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Plasma detachment from divertor targets and limiters

G.F. Matthews

JET Joint Undertaking, Abingdon, Oxfordshire, UK

Abstract

Plasma detachment from a divertor target is defined as the state in which large gradients in total plasma pressure (static plus dynamic) are observed parallel to the magnetic field with consequent reductions in the plasma power and ion fluxes to the limiting surfaces. The origins of this concept and the first experiments in a linear divertor simulator are described. Experimental evidence for this phenomenon from the JET, JT60-U, DIII-D, Alcator C-Mod, and ASDEX-U tokamaks is reviewed along with recent advances in the theory and modelling of detached plasmas applicable to current experiments. Plasma detachment from limiters was first reported by TFTR in 1985, shortly followed by DITE and TEXTOR. This phenomenon occurs in low power discharges near the density limit and is characterised by a shrinking of the layer where most of the ionisation occurs away from the limiter. The physics, phenomenology and relevance to fusion of detachment from limiters and divertors are contrasted.

1. Introduction

In the context of plasmas, the meaning of *detachment* can provoke considerable debate. A dictionary offers the following definitions [1]:

- *detachment,* state of being detached,
- *detached,* unconnected: separate: aloof: free from care, passion, ambition and worldly bonds.

If *worldly bonds* are the material surfaces defining the boundaries of a laboratory plasma, then *detachment* implies that the primary boundary condition for the plasma is no longer at these surfaces. However, this definition is vague and so I propose the following alternative: *plasma detachment*, state in which large pressure gradients (static plus dynamic) are observed parallel to the magnetic field with consequently low plasma power and ion fluxes to the material surfaces bounding the system.

Although the concept of *plasma detachment* may sound rather esoteric, reducing the peak power load to the first wall of a fusion reactor such as ITER [2] is of great practical importance and current interest. For this reason *detached divertor plasmas* are now considered the primary solution to the problem of engineering the ITER divertor. However, as will be described in this paper, *plasma detachment from limiters* although appearing quite frequently in the literature, does not fit within the above definition of *detachment* and seems doomed to remain a fascinating but inconsequential phenomenon.

The basic concept that one might extinguish the exhaust plasma from a fusion reactor in a box of neutral gas originated in the gaseous divertor scheme presented by Tenney and Lewin [3] in 1974. In this conceptual reactor design, the neutral pressure is allowed to build up in a remote divertor chamber to a large density ($\sim$ 1 Torr). Charged particle–neutral interactions and radiation from seeded argon impurities were to cause the temperature to fall along the divertor channel until, on entering the divertor chamber, the temperature fell bellow 0.1 eV. At this point it was envisaged that the recombination rate would become so high that the plasma would recombine before reaching the chamber walls. Plans for ITER also involve extinguishing the divertor plasma in a neutral gas but in a regime of much lower pressure [2] which is more in keeping with experience from current tokamak experiments. Since the catalytic paper by Watkins and Rebut [4] there has been such a huge amount of analytical and code work on detached plasmas in reactor relevant

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regimes that it deserves a review of its own [5]. In this paper therefore the scope is restricted to simulations and theories relevant to existing experimental results.

2. Detachment in linear simulators

The gaseous divertor concept of Tenney was first put to test in a device which, if it were built today, would probably be described as a low power density divertor simulator. The QED (quiet energetic dense) device was built at Princeton Plasma Physics Laboratory in 1976 for the study of magnetic divertor physics [6]. It consisted of a cylindrical vacuum vessel in which an axial magnetic field was generated by a series of external circular coils as is shown in Fig. 1a. The plasma was generated in an arc jet and flowed down the axis of the device through two limiting apertures for a total distance of about 1.2 m before striking the end collector. The parallel power density in the 1–2 cm diameter beam was ~ 5 MW m^{-2} in the central section of the machine giving electron temperatures around 5 eV and densities around 10^{20} m^{-3}. Although very much smaller than the parameters expected in ITER, these conditions are comparable to those seen in the divertors of smaller tokamaks.

Gas target experiments on the Princeton QED by Hsu [7,8] showed that stable detached plasmas could be produced by puffing gas into the divertor chamber. Fig 1b shows the decrease in the axial heat flux seen on calorimeter C_A and the associated rise in the radial heat flux C_R as the neutral pressure in chamber D is raised. One can see from Fig. 1b that detachment occured well bellow the plasma pressure which was between 1 and 2 orders of magnitude larger. In these experiments it was shown that the neutral pressure in the end chamber could be varied over an enormous range limited only by the point at which the finger of plasma was pushed out of the chamber altogether. As one might expect this expulsion occured when the neutral pressure exceeded the plasma pressure and resulted in a large (> 10) abrupt reduction in the differential pressure between the middle and end chambers. The QED results were modelled by Hsu assuming that the dominant process for energy and momentum removal was collisions between ions and neutrals. This interpretation relies on collisions between ions and molecules. Molecules dominate the neutral population when the electron temperature is too low to produce much ionisation ($T_e < 5$ eV). Hsu's model produced a good fit to the QED data and also showed that ion–neutral collisions increased the diffusion coefficient well above the classical ambipolar value based on ion–ion collisions alone. At sufficiently high neutral pressures the electron temperature fell to $T_e \sim$ 0.2 eV and the plasma appeared to recombine. Many of these results have more recently been reproduced and elaborated in a small pulsed device [9,10] including an experiment proving momentum transfer to the neutral gas by direct measurement rather than inference [11].

The main weakness of the QED results, from the perspective of extrapolation to a tokamak, was the fact that the plasma column was not much larger than the ion gyro-radius and the electron temperature was low throughout the device. In a tokamak with a poloidal divertor we would expect to see a hot scrape-off layer $T_e = 30$–100 eV in the region adjoining the core plasma with a relatively sharp decrease in temperature at the point at which the ionisation and charge exchange occur. The PISCES machine is very similar to the QED only significantly larger and has performed very similar gaseous divertor experiments [12,13]. In PISCES the plasma column entered a 4.5 cm diameter tube which

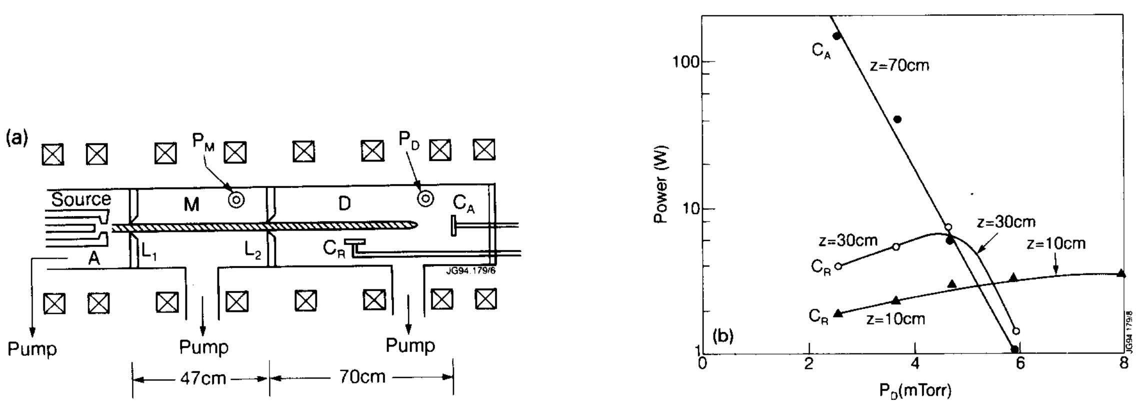


Fig. 1. (a) Schematic of the Princeton QED used for exploring the gaseous divertor concept [8]. C_A and C_R are calorimeters for measuring the axial and radial heat fluxes respectively. (b) Scaling of calorimeter signals with gas pressure in chamber D at various distance, z, from L2.

was 90 cm long and closed at the far end forming a close fitting channel rather than a gas box. In general the results from the two machines look very similar. However, PISCES has sufficiently high electron temperature and plasma size to go from the high recycling regime, where a large fraction of the ions reaching the end are recycled as neutrals and reionised in the divertor channel thus amplifying the ion flux reaching the end, to the detached state where the ion flux arriving at the end plate is very substantially reduced. The PISCES experiments confirm the large increase in cross-field transport with neutral pressure reported from the QED device but in a plasma column that is many ion gryo-radii in diameter. Values of $D_\perp$ up to 20 times the Bohm value are reported in PISCES but, unlike the QED data, these results are said to be inconsistent with the classical ambipolar value $D_{\perp \mathrm{cl}} = kT_e \nu_{in}/(m_i \omega_{ci}^2)$; where ν_{in} is the ion–neutral collision frequency and ω_{ci} is the ion cyclotron frequency. In PISCES the decrease in ion current reaching the end has been shown to be primarily a consequence of the enhanced flow of ions to the sides of the channel. In that sense it is not a purist's gas-target in which the plasma is totally quenched in the neutral gas.

3. Detachment in divertors

The most characteristic signature of detachment from a divertor target is an unexpected and large decrease in the ion flux recorded on the target by Langmuir probes without a corresponding decrease in the H_α emission from the vicinity of the divertor. An example of this can be seen in Fig. 2 [14] which shows the ion saturation current from 10 probes in the outer target of the C-MOD divertor. At 0.715 s this data shows a relatively sharp decrease on all the probes below the knee in the divertor target whilst those above it actually show a slight rise in current. Close examination of the time history of the detachment shows that it starts closest to the separatrix first and moves outwards. Similar findings have been reported from JET [15] and DIII-D [16]. In DIII-D [16], ASDEX-U [17] and JET [18] the reduction in the ion flux has been shown to be accompanied by a fall in the surface power loading observed on the divertor targets with infrared diagnostics.

Three main questions arise out of the observations of detachment:

- Why does the ion-saturation current decrease and where does that current go?
- On open field lines we normally expect the plasma pressure at the divertor target to be about half the value near the stagnation point. So what has happens to the pressure parallel pressure balance?
- Last but not least, where and how is the power lost?

3.1. Parallel pressure balance and ion flux

A simple one-dimensional fluid or kinetic theory of the flow of plasma to a solid surface along the magnetic field, which ignores volume sources of momentum, gives the following expression for the plasma pressure at the sheath edge [19]:

$$P_s = \frac{P_0}{1 + M_s^2},$$

where P_0 is the plasma pressure at the stagnation point of the scrape-off layer (SOL) and M_s is the Mach number of the plasma at the sheath edge. The Bohm condition requires that $M_s \geq 1$ at the sheath edge it is conventionally assumed that $M_s = 1$, giving $P_s = 0.5P_0$. A fluid dynamicist's expression of this condition is that the total plasma pressure (static plus dynamic) is constant along a magnetic flux tube.

Probe measurements of electron density and temperature show that the simple parallel pressure balance is lost during detachment. This can be seen in experiments where target Langmuir probe data is complemented by reciprocating probe measurements in the scrape-off layer, or in discharges which detach at only one strike point such that a pressure imbalance between the inner and outer strike region can be seen. An example of this in given in Fig. 3 which shows data from a discharge in JET which detaches at the inner strike point [20]. The SOL profile was measured with a fast reciprocating probe and is very similar to that obtained in an attached case. Similar data has been

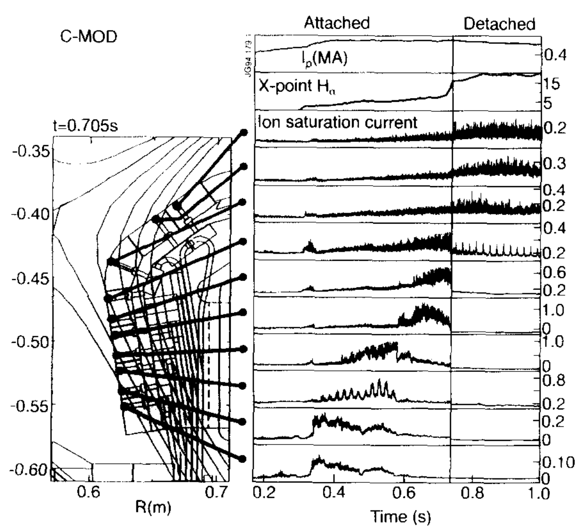


Fig. 2. Time history of the divertor ion saturation currents, plasma current I_p and X-point H_α recorded in C-MOD during the transition from the attached to detached states [14].

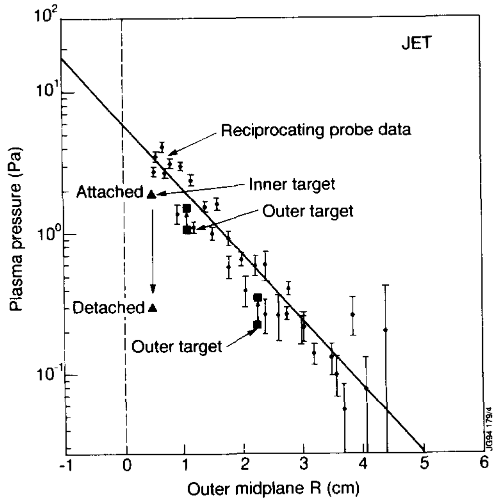


Fig. 3. Profiles of electron pressure derived from the JET reciprocating probe located near the stagnation point and target Langmuir probes during the detachment of the inner strike-zone. No significant changes in the reciprocating probe profiles are observed during detachment of a single strike zone.

obtained in Alcator C-Mod but in this case the data is from discharges which detach at both strike zones [14] and show significant changes in the SOL profiles, a point which I will return to later.

The static plasma pressure at sheath edge is actually the sum of the electron and ion pressures $P_s = n_{es}eT_{es} + n_{is}eT_{is}$, where T_{es} and T_{is} are the electron and ion temperatures at the sheath edge in units of eV. Langmuir probes can only measure T_{es} and the derivation of n_{es}, the electron density at the sheath edge, also requires assumptions about M_s and T_{is}. Fortunately, although the static plasma pressure is quite dependent upon the Mach number and ion temperature, the ion flux is more closely related to the total static plus dynamic pressures and is much less sensitive [2]. For this reason large drops in the ion-saturation current seen on target Langmuir probes provide one of the best pieces of evidence for detachment.

The experiments carried out in linear simulators show that if the electron temperature is around 5 eV or less, ion–neutral collisions can dominate over ionisation and significant momentum removal can be observed. Electron temperature measurements made with target Langmuir probes in ASDEX-U [17], C-MOD [14], JET [20] and DIII-D [16] all show that in the detached regions of the plasma the electron temperature falls to $T_e = 2$–5 eV. However, the fact that this is a necessary but not sufficient condition for detachment has been shown with JET data [20] where there are cases of attached discharges with temperatures in this range.

As with the linear simulators, the neutral pressures measured in the private flux regions of DIII-D [21] and C-MOD [22] at which detachment occurs are 2–3 orders of magnitude lower than the plasma pressures and in the region of a few mTorr. Unlike the QED results [8] continued puffing into these tokamaks does not substantially raise this pressure but instead drives the main plasma to the density limit. A more closed divertor geometry clearly helps reduce the leakage of neutrals back into the main plasma and should raise achievable divertor neutral pressure, at the price of bringing material surfaces closer to the plasma. However, it should not be assumed that closing the divertor will decouple the SOL plasma density from the divertor plasma density. The record divertor neutral pressure is held by the DITE bundle divertor which reached 30 mTorr [23] in a very closed geometry. Even at this pressure the hot core of the flux bundle was not detached, although detachment of the outer layers may have led to a partial unplugging of the ducts thus leading to a density limit disruption in the main plasma.

3.2. Comparison with analytical models

Perhaps the simplest model of detachment is one where we regard the neutral density in the divertor chamber as something we can set to any value we choose. If we think of it in this way then there is nothing surprising about detachment, since if we raise the neutral density high enough there will always come a point at which the ion neutral interactions carry away the momentum. Such a model is not that unrealistic for a linear simulator but in a tokamak the detachment must be self-sustained. Stangeby [24] has developed an analytical theory for the self-sustained gas-target by which he means that the residual ion flux arriving at the target after detachment must balance the ionisation sources. Without this condition the main plasma density would evolve in an uncontrolled way. For this reason N – the number of elastic collisions experienced by a neutral atom or molecule before being ionised – is crucial to this picture and is shown in Fig. 4b [24].

When N is large there is a natural segregation into a neutral collision zone close to the target where ion–neutral collisions dominate and an ionisation zone further away as shown in Fig. 4a. In his analysis, Stangeby takes this one step further by assuming complete separation of the two zones and then solves the equations for conservation of mass and momentum between the ionisation front and the target plate. The result of this analysis is a reduction in the plasma density at the target which may be understood as follows. To satisfy the Bohm condition the presheath electric field is set up to accelerate the ions to the ion acoustic speed at the sheath. Ion-neutral collisions produce a viscous drag which makes this more difficult and so a larger electric field develops to compensate. This electric field repels electrons and depresses their density via the Boltzman relationship. Fig. 4c shows the reduction in ion-saturation current that is predicted by this theory allowing also for the fact the collisions remove energy from the ions. This model therefore appears to predict that in the temperature range observed experimentally, large reductions in ion-saturation current might be expected.

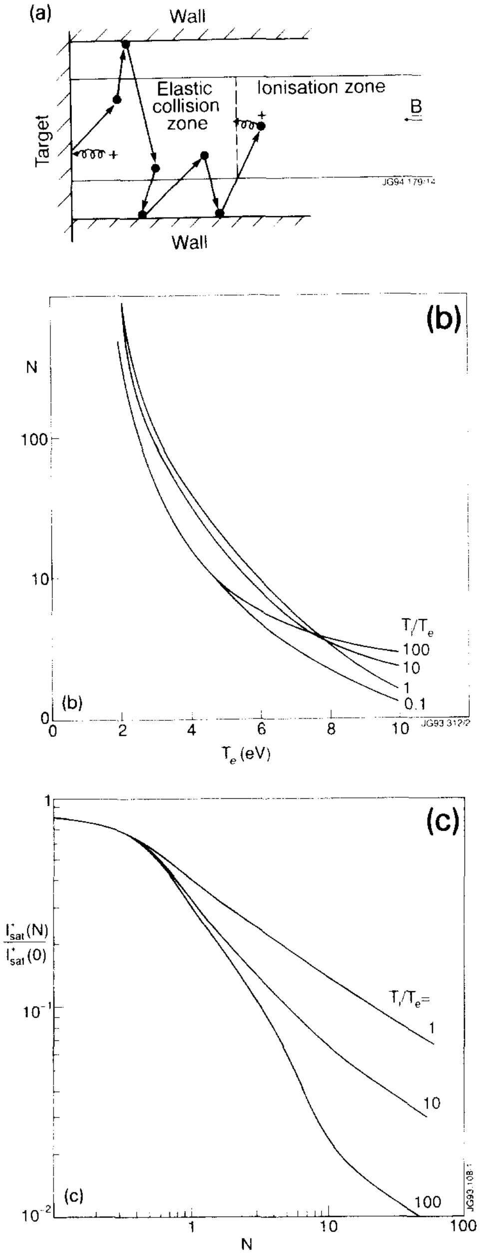


Fig. 4. (a) Schematic showing transfer of ion momentum to the wall when N, the ratio of elastic ion-neutral collisions to ionisations is large. (b) N versus T_e for deuterium molecules [24]. (c) Reduction factor for ion-saturation current versus N [24].

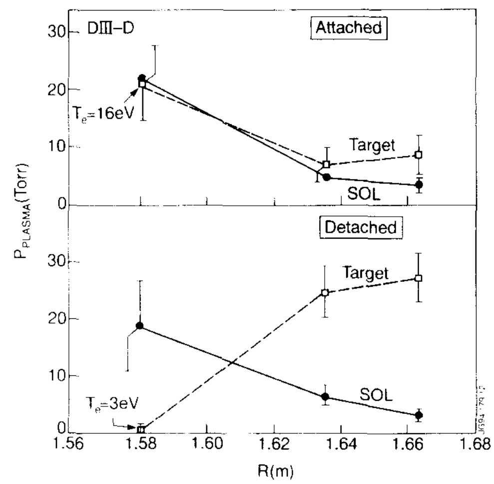


Fig. 5. Plasma pressure in DIII-D measured in the main SOL, using Thomson scattering and charge exchange recombination, is compared with the plasma pressure measured in the divertor with target Langmuir probes assuming that $T_i = T_e$ [16]. Attached and detached cases are compared.

It is worth noting that Fig. 4c assumes that all the elastic ion-neutral collisions are effective, by which we mean that the momentum is transferred to the wall after each elastic collision as illustrated in Fig. 4a. If instead, additional elastic collisions occur on the way out to the wall momentum will merely be transported around within the plasma column. The only experimental evidence for this is shown in Fig. 5 and comes from DIII-D [16] target probe data which seems to show a redistribution of plasma pressure with a reduction near the separatrix and a significant increase further out. However, the huge inverted pressure gradient far from the separatrix may be hard to explain.

Geometry might also reduce the number of effective momentum removing collisions. In the special circumstance that the mean free paths are ordered as:

$$\lambda_{\text{ionisation}} \gg \lambda_{\text{elastic ion—neutral}} \approx \text{divertor plasma width},$$

it is easy to imagine that the number of effective momentum removing collisions $N_{\text{eff}} \approx N$. However, it is not obvious that in an open divertor geometry there will be enough effective momentum removing collisions before neutrals are elastically scattered into ionising regions of the plasma. Only a two-dimensional code can answer this question.

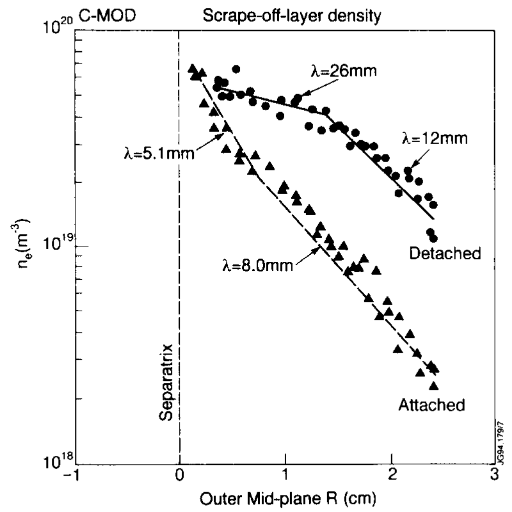


Fig. 6. Density profiles recorded in C-MOD with the reciprocating probe for attached and detached plasma conditions [50]. Profiles are plotted as a function of equivalent distance from the separatrix at the outer mid-plane.

Borass has looked at the problem of the gas-target divertor from the perspective of how it modifies the SOL parameters [25]. The end of his system is the entrance to the elastic collision zone or "cushion". At this point he derives a boundary condition for the power flow which looks like the normal sheath power transmission factor (≈ 8) but much smaller (0.5–1.5). As in Stangeby's model there is a very low Mach number at this point since the flow velocity is being dragged down by friction with neutrals in the elastic collision zone. This common idea might lead one to expect that the ions become bottled up in the SOL due to friction with the neutrals thus leading to an increase in the particle confinement time for the detached state and therefore a rise in the upstream SOL density. In practice it requires care to test the predictions of the Borass model because attached and detached states involve simultaneous changes in a number of key parameters. However, it still interesting to ask what happens to the SOL plasma profiles during detachment. Fig. 6 shows reciprocating probe data from C-MOD which shows no increase in mid-plane separatrix density on detachment. However, there is a substantial broadening of the profile which means that the density averaged across the profile does indeed rise. This result is not however confirmed by the results from the DIII-D Thomson scattering system which show no significant change in the edge profiles between the attached and detached cases [26]. JET has published data on this point [25] but the spatial resolution of the LIDAR diagnostic used for this measurement must be regarded as very marginal for the task.

3.3 Power balance

From the practical point of view the most important aspect of detached plasmas is that the target power loading is drastically reduced. A good example of this is the JET pulse with 22 MW of additional heating which is illustrated in Fig. 8a [18]. Measurements of the surface temperature of the beryllium tiles indicated that the power loading had dropped to less than 10% of the input power. One can see from the ion-saturation current traces from the outer and inner target Langmuir probes that both strike zones become detached early on in the pulse. Similar high power gas-target experiments have been carried out on DIII-D using deuterium and neon injection. These both show large reductions in peak power loading (~ 10) and total power loading although the detachment at the outer strike zone is not total. Far from the separatrix the power profile broadens and the power flux density does not decrease. Fig. 8b shows the configuration of the JET pulse and the approximate distribution of the radiation. However, it is worth noting that the bolometry is not consistent with the low (< 3 MW) power conducted to the target. This may be due to the shielding of the bolometer system from the charge exchange losses.

Although one might imagine that the problems of pressure balance and power balance are decoupled McCracken and Pedgeley [27], have shown that this is not the case. Taking the conventional picture that the plasma pressure in the divertor is a half of the upstream value, simple two-point analytical models show that as more power is radiated the divertor temperature falls and the ion flux Γ_i to the target increases. The usual equation used for the power flow to the target surface is $P_t = \gamma \Gamma e T_e$ where the sheath power transmission factor $\gamma \approx 8$. This allows the temperature to fall to an arbitrarily low level with a corresponding rise in ion flux thus allowing any fraction of the input power to be radiated. However, when T_e becomes sufficiently small the recombination energy for hydrogen ($E_H = 13.6$ eV) cannot be ignored. Hence the power flow to the surface becomes $P_t = \gamma \Gamma_i e(E_H + T_e)$. Since Γ_i rises as T_e falls there is a minimum in the target power load corresponding to a fractional radiated power $\ll 100\%$ [27]. This type of behavior may have been observed in JT60-U whose radiative divertor experiments are limited to fractional radiated powers of around 60% whilst no decrease in the ion-saturation current seen by the divertor target probes is observed [28].

Borass and Janeschitz [29] have shown that if parallel momentum can be removed from the SOL via ion–neutral interactions then Γ_i need not rise as T_e falls and so the radiated fraction can reach a high level. This connection between fractional radiated powers of

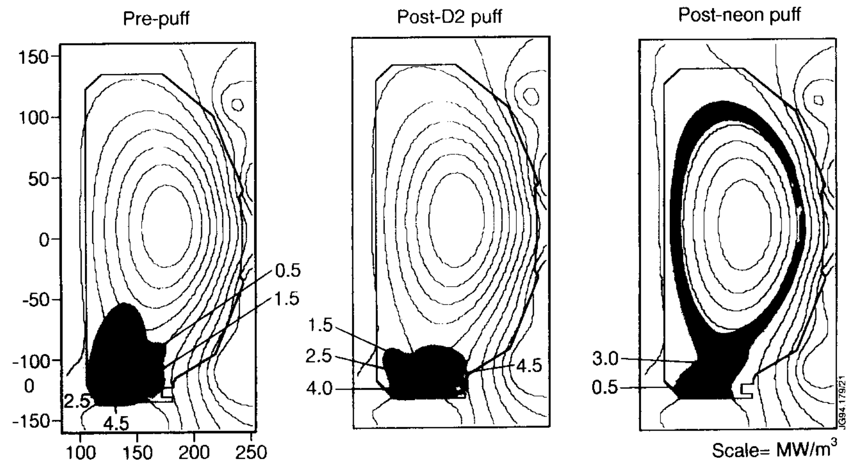
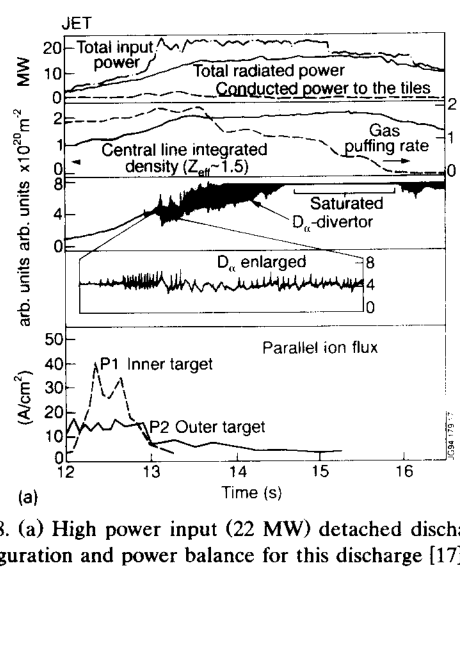


Fig. 7. Tomographically inverted bolometer data from DIII-D [21]: (a) normal attached case showing radiation near strike points, (b) detached phase with radiation near X-point and (c) radiating boundary produced by neon injection.

80–90% and large drops in parallel plasma pressure has been demonstrated in JET [18], DIII-D [16] and C-MOD [22].

Tomographic reconstruction using multi-chord bolometer data is now being used to unfold the distribution of the radiation [30,22,21]. Fig. 7 shows the results of such an analysis applied to DIII-D [21]. Fig. 7a is before gas-injection, Fig. 7b shows the distribution of radiation near the X-point in a detached plasma with deuterium injection and Fig. 7c shows the more uniform distribution of radiation associated with neon injection. The injection of impurities to produce attached radiating boundary plasmas which has been pioneered on TEXTOR seems a viable scheme for reducing heat load in limiter and divertor machines [31] but is beyond the scope of the current paper.

In the simplest models of detachment [4,32] the majority of the power is lost by charge exchange and hydrogenic radiation. On JET diagnostic simulations of bolometric data have been carried out for detached discharges with the DIVIMP (for beryllium impurities) and NIMBUS (hydrogen neutral) Monte Carlo codes [33]. These discharges were run on the beryllium divertor target but the simulations indicate that neither the



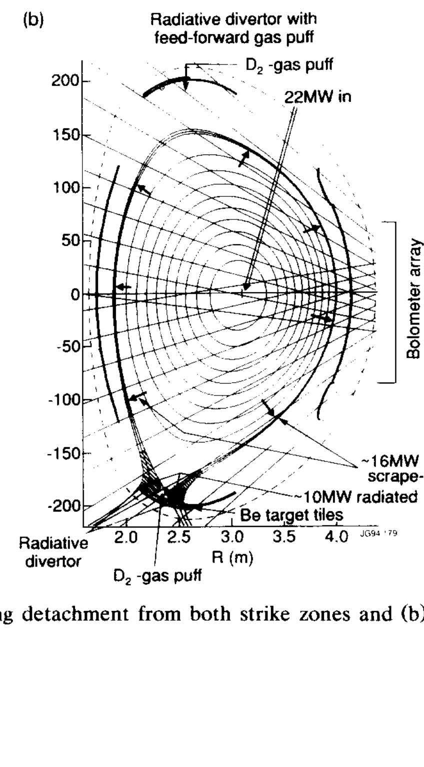


Fig. 8. (a) High power input (22 MW) detached discharge in JET showing detachment from both strike zones and (b) magnetic configuration and power balance for this discharge [17].

hydrogenic processes nor the beryllium impurity radiation are sufficient to account for the power loss. The current conclusion is that carbon impurities, which were not well diagnosed, are responsible for the deficit. JT60-U has the most complete array of spectroscopic divertor diagnostics to date and a preliminary analysis of their radiative divertor data shows that when the radiating region reaches the X-point the radiation is carbon dominated. This is in contrast to the normal case where the radiation is near the target where up to 40% of the power comes from the deuterium [34].

3.4. Location and stability of the radiating zone

In the original ITER concept, most of the power is exhausted in the divertor channel due to charge exchange at a relatively high temperature [4]. This idea has evolved to encompass low temperature gas-target divertors and the need for radiation to cool the electrons. However, it is still intended that the radiating zone be located in the divertor channel with a fairly uniform distribution between the target and the divertor entrance [35]. Results from C-MOD [22], ASDEX-U [17,30], and DIII-D [21] indicate that the stable location for the radiating region is near the X-point. The results from JET [18] are ambiguous in this respect because the X-point was quite close to the target and the bolometer system had insufficient spatial resolution to precisely locate the source of the radiation as can be seen from Fig. 8b. Results from JT60-U show that a radiating region can be stably maintained between the X-point and the target for several seconds [34] but these discharges do not show the drop in ion-saturation current which signifies detachment [28].

Ghendrih has produced a theory of detachment which has similarities to Stangeby's but solves for the length of the detached region assuming that the neutrals enter uniformly from the private region along the separatrix [32]. He obtains a bifurcated solution consisting of attached and detached states where the detached solution has the ionisation zone up near the X-point. To prove experimentally that there is a bifurcated solution is extremely difficult since you need to prove that either state can exist for a given set of control parameters. However, formal proof of a bifurcation is rather academic since what we really would like to know is whether intermediate stable states exist. The evidence for this is rather mixed. JET data seems to show that detachment can be a gradual process compared to any plasma time scale occurring over many hundreds of milliseconds as can be seen in the inner divertor ion-saturation current trace of Fig. 8a. On ASDEX-U the jump of the radiating region to the X-point appears to be quite fast [30]. On C-MOD the plasma pressure near the separatrix decreases gradually but there comes a point in the process where there is a sudden jump of the radiation to the X-point over a period of a few milliseconds which can be seen in Fig. 2. This data suggest that detachment is complex and not universally consistent with a bifurcation or bistable state.

Hutchinson [36] has recently produced a theory which addresses the whole issue of stability in both detached divertor plasmas and MARFEs. This assumes that momentum conservation is satisfied and that heat flow is via electron heat conduction, and uses a simplified radiation function for the power loss. He then analyses the stability of a thermal front. The thermal

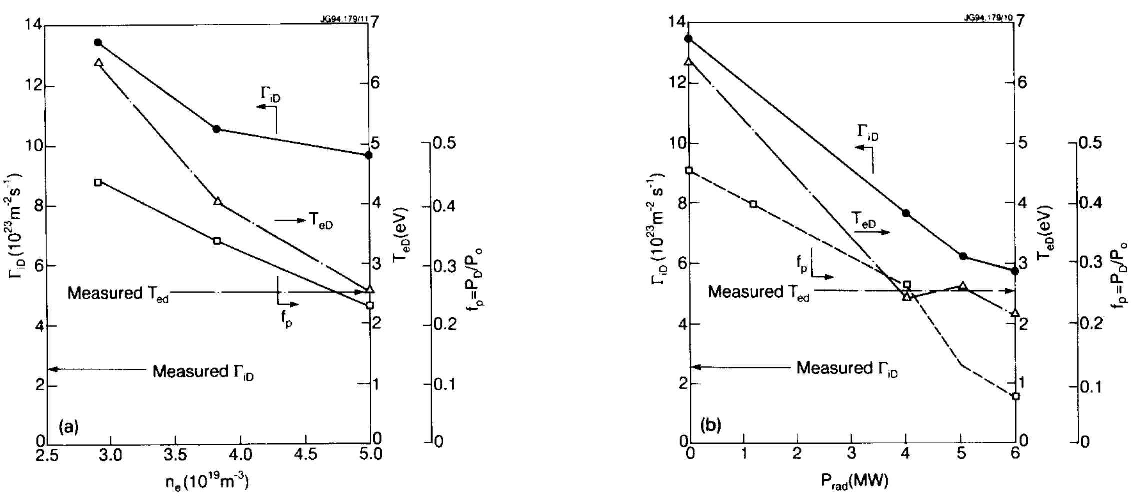


Fig. 9. Simulation of a real 10 MW detached JET discharge with EDGE2D [38]: (a) pressure drop along the separatrix, f_p, electron temperature, T_e, and target ion flux, Γ_{iD}, versus mid-plane separatrix density and (b) the same parameters plotted as a function of radiated power for the lowest density case in (a).

front is a region of the parallel temperature profile which is dominated by radiation. Hutchinson's conclusions are that in the detached state the thermal front is stabilised near the X-point due to the cross-field heat transport experienced above the X-point, and that the thermal front is probably only stable at positions intermediate between the target and X-point for a narrow range of upstream densities.

3.5. Code simulations of detached divertor plasmas

Much work has been done on predictive simulations of gas-target divertors for ITER but this is beyond the scope of the current review. I therefore concentrate on fluid code simulations of real plasma pulses in realistic geometries. The realistic geometry is important because we would like to know if the codes can simulate the detachment which has been observed in very open divertor geometries (see Section 3.2). Simulations of detached plasmas in ohmic ASDEX-U discharges have been carried using the Braams B2 code [37]. At JET the EDGE2D code has been used to simulate a pulse with 10 MW of additional heating [38], which is rather similar to that shown in Fig. 8b.

In both cases the neutrals were modelled with a full Monte Carlo model and impurities treated using a full multi-fluid calculation or with a single species and a simple radiation formula. There are two common conclusions arising from the B2 and EDGE2D work which are important:

- Large pressure drops can be achieved even in open geometries.
- In order to reproduce the experimental data a substantial wall source of carbon is required. The yield required is in the 1–4% range which is consistent with chemical sputtering of graphite.

Fig. 9 shows the results of a series of EDGE2D simulations for the 10MW detached discharge [38]. Fig. 9a shows how the simulated pressure drop and ion flux density near the separatrix scale with mid-plane separatrix density in a purely hydrogenic plasma. The density range was chosen to be consistent with experimental uncertainties. Although the pressure does start to fall at the highest density the ion flux is still far higher than the experimental value. Fig. 9b shows what happens in the lowest density case when the radiated power is artificially raised by the introduction of a carbon impurity. Larger pressure drops can then be achieved and the ion flux falls to approximately the level seen in the experiment. The electron temperature is also in the correct range.

The B2 simulations of ASDEX-U also show that the radiating region (MARFE) is not stable in-between the X-point and divertor. Its preferred location is in the SOL near or just above the X-point as seen in experiments.

3.6. The high pressure divertor solution

The basic principle that the power exhaust and particle flux from a diverted tokamak reactor could be substantially dissipated if not extinguished in a neutral gas appears to have been demonstrated on a modest scale in tokamaks and linear simulators. Current tokamak experiments generally appear to operate in a regime of scale lengths where neutrals enter and leave the plasma in relatively few steps. The high pressure solution where the plasma actually recombines before reaching the walls, which formed part of Tenney and Lewin's original concept [3], has not yet been demonstrated in any fusion relevant devices. This is also a regime where neutral–neutral collisions, radiation transport and multiple elastic collisions must be considered [39]. Simulations have shown that the high pressure regime may be relevant to ITER [40] but many simplifications were made in achieving the result. The fact that high pressure solutions are achievable at power levels more than adequate for ITER can be routinely observed when around 1 TW of power is diverted from a magnetically confined fusion powered plasma into a high density neutral gas. These spectacular pulses lasting up to 3 h are the *aurora borealis* [41]. However, in the case of the *aurora borealis*, the large neutral pressure ratio between the magnetosphere (SOL) and the earth's atmosphere (gas-target) is achieved by gravity rather than geometry.

4. Detachment from limiters

Detachment was first used to describe results from current ramp down experiments in TFTR [42]. Radiative condensations known as MARFEs had been observed in many machines and have been reviewed by Lipshultz [43]. MARFEs are usually observed when operating close to the density limit, appearing as an axisymmetric strongly radiating belt of short poloidal extent on the high field side of the tokamak. The interesting thing about the TFTR data was that a transition occurred from the MARFE to a state where the radiation was poloidally symmetric with the radiation in a ring extending 20 cm from the limiter where it essentially dropped to zero. In this ring the temperature and density also dropped bellow the detection threshold for the Thomson scattering system.

At about the same time similar observations were made in DITE [44]. Current ramp down was again used to achieve the detached state in ohmic discharges but in this case there was a gradual transition from the attached to detached states without the formation of a MARFE. Most persuasive in the decision to use the term *detached plasma* for the DITE discharges were the high speed cine pictures [45]. In the the normal *attached* state a thin reddish ring shows the ionisation of the recycling hydrogen immediately in front of the poloidal limiter. Few neutrals reach the core and so this region appears darker. Detachment occurs when the ring of H_α light has moved inwards leaving little evidence for ionisation near the limiter. Extensive studies of MARFE formation and detachment have been carried out in the TEXTOR tokamak [46]. Two discharges, one with high and the other low input power but similar fractional radiated powers, γ, always behave differently, as shown in the TEXTOR data of Fig. 10. The low input power discharge will detach but the one with high input power remains attached and, when γ is high enough, forms a MARFE. Samm speculates that the Shafranov shift associated with the high power cases creates a poloidal power asymmetry which precipitates the MARFE [31].

In TFTR it is reported that detachment can be obtained with a neutral beam heating power $P_b \leq 2$ MW using current ramp down in the ohmic phase to initiate the detachment [47]. With heating in the range 2 MW $\leq P_b \leq 3.5$ MW additional deuterium gas puffing is required to sustain the detachment. At $P_b \geq 3.5$ MW neon puffing was required to sustain the detached state. Unlike the TEXTOR results this data seems to show that detachment can be achieved at high powers. However, the data does not show that both the ionisation front and the radiating region are detached from the limiter. It is possible therefore that this discrepancy is merely dependent on whether one makes the distinction between a detached plasma and a radiating plasma boundary with the radiation peaking away from the limiter.

The fast reciprocating probe system on DITE allowed measurements to be made before and after the detachment in the very edge of the plasma. These results are shown in Fig. 11. Interestingly, the density

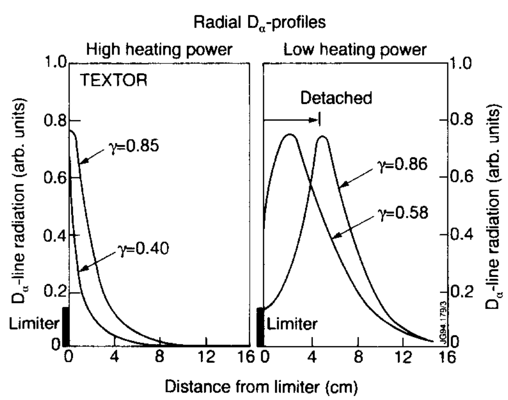


Fig. 10. Radial profiles of D_α from TEXTOR showing high and low power cases. Despite similar radiative fractions, γ, only the low power case detaches.

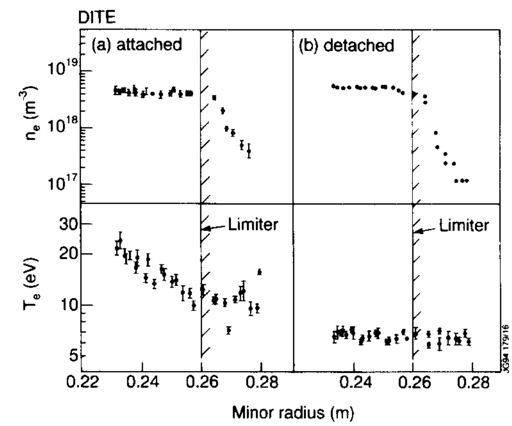


Fig. 11. Reciprocating probe profiles of density and temperature from DITE [44] showing a reduction in edge temperature and a flattening of the profile in the detached state.

profile hardly changes at all whilst the temperature falls to ~6 eV and the profile becomes very flat. The ion flux and plasma pressure at the limiter radius are not substantially reduced and so the term "detached plasma" really means something rather different than in the divertor case. Detachment in a limiter discharge refers to the fact that a poloidally symmetric ionisation front moves away from the limiter surface. This only appears to occur in low power discharges.

The most complete model for detachment from limiters has recently been described by Tokar [48] and this paper includes an extensive discussion of previous work. Tokar is the first to tackle the problem of numerically coupling together the transport of energy with that of plasma and impurity particle transport. This approach successfully reproduces the radiation level as a function of plasma current and density. It predicts similar changes in SOL parameters to those of Fig. 11. The model also explains how in ohmic discharges the thermal collapse induced by an advancing ring of impurity radiation is halted by the contraction of the current channel which in turn raises the ohmic power input thus balancing the radiation.

5. Discussion

Detached limiter plasmas show no evidence for significant changes in parallel pressure balance or ion flux and so are, at least by my definition, incorrectly classified as *detached*. They represent a very interesting phenomenon which appears to be fairly well understood but, owing to the low powers at which it is observed, seems to have little relevance for fusion reactors. This type of limiter discharge must be distinguished from the attached radiating boundary layer which has been extensively studied in TEXTOR [31] with injected impurities and is likely to prove important for both limiter and divertor tokamaks. Similar results have been reported from TFTR at high power with neon injection but here the discharges were classified as detached [47].

Detached divertor plasmas appear very complex in their behaviour and we are only just beginning to obtain a crude understanding of the physics involved. The level of interest is however intense as detached plasmas appear to offer a solution to the very tough problem of designing a divertor capable of handling the power and particle exhaust in ITER. Here are just a few of the questions that await experimental verification:

- Both JET [17] and DIII-D [16] have studied detached H-mode plasmas and find that the confinement is degraded to between 0.8 and 0.5 of the normal H-mode value, depending on the degree of detachment. It is important to know what causes this and whether it would still be observed in a more closed divertor geometry.
- Impurity radiation seems to be required for gas-target operation. This can only be controlled if injected impurities are used. Results from DIII-D [16] and JET [17] indicate that injected neon is poorly retained by the divertor. Further experiments are required to seek a regime which overcomes this problem.
- Theory indicates that divertor geometry affects detachment and so experiments are required to show how open divertors compare with slots and gas-boxes.
- We need to see whether the enhanced cross-field diffusion seen in linear simulators (Section 2) plays a role in tokamak divertors.
- Gas-target burn through by ELMs may be a problem when scaled to an ITER and so needs further study.

There is however still plenty to be learned about detached divertor plasmas from existing experimental results. Particularly challenging to our ideas are the exceptions which should not be ignored. For example, JT60-U has performed a more thorough scan of parameter space with a more complete array of boundary diagnostics than almost any other machine and yet do not appear to see detachment, as defined here, from the divertor targets with the $B \times \nabla B$ drift towards or away from the target [28]. Even the machines which do see clear evidence for detachment report significant differences which must be understood. For example, the high performance gas-target discharges in JET seemed to require the $B \times \nabla B$ drift away from the target [49] whereas with the $B \times \nabla B$ drift towards the target, detachment occurred only on the inner divertor leg and before any detachment of the outer leg was observed a MARFE was ejected from the divertor into the inner SOL. It was argued that this was caused by greater in/out divertor asymmetries which were observed when the $B \times \nabla B$ drift was towards the target. However, C-MOD [14] and DIII-D [16] produce good detached plasmas when the $B \times \nabla B$ drift is towards the target. JT60-U [28] and ASDEX-U [17] find that the MARFE has a tendency to move to the top of the machine when the $B \times \nabla B$ drift is away from the target. Further work is clearly required to clarify this issue.

Little has been said about materials and erosion in gas-target divertors because little or no experimental or theoretical work has been done in this area for detached plasmas. In a conventional divertor one is almost totally reliant on extremely efficient local redeposition to reduce the net erosion rates by factors of 10^2 to 10^3 or on the use of high Z materials. With a detached divertor plasma local redeposition can effectively be ignored. On the plus side the ion flux has been reduced but it has been replaced by a larger flux of somewhat less energetic neutrals. The energy spectrum of these neutrals and the sputtering threshold of the divertor materials are critical determining the erosion rate. In current machines erosion is so small it is hard to study but in ITER by virtue of integrated pulse duration alone it will be $\sim 10^4$ times larger – sufficient to transform microns into centimetres. This should, I believe, be regarding as one of the most critical outstanding issues by both ITER and the plasma–surface interactions community.

6. Conclusions

Although the concept of the detached divertor plasma was thought of and demonstrated in principle over a decade ago in a linear divertor simulator, it generated little interest until the start of the ITER EDA. Now there is an explosion in theoretical, computational and experimental work in the area which may render this review obsolete before it comes out in print.

The use of the term *detachment* in the context of limiters is mainly the result of a visual impression rather than physical definition of what happens. A *detached* limiter plasma usually describes one in which the ionisation front moves inboard of the limiter. The ion flux and plasma pressure at the limiter radius are however little altered. Detachment from limiters still remains the minority interest it always was since there is no experimental evidence that this detached state can exist in anything other than low power discharges. The related use of controlled impurity injection to create radiating boundary layers [31,47] whose peak emissivity is inside the limiter radius seems much more relevant to fusion reactors with limiters or divertors. However, the more detailed studies carried out on

TEXTOR suggest that these should be classified as *attached* in the context of the above definition.

Detachment from divertors seems to be a very complicated phenomenon involving large gradients in plasma pressure parallel to the magnetic field. Many inconsistencies or at least differences between observations in what is reported from different machines. Geometry appears to play an important role in detachment but the gas-box or slot type divertors proposed for ITER [35] have so far only been adequately tested in small linear simulators. Current experiments all show that in detached discharges the radiating region is located near the X-point and it remains to be seen whether changes in geometry will bring about the uniform distribution of radiation envisaged for the ITER divertor channels. Experiment and theory now show that impurities seem to be required to make detached divertor plasmas work – not just charge exchange as in the original ITER divertorconcept. Experiments have begun in the seeding of detached plasmas with recycling impurity gases but our current understanding of impurity transport in these complicated conditions must be regarded as inadequate. There is now a real for new tokamak experiments with a range of closed divertor geometries, as planned by JET and DIII-D, combined with better diagnosis of the detached divertor state.

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