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A STUDY OF DETACHED PLASMAS IN THE DITE TOKAMAK

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Detached discharges are described in which the radiated power loss is from within a maximum radius up to 50 mm less than the limiter radius. Outside this radiating zone the plasma density and temperature profiles are flat with values of approximately 5×10^{18} m^{-3} and 7 eV respectively. Typical conditions for detached discharges in DITE are a plasma current of 100 kA ,a safety factor of ≈ 7 (toroidal field 2.5 T), and a line average density of 3×10^{19} m^{-3} in deuterium. Detachment can also be observed in similar discharges in helium at a density of 6×10^{19} m^{-3}. These values are 70–100% of the critical density for disruption.

1. Introduction

In some circumstances the cool boundary of a tokamak discharge, where most of the low Z impurity radiation occurs, moves inwards from the limiter position. This can lead to a disruption of the plasma current [1,2], but can also occur more slowly at the end of a discharge as the plasma current (and hence the power input) is gradually reduced. The effect is readily observed with a TV camera or with a bolometer array. More recently it has been observed that the radiating ring can be thermally stable at a radius significantly less than the limiter radius. This state has been called a "detached" discharge [3,4]. It remains stable for more than 10 times the energy confinement time. In DITE [3] the plasma temperature between the radiating ring and the limiter dropped to less than 10 eV while the density remained at typically 5×10^{18} m^{-3}.

The existence of a radiating layer inside the limiter has been predicted by 1-D transport models [5]. Such a condition was termed a "cold plasma mantle". The thermal stability of such a layer is difficult to assess because it is not clear how the density profile varies as the temperature profile contracts [6]. It is of interest that thermal stability is observed in a tokamak as small as DITE ($R = 1.17$ m, $a = 0.26$ m).

In the present paper we describe the conditions under which detached discharges occur and present detailed measurements of plasma parameters during these discharges.

2. Diagnostics

The inward radial movement of the visible radiating layer has been routinely observed using a TV camera looking into the torus through a tangential port. More quantitative measurements have been obtained with a bolometer array looking vertically from the top. With this array both the radial and temporal dependence of the total radiation can be followed. A typical 3-D plot showing a shrinking of the profile is shown in fig. 1. The edge of the total radiation profile detaches between 150 and 250 ms, then it stabilizes and remains constant for the rest of the discharge. Line radiation in the wavelength range 200–700 nm has been investigated using a spatially scanning Monospec spectrometer. A mirror scanning at 120 Hz allows the radial distribution of any specific line to be followed as a function of time throughout the discharge. An X-ray diode array, a normal incidence vacuum ultra violet spectrometer [7] and a Bragg rotor spectrometer [8] have also been used to diagnose the behaviour of impurities in the centre of detached plasmas.

The edge plasma has been investigated using two arrays of double Langmuir probes, one inserted from the top of the torus with three pairs of double probes [9] and another inserted horizontally with probes at three different poloidal positions. These arrays are moved

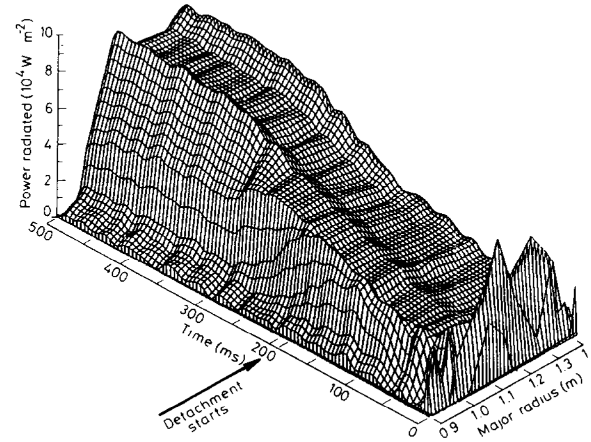

Fig. 1. Chord integrated total radiation intensity for a detached discharge with $I_p = 100$ kA and $\bar{n}_e = 3 \times 10^{19}$ m^{-3}.

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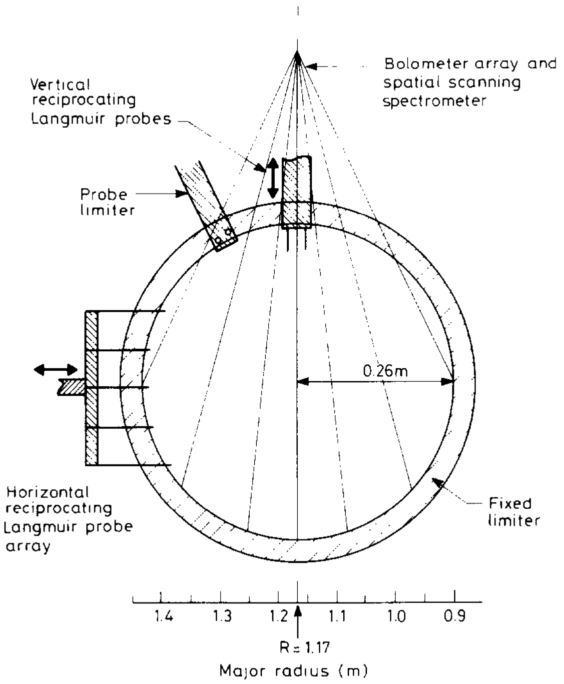

Fig. 2. Cross section through the DITE torus showing schematically the poloidal position of the main diagnostics.

pneumatically 30 mm in and out in a time of 200 ms so that a radial profile can be measured in a single discharge. In addition two fixed single Langmuir probes allow the time dependence of the density and temperature to be measured close to the limiter radius. The poloidal positions of these probes are shown in fig. 2. A 2 mm μ-wave interferometer is used to obtain the line average density and a single-point Thomson scattering system is used to determine electron density and temperature profiles in a series of discharges.

3. Conditions for obtaining detached discharges

In general, detached discharges occur at $q \gtrsim 5.5$ when the density is between 70–100% of the limit set by disruption. It can occur spontaneously, particularly at the beginning and end of the discharge when the plasma current is low.

For the purpose of studying the detached state, we use either the procedure described by Strachan [2], of lowering the plasma current while maintaining the density, or simply raising the density at constant current. At $B_T = 2.5$ T, detached discharges are readily obtained at currents from 100–130 kA ($q \sim 7$ to 5.5). In deuterium detachment occurs for $\bar{n}_e > 2.5 \times 10^{19}$ and in helium for $\bar{n}_e > 6 \times 10^{19}$, both values being within 30% of the corresponding density limit.

4. Characterization of a high q detached discharge

We describe a discharge in deuterium with the general characteristics listed in table 1. The current rises to a maximum of 105 kA at 150 ms and stays roughly constant until 500 ms, fig. 3. The density rises approximately linearly to a value of 3.0×10^{19} m^{-3} at 340 ms and stays constant until 500 ms. The plasma detaches between 150 and 250 ms as observed by the bolometer array, fig. 1. The main plasma parameters are shown in fig. 3. Before detachment the uninverted radiation profile is relatively flat with a slight peak on the inside edge. On detachment the radiation profile shrinks and moves in radially approximately 50 mm. As the plasma detaches the plasma β_p remains constant at 0.4 while the plasma inductance increases from 2 to 2.4. This increase of the plasma inductance implies that the current channel is shrinking. Direct evidence that $q = 1$ at the centre is obtained from the X-ray diode array. The sawtooth inversion radius increases from < 23 mm

Table 1
Conditions for detached discharges

Shot no.	(a) 29483 Detached	(b) 29493 Normal	(c) 29477 Normal	(d) 27341 Detached
Gas	D_2	D_2	D_2	helium
Plasma current (kA)	102	130	102	100
Toroidal field (T)	2.5	2.5	2.5	2.53
Safety factor q at limiter	7.0	5.6	7.0	7.2
T_e (0) (eV)	800 ± 100	800 ± 100	800 ± 10	700 ± 100
Density $\bar{n}_e$ (10^{19} m^{-3})	2.8	2.6	2.2	6.0
Ohmic power at 400 ms (kW)	305 ± 10	300 ± 10	230 ± 10	250
Radiated power at 400 ms (kW)	210 ± 10	190 ± 10	145 ± 10	140
Power conducted to limiter (kW)	55			
Inductance	2.4 ± 0.2	2.05	2.25	
Λ_c	0.55	0.25	0.4	0.9
β_p	0.35 ± 0.1	0.27	0.24	

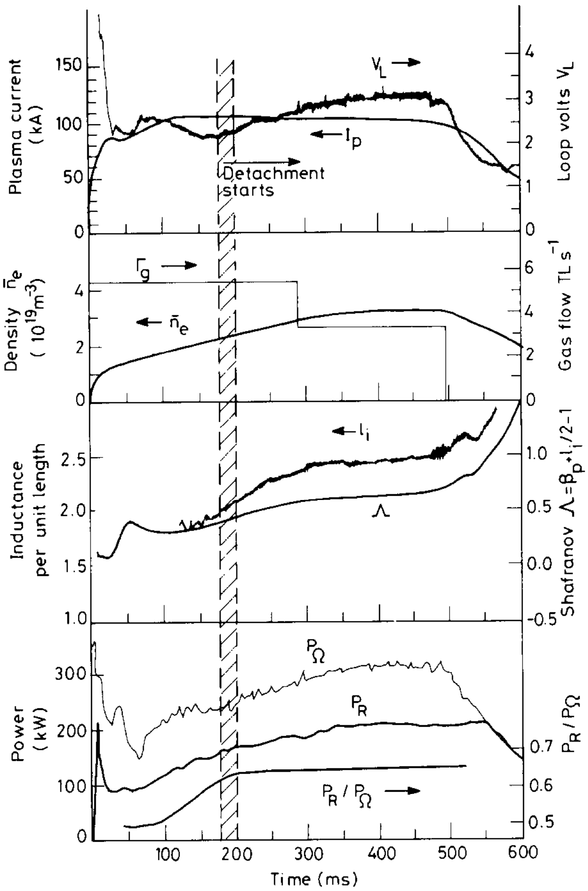

Fig. 3. Plasma parameters for a typical detached discharge in deuterium.

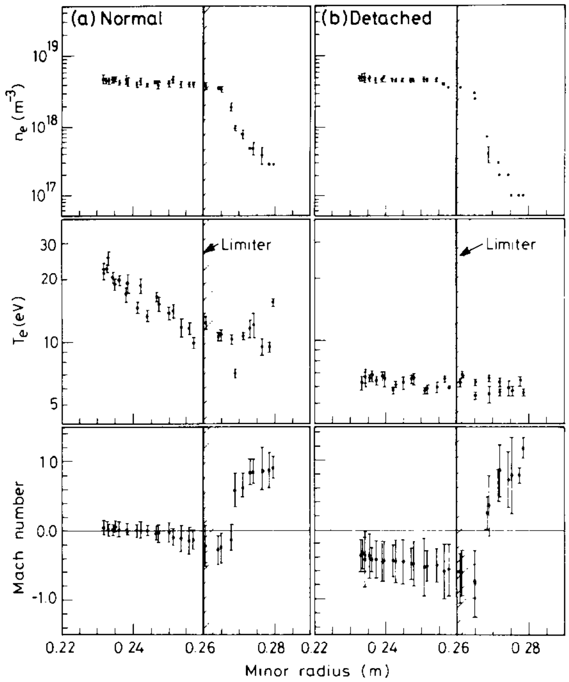

Fig. 4. Plasma edge profiles for detached and normal discharges (discharge A, 100 kA and discharge B, 130 kA as in table 1). Measurements made at 450 ms at the top of the torus.

at 115 ms to 47 mm at 400 ms. The loop volts increase from 2.2 to 2.8 V and the ohmic power increases by a similar factor. The fact that β_p stays constant while the ohmic power increases indicates that the energy confinement time is falling – typically from 11 ms to 8 ms.

The gas puff programme is shown in fig. 3. After a prefill of 0.22 mbar l a constant gas feed of 1.7 mbar l s^{-1} is supplied from 0 to 290 ms and this is then reduced to 0.75 mbar l s^{-1} from 290 to 500 ms. The latter value is sufficient to maintain the density constant over this period.

The edge plasma parameters are shown in fig. 4. Both the density and the temperature profiles are flat from 0.23 m to 0.26 m. The density is typically 6×10^{18} m^{-3} and the temperature 6 to 7 eV. The electron temperature at the limiter radius is ~ 10 eV at the start of the discharge but falls to ~ 6 to 7 eV between 200 and 300 ms as detachment takes place. The density at the limiter reaches a maximum of 4×10^{18} m^{-3}. These density and temperature profiles are surprisingly flat and are difficult to reconcile with the observed particle flux to the limiter.

The radial profiles measured with probes on the top, 30° above the midplane, at the midplane and 15° below the midplane are almost identical both in temperature and density. Moreover the CCD camera shows there to be relatively little radiation up to 50 mm inside the limiter at the small major radius side indicating a low electron temperature here also. Thus we have good evidence of poloidal symmetry in these discharges.

The probes also measure the Mach number inside the limiter radius. During the detached plasmas the magnitude and direction of flow varies from M ~ 0.4, anticlockwise (away from the nearest limiter) at the top, to M ~ 0.2, clockwise below the median plane. These results reveal the presence of strong, large-scale convection in the boundary region between the edge of the detached plasma (inferred by the radiation edge) and the limiter radius. However, we have insufficient data to determine the complete flow pattern.

We have compared the probe profiles in detached discharges with two types of normal discharge. One is obtained simply by using lower density at constant current. The edge temperature rises slightly to ~ 10 eV and the edge density stays constant. The second is at similar density but at higher plasma current of 130 kA. The edge temperature is significantly higher and has a larger gradient, fig. 4. It should be noted that the ohmic heating in the 130 kA discharge is very similar to that of the detached discharge due to the lower loop volts (table 1).

As the discharge is detaching from the limiter the ohmic power increases slowly, but the total radiation increases as a fraction of the ohmic power from typi-

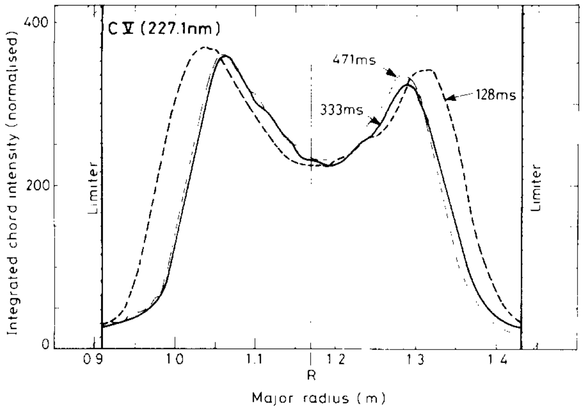

Fig. 5. Radial profile of CV measured in a detached discharge at different times.

cally 50% to 70%. Complete radial profiles of a number of spectral lines of partially ionized, low-Z impurities have been obtained with the spatially scanning monospec. The data are chord integrals and results are shown in fig. 5 for CV at different times. Abel inversion of such data shows that the peak in the uninverted profile is a good measure of the position of the radiating shell, and so the uninverted peak positions are used in the analysis. The variation of the position of the peak radiation with time is shown in fig. 6 for C III, C V, O II, O III, O IV and O V. It can be seen that each of the lines moves radially inwards. The lower ionization states O II and O III move about 40 mm while the C V moves in about 20 mm. Data for O VIII obtained using the Bragg rotor spectrometer has also been obtained.

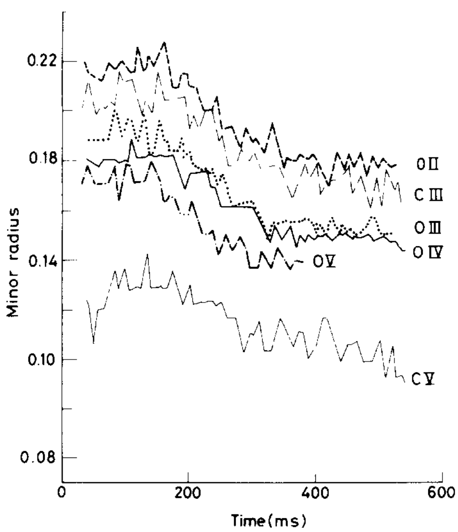

Fig. 6. Position of the peaks in the radiating bands of different charge states as the discharge detaches from 150 to 300 ms. (Discharge A, table 1.)

The Abel inverted data show that the position of the peak does not move within experimental error, but the width of the radiating band narrows considerably.

The inward movement of the low-Z impurity radiation peaks together with the expansion of the sawtooth inversion radius and increase of inductance noted above, all point to a contraction of the current channel at constant total current. A simple model for the current channel, in the form of a gaussian, truncated at $q = 1$, is in reasonable agreement with the experimental data. It indicates that the fraction of current flowing inside the sawtooth reconnnection radius increases from ~ 0.1 before detachment to ~ 0.45 in the detached phase.

The variation of impurity content with density has been monitored by measuring the central, horizontal chord intensity of lines of C III (97.7 nm) and Fe XV (28.41 nm). Increasing the density in successive discharges until detachment occurs shows that detachment produces no abrupt change in the general trend of impurity behaviour. Measurements of impurity confinement time, using Al injected by laser ablation, show that this is not affected by detachment. These data together with the measured total radiated power shows that the carbon density remains approximately constant as the plasma density increases, while the iron density decreases rapidly.

4. Discussion

One of the possible advantages in detached plasmas, sought for in the modelling of cold plasma mantles, is a regime where most of the power is radiated, resulting in a low temperature edge plasma and hence a low impurity production rate. It appears that in the present discharges, although the edge temperature falls, there is only about a 30% reduction in the power transported to the limiter as deduced from the flux and temperature measurements from the probes. By subtracting the ohmic power and the radiated power the change appears to be less than 30%. However this is the difference between two large numbers each with substantial errors and it is common not to be able to obtain a satisfactory power balance in tokamaks. Because of the slow change of carbon sputtering yield with deuteron ion energy in this energy range [10], the change is carbon impurity production rate is small. A much greater reduction might be expected for a metal limiter where the ion energy would be close to the sputtering threshold and a large reduction in yield would be expected for a comparable reduction in electron temperature.

At higher plasma currents with increased ohmic heating it might be expected that detachment is more difficult. However as stated earlier detachment can be observed at least up to 130 kA at slightly higher line average densities. Preliminary experiments with neon injection indicate that detachment can be obtained at slightly lower densities than without neon.

5. Conclusions

Clear evidence has been presented for the existence of stable "detached" plasmas in the DITE tokamak. The conditions required for their occurrence are high density and high safety factor q. Most of the radiated power occurs within a radius ~ 50 mm less than the limiter radius. Outside this radius the plasma density and temperature are approximately constant at values typically 5×10^{18} m^{-3} and 7 eV. When detachment occurs the loop volts and plasma inductance rise but the β remains constant indicating about a 30% reduction in τ_E. The current channel is significantly compressed. A slight increase in density causes disruption.

During and after detachment the light impurity concentration remains approximately constant despite an observed decrease in edge temperature. The metallic impurity concentration decreases significantly but this occurs normally as the density rises whether the discharge is detached or not.

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