, the neutral flux is calculated and compared with the measurements from the sub-divertor ionisation gauges in Fig. 5 for an ohmic discharge. Considering the simplicity of the model, there is reasonable agreement with experiment although during the latter stages of detachment the neutral flux is predicted to increase more strongly than observed. This effect is mainly caused by the large decrease in the integrated ion flux at the inner divertor.

4. Electron temperature measurements with Langmuir probes

Langmuir probes mounted into the divertor target plates are commonly used to determine the localised electron temperature and density. Such measurements are essential for validating predictive edge code calculations and for the interpretation of spectroscopic measurements. The new array of single and triple Langmuir probes installed in the JET Mark I pumped divertor has facilitated an extensive study of probe measurements under a wide range of plasma conditions [1].

During discharges in which the main plasma density is steadily increased by gas fuelling, it is observed that the functional form of the probe current–voltage (I–V) characteristics may evolve as shown in Fig. 6. At low density, the electron to ion saturation current ratio is large ($j_{sat}^-/j_{sat}^+ > 10$) and the characteristic may be fitted with the conventional single probe exponential formula. Under high recycling conditions, however, the electron saturation current is suppressed ($j_{sat}^-/j_{sat}^+ \sim 2$) and the exponential fit can no longer be applied to the whole characteristic. In this case, it is commonly assumed that fitting an exponential up to the floating voltage may be used to derive the correct temperature [8].

An alternative approach which has been recently adopted at JET is to assume that the single probe behaves as an virtual asymmetric double probe [9] upon which the whole characteristic may be fitted. The asymmetric double probe fits are shown in Fig. 6 and reproduce well the shape of the measured I–V characteristics. During strike point sweeping the ion flux and electron temperature profiles at the outer divertor for three phases of an ohmic discharge are shown in Fig. 7. The electron temperature from the asymmetric double probe fit is compared with the expo-

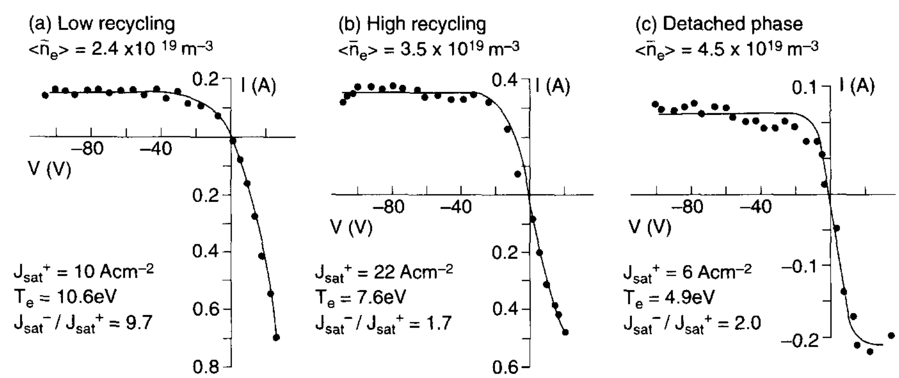

Fig. 6. Evolution of the single probe current–voltage characteristics with increasing main plasma density.

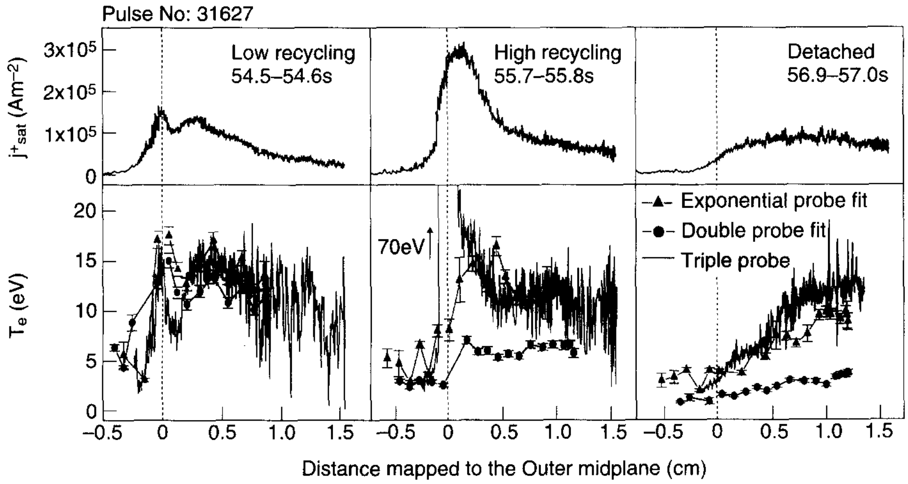

Fig. 7. Comparison of the ion flux and electron temperature profiles at the outer divertor for three phases of an ohmic density ramp discharge. The electron temperature measurements are derived from the single probes (using the exponential and virtual double probe fit) and triple probes.

nential fit and the triple probe measurements. Under low recycling conditions, all three methods of probe interpretation are in agreement. However, under high recycling and detached conditions the temperature derived from the virtual asymmetric double probe fit is significantly lower than conventional methods due to the reduction of the electron to ion saturation current ratio. Under these conditions, the triple probes can measure unphysically high values of the electron temperature (> 70 eV in this example) and should be used with caution due to the implicit assumption of $j_{sat}^{-} \gg j_{sat}^{+}$ used for their interpretation.

4.1. Comparison with infra-red thermography

Infra-red thermography of the divertor plate has been used to calculate the power deposition during additionally heated discharges [3]. In order to assess the probe interpretation models described above, the power from IR thermography may be compared with the power derived from the probes where a sheath power transmission factor of $\gamma = 8$ is assumed ($T_i = T_e$ and $\delta_e = 0$). The results are shown in Fig. 8 for a series of 4 MW L-mode discharges at different main plasma density. Under low recycling conditions, the power derived from the probes is in good agreement with the IR thermography measurements. However, at higher density the triple probes clearly overestimate the deposited power while the asymmetric double probe fit remains in agreement with the IR thermography. It is proposed that the overestimation of the electron temperature due to the low electron to ion saturation current ratio may account for earlier observations of apparently low values of the sheath power transmission factor in DIII-D [10]. In the case of the JET experiments, one would infer from the triple probes that $\gamma = 8$ at low density and falls to unphysically low values of $\gamma = 2$–3 under high recycling conditions.

4.2. Comparison with spectroscopic measurements

Interpretative DIVIMP modelling [11] has been used to simulate spectroscopic measurements of the CIII and BeII photon flux at the divertor using the different methods of

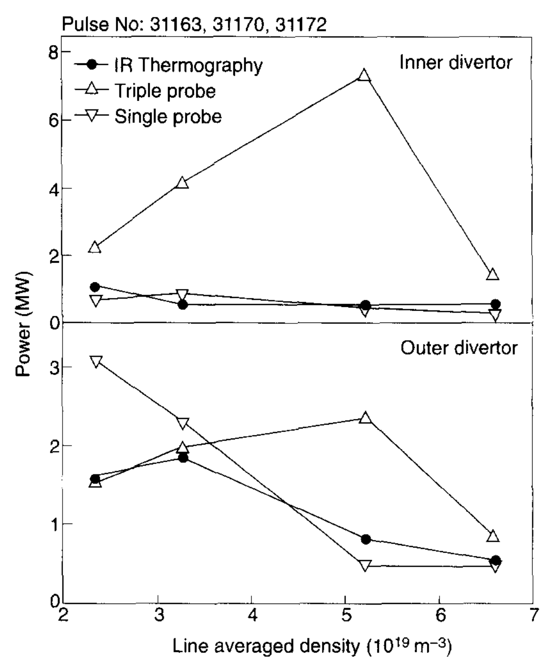

Fig. 8. Comparison of the deposited power derived from triple probe and single probe (asymmetric double probe fit) measurements with IR thermography for 4 MW additionally heated discharges at different main plasma densities.

probe interpretation. In the case of the carbon divertor target, the analysis was inconclusive due to the assumptions required for the form of the chemical sputtering yield [12]. In the case of the beryllium target, the DIVIMP simulations using the virtual double probe fit were in better agreement with the spectroscopic measurements than for the conventional methods of probe interpretation. It was, however, necessary to assume that the sputtering yield approximated to beryllium oxide rather than pure beryllium [1]. Direct comparison of the electron temperature with spectroscopic line ratios of CII at the inner divertor from VUV spectroscopy and the outer divertor from the thermal helium beam has shown that results from the asymmetric double probe fit are in good agreement [13].

5. Conclusions

During high recycling discharges, the ion flux profile at the outer divertor often exhibits an additional peak which is toroidally symmetric and grows rapidly with increasing main plasma density. These features are not understood and cannot be reproduced by 2D fluid edge codes.

Divertor detachment is characterised by large decreases in the peak ion flux at both strike zones. By itself, however, this measurement can be misleading since the integrated ion flux at the outer divertor does not decrease by the same amount due to broadening of the profile. Using measurements from probes in the vertical divertor plates it has been possible to show that anomalous perpendicular diffusion cannot, by itself, explain the large decrease in the parallel ion flux observed at the inner divertor during detachment. At the outer divertor, the decrease in the number of ionisations per photon during detachment is consistent with the decrease in the electron temperature while the larger decrease at the inner strike zone cannot be reproduced. The large decrease in the number of ionisations per photon at the inner divertor indicates very low electron temperatures and volume recombination. With suitable assumptions, the evolution of the neutral pressure during detachment may be approximately described using the model by Stangeby [7].

Divertor probe current–voltage characteristics become increasingly distorted away from the simple exponential during the high recycling and detached discharges. Under these conditions, the ratio of the electron to ion saturation current is reduced and the conventional single probe cannot be used to fit the whole characteristic. It is also observed that triple probes can produce large overestimates of the electron temperature. By assuming that the single probe behaves as an virtual asymmetric double probe [9], it is possible to fit the whole characteristic and significantly lower electron temperatures are derived when the electron to ion saturation current ratio is low. The temperature from the virtual double probe fit is shown to be consistent with independent diagnostic measurements. During the forthcoming Mark II divertor campaign at JET 'pin and plate' probes [14] will be used to further investigate the effects of plasma resistivity on the measurements.

References

[1] R.D. Monk, Ph.D. thesis (University of London, 1996).
[2] J.K. Ehrenberg et al., Proc. 22nd Eur. Conf. Bournemouth, Plasma Phys. Controlled Fusion 19C, Part I (1995) 309.
[3] S. Clement et al., Proc. 22nd Eur. Conf. Bournemouth, Plasma Phys. Controlled Fusion 19C, Part III (1995) 309.
[4] R.D. Monk et al., Proc. 22nd Eur. Conf. Bournemouth, Plasma Phys. Controlled Fusion 19C, Part III (1995) 293.
[5] A. Loarte, these Proceedings, p. 118.
[6] H.P. Summers, Atomic Data and Analysis Structure User Manual, JET-IR(94) 06.
[7] P.C. Stangeby, Nucl. Fusion 33 (1993) 1695.
[8] J.A. Tagle et al., Plasma Phys. Controlled Fusion 29 (1987) 297.
[9] K. Günther et al., J. Nucl. Mater. 176–177 (1990) 236.
[10] A. Futch et al., J. Nucl. Mater. 196–198 (1992) 860.
[11] P.C. Stangeby and J. Elder, J. Nucl. Mater. 196–198 (1992) 258.
[12] H.Y. Guo, these Proceedings, p. 385.
[13] R.D. Monk et al., Contrib. Plasma Phys. 36 (1996) 37.
[14] P.C. Stangeby, Plasma Phys. Controlled Fusion 37 (1995) 1337.