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Preprint

DITE TOKAMAK PRESENTATIONS EIGHTH CONFERENCE ON CONTROLLED FUSION AND PLASMA PHYSICS PRAGUE SEPTEMBER 1977

DITE TOKAMAK GROUP

CULHAM LABORATORY
Abingdon Oxfordshire

1977

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EIGHTH CONFERENCE ON CONTROLLED FUSION AND PLASMA PHYSICS

PRAGUE September 1977

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Papers submitted to the Eighth Conference on Controlled Fusion and Plasma Physics

Prague September 1977

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Culham Laboratory

June 1977

ORIGIN AND CONTROL OF HOLLOW TEMPERATURE PROFILES IN DITE

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Abstract: Hollow temperature profiles associated with centrally peaked total radiation profiles and metallic impurities have been observed recently in DITE. These can be avoided by cooling the periphery of the discharge by various means, by neutral injection heating or by using the DITE divertor.

During the first 10 months of operation of the DITE tokamak the peak electron temperature, T_{eo} in a typical discharge with $I_p \sim 200$ kA, $B_T \sim 2.7$ T fell from ~ 1100 eV to 800 eV. Machine parameters and initial results are given in reference [1]. A few hundred discharges in hydrogen with $I_p \sim 20$ kA, $B_T \sim 0.15$ T were used to condition the vacuum walls each day, and it was thought that their condition had stabilized.

A total radiation thermopile measuring the fraction of ohmic power lost by radiation and charge-exchange gave an almost constant value between 0.5 and 1.0, the uncertainty being due to the thermopile calibration factor. Photospectrographic measurements of radiation between 10 Å and 300 Å showed the principal impurities to be Fe (~ 0.004 n_e), Cr (~ 0.002 n_e), Mo(~ 0.002 n_e) and O (~ 0.01 n_e); similar in composition to the metal-dominated discharges in ST-tokamak [5]. The metals account for ~ 97% of the radiated power and ~ 76% of the mean ion charge excess, $Z_{eff} - 1$.

More recently persistent hollow temperature profiles with $T_{eo} \sim 200$ eV have been observed, occasionally at first, then regularly and reproducibly as shown in Fig. 1. Similar profiles have been observed in Ormak [3].

The radiated power is measured with a thermopile mounted behind a collimator with a spatial resolution of 25 mm which can be scanned across the discharge diameter. It shows a large central peak and little indication of the peripheral radiating layer typical of oxygen dominated discharges in TFR [2]. Indeed, in the centre of the discharge, the radiated power exceeds the ohmic input, calculated from the temperature profiles assuming $j \sim T_e^{\frac{3}{2}}$, by 70%, although the thermopile calibration allows an uncertainty of - 20% + 60% in the values of radiated power given in the figures. This excess of radiated power, mainly line radiation from highly ionized metallic impurities, explains why these hollow profiles persist, inserting a probe 'limiter' into the discharge periphery [1]. It is uncertain whether this acts by reducing metallic impurities, by simply cooling the periphery by conduction, or both.

All the methods of avoiding hollow profiles described above tend to produce disruption by cooling the edge of the discharge, and result in high $Z_{eff} \sim 6$. More satisfactory, and equally successful, is to compensate the power imbalance at the centre by additional neutral beam heating [8] or to use the DITE divertor to screen out metallic impurities [9].

Acknowledgements We are indebted to the DITE operating and engineering teams for reliable operation of the machine and to our colleagues in the physics team for stimulating discussions.

Table 1

	1 (hollow profile)	2 (air contaminated)	3 (2% Neon)
I_p (kA)	176	199	120
V (V)	4.7	3.3	3.3
B_T (T)	2.7	2.7	2.0
$\bar{n}_e$ (10^{19} m^{-3})	1.7	2.1	1.6
Z_{eff}	6.3	6.6	6.3
T_{eo} (eV)	205	1100	940
β_{pe}	0.09	0.14	0.20

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ELECTRON AND ION HEATING BY NEUTRAL INJECTION IN DITE TOKAMAK

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Abstract: Neutral injection heating experiments are reported in which we have observed ion temperature rises of 52% and central electron temperature rises of 75%.

The DITE tokamak (R = 117 cm, a = 27 cm, B_φ = 9 - 27 kG and I_G = 50 - 200 kA) has been used to study the heating effects of neutral injection on both the electrons and ions. The two neutral beam sources deliver a combined power of 200 kW in the direction of the plasma current and along a line tangent to a major radius R = 105 cm. The ion sources produce roughly equal fluxes of H neutrals with energies E_o, $E_o/2$ and $E_o/3$ where $E_o \leq 30$ keV.

This injection system has been previously [1] used to study the ion heating at I_G = 150 kA and it was found that the ion temperature, T_i, measured by charge-exchange, approximately doubled. A detailed analysis of these results has subsequently been carried out. Deposition and Fokker-Planck computer programs have been used to describe the transfer of power from the neutral beams to the plasma ions and an ion energy balance program [2] was used to determine the radial power transfer. The effects of electron-ion heating, charge-exchange, particle diffusion and neo-classical thermal conduction were considered and good agreement has been attained between experiment and theory. A typical analysis is shown in Fig. 1, where the radial power balance is plotted as a function of the minor radius. The dominant heat loss in the plasma centre is due to thermal conduction, but as $T_i > T_e$ collisional transfer to the electrons is also significant.

We have now carried out a further series of experiments to investigate the degree of ion heating under a number of different conditions. In injection experiments designed to study ion heating it is desirable to inject into a plasma with a high electron temperature and this was achieved in DITE by the addition of 2% of Neon to the discharge [3], producing the plasma conditions listed in the table. At I_G = 150 kA, the time variation of T_i was measured for co-directional injection with

$\Delta T_i/T_i = 52\%$.

One of the main difficulties in the interpretation of this experiment is the fear that the injection process may change the energy balance in the plasma by the introduction of impurities and thus increase the electron temperature [3]. The measured loop volts and ohmic power input are observed to decrease slightly during injection and this would argue against increased impurity levels. Stronger evidence was obtained from measurements of the soft X-ray emission from the plasma.

Without injection, the X-ray spectra, from an Si(Li) detector, showed that the X-ray anomaly factor was about unity, as expected for a plasma with $Z_{eff} \approx 1$. This anomaly factor is very sensitive to changes in the impurity level and can easily change by orders of magnitude on the introduction of small amounts of impurity. We observed the time dependence of the intensity of X-rays with $E_x > 700$ eV and found that it rose by a factor of 3 during injection, returning to its previous level after injection. The expected rise in this intensity deduced from the laser measurements of $T_e(r)$ was a factor of 2.7. This is consistent with an unchanged anomaly factor during injection and provides strong evidence that impurities are not being introduced by the injection.

Calculation of the expected rise in T_e requires a thorough evaluation of the different processes contributing to the energy balance in both hollow and non-hollow discharges. The calculation of the ion temperature increase requires a detailed treatment of the electron-ion heating and this is also in progress. However, rough estimates show that 72 kW of the injected power should go to the electrons and heat them by 24% if the energy containment time is unchanged.

It is a pleasure to acknowledge the assistance given by the DITE engineering and operating teams and the Neutral Injection Group.

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ON THE ORIGIN OF METAL IMPURITIES IN THE DITE TOKAMAK

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ABSTRACT: The metal flux into the plasma has been measured using a time resolved surface technique and optical spectroscopy. On the basis or our results we propose that arcing is the principal mechanism for metal impurity production.

The process whereby metal impurities enter tokamak discharges is not well understood. Possible mechanisms are sputtering, evaporation and arcing. However, two general arguments seem to rule out sputtering. One is the appearance of metals very early in the discharge ($\sim$ 5 ms) when the ion temperature is low. The second is that the metal impurity concentration is very similar in hydrogen and helium discharges(1) when the sputtering coefficients of the two species are about an order of magnitude different. Evaporation due to thermal conduction from the plasma appears very unlikely as a mechanism in normal (undisruptive) discharges on the basis of measurements of the surface temperature of the limiter.(2) In order to investigate the possible processes involved we have made measurements of the flux of metals into and out of the DITE tokamak. In addition we have inserted polished molybdenum specimens into the discharge and obtained direct evidence of arcing.

It is clear from an examination of the optical windows on the torus that metal is removed from the wall and then redeposited in a thin layer over the whole torus wall. The thickness of the deposit varies by only a factor of 2 to 3 along the length of 0.45 m windows, and windows in different azimuthal positions and over different periods of operation of the tokamak have given results which are consistent. The typical composition of these films is Fe 1.8×10^{17}, Ni 2.9×10^{16}, Cr 1.8×10^{16}, Mo 2.0×10^{16} atoms m^{-2} discharge^{-1}. Thus the total amount of metal removed from the wall each discharge is $\sim 3 \times 10^{18}$ atoms. On the basis of the average density and confinement time the effective removal rate per incident plasma ion is 0.04 atoms/ion compared with the estimated sputtering coefficient for 200 eV H^+ ions on stainless steel $\sim 10^{-4}$ atoms/ion. The composition of the film is mainly stainless steel (from the walls) with about 10% from the molybdenum limiter. The composition of the stainless steel is different from the bulk material and from that of evaporated stainless steel.

The introduction of hydrogen, via a fast gas valve during a discharge results in an immediate reduction in the flux of iron. Similar effects have been observed with hydrogen in PULSATOR[5] and with oxygen in ST[6] and TFR.[7] Although we have not yet made any direct experimental measurements it is suggested that the introduction of cold gas at the edge of the discharge lowers the electron temperature and hence reduces arcing. The fact that the metal flux is reduced by introducing oxygen makes it improbable that light impurity sputtering is responsible for heavy impurities.

The direct observation of arcs on the torus wall has proved difficult because the arcs tracks are small and only readily observed on carefully polished surfaces. Arcs have been directly observed, however, on polished molybdenum probes which have been placed at radii from 0.27 to 0.18 m and subsequently examined in the optical microscope and the scanning electron microscope. Similar arcs have also been observed at the divertor target plate in DITE. They are of two principal types but both tracks run predominantly at right-angles to the B_ϕ field lines. One is fern like, similar in structure to those seen in Zeta,[4] with a total length up to 10 mm. The other consists of tracks typically 20 μm wide and ∿ 10 mm long. The tracks consist of a series of melted blobs ∿ 10 μm diameter.

It is commonly argued that arcing cannot occur in tokamaks because the cross field diffusion leads to the plasma potential being negative with respect to the wall. However, such a condition does not obtain in the region in the shadow of the limiter or at divertor targets. The direct observation of such arcs and the other evidence put forward indicate that arcing must be considered as a potentially serious form of wall erosion both in contemporary tokamaks and in reactors.

ACKNOWLEDGEMENT: We are indebted to the DITE operating and engineering teams for the operation of the machine, in particular to G W Reid and B C Sanders.

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CONTROL OF IMPURITIES BY THE DITE BUNDLE DIVERTOR

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Abstract: The divertor is shown to reduce both the low and high Z impurity content of the plasma. However when extra gas is fed in to maintain the same density during diversion, there is an increased desorption of oxygen and no change in Z_{eff}.

The bundle divertor improves the purity of a tokamak discharge, firstly by reducing the flux of plasma particles bombarding the limiter and torus wall and thereby reducing the release of impurities, and secondly by attenuating their influx into the centre of the discharge. The magnetic configuration is complex and is discussed in detail elsewhere [1]. It can be described approximately by saying that there is a central core of undiverted plasma which is surrounded by an annular layer between the separatrix radius $a_s = 0.19$ m and the torus wall $a = 0.27$ m, which is connected to the divertor target and will be referred to as the scrape-off layer.

The successful operation of the DITE bundle divertor at a toroidal field $B_T = 1.0$ T with discharge currents $I \simeq 50$ kA has been reported previously [2,3]. The present paper extends the earlier results, and discusses their interpretation in terms of three specific divertor effects which contribute to the overall improvement in plasma purity.

(1) The magnetic limiter effect of the bundle divertor transfers the 'plasma-limiter' interaction out of the torus and onto the divertor target. This is demonstrated directly by photographic observation of the diverted plasma striking the target, by measuring the reduced temperature rise of the limiter and the large temperature rise of the target when the divertor is operated. The reduced interaction of the plasma with the molybdenum limiter and stainless-steel torus wall is shown by a reduced influx of heavy metal impurities at the plasma edge. A carbon probe positioned close to the torus wall is exposed to the plasma and later analysed using Rutherford backscattering [4]. When results from diverted discharges are compared with undiverted ones, the combined influx of Fe, Cr, and Ni falls by a factor 4 and the Mo flux by a factor 6. Spectroscopic measurements in the V.U.V., described later, show that the divertor reduces the

different chords of the minor cross-section, and the results when Abel-inverted give radial density profiles of the various impurity ions. The analysis of these data is at present incomplete, but the large changes in typical line intensities for Mo and Fe has been quoted earlier. There is little change in the intensity of the oxygen lines (eg O VIII 18.97 Å) when the plasma density is maintained constant during diversion.

In order to maintain the diverted discharges at the same density as the undiverted ones, the hydrogen gas feed must be increased. Unfortunately this increases the plasma recycling and there is a consequent increase in the influx of oxygen desorbed from the wall. This additional influx is sufficient to offset the 50% screening effect, with the result that there is no net reduction in the oxygen level recorded by the V.U.V. spectrometer. The increased oxygen influx also means that there is little change in the value of Z_{eff} calculated from the plasma resistivity and the measured electron temperature profile. The 50 kA undiverted discharge already has a low value of $Z_{eff} \simeq 2$ produced mainly by oxygen, and this does not change significantly when the divertor is operated. However if additional oxygen gas is added to the discharge, without the divertor, Z_{eff} rises to 3 but remains close to 2 with the divertor. The desorption of oxygen, resulting from the gas feed, explains the anomaly, reported earlier [2], that Z_{eff} remains constant although the divertor screens out both low and high Z impurities.

The reduced concentration of heavy metals in the diverted discharge causes the total radiated power loss to fall to ≈ 25% (Fig. 2). The radiation power profile for an undiverted discharge (Fig. 3) is strongly peaked on axis and represents 50 - 100% of the ohmic power input. This substantial radiation loss due to heavy metal, is sharply reduced by the divertor, and there is a major change in the power balance with radiation losses accounting for only 20 - 30% of the ohmic power input, and more than 60% being transferred to the divertor target.

We wish to acknowledge the assistance of the DITE operating and engineering teams.

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RECYCLING IN DITE TOKAMAK

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Abstract: Recycling has been studied in DITE tokamak by changing the working gas from hydrogen to deuterium. The results show that the recycling gas is composed of approximately equal fluxes of plasma reflected from the wall and gas released from the wall.

The present experiments have been carried out at plasma currents of 50 kA and 100 kA without the divertor or neutral injection. The H/D recycling has been investigated with a scanning Fabry-Perot interferometer to monitor the H_α and D_α lines [1], a mass spectrometer to measure neutral gas concentration and a carbon desorption probe [2] to measure the flux of particles arriving at the torus wall.

Figure 1 shows the behaviour of hydrogen and deuterium as observed by the Fabry-Perot, for the first two discharges in deuterium following many in hydrogen. Also shown are the current, electron density and the deuterium flux ratio $D_\alpha/(H_\alpha + D_\alpha)$. Near the end of the discharge $D_\alpha/(H_\alpha + D_\alpha)$ reaches an equilibrium value and at these times the fluxes of hydrogen and deuterium represent the relative gas concentrations on both the wall and in the plasma. Figure 2 shows that in successive discharges the equilibrium proportion of deuterium slowly rises and approaches asymptotically a value of ~ 0.65. Similar results are obtained from the carbon probe.

After each discharge the hydrogen and deuterium pressures initially rise and then decrease slowly with time, indicating gas being released from the walls.

The results of the Fabry-Perot shows that deuterium, which is ionised at the start of the discharge, is rapidly lost and replaced by hydrogen, indicating that wall recycling is playing a major role during the discharge. We would expect two principal processes to occur (1) reflection of a proportion of the incident particles with an energy dependent reflection coefficient β, (2) release of previously trapped atoms with a probability which depends on an energy dependent cross-section σ and the concentration of atoms in the solid.

Equation (1) describes the change in wall composition on the basis of these two processes.

gas to another, eg hydrogen to deuterium. We assume that a fixed quantity of deuterium is pulsed into the torus at the start of each discharge, equal to a fraction f of the total quantity of gas in the system. At the end of a discharge all the gas in the system goes to the wall and during the time before the next discharge some of this is desorbed and pumped away, and a fraction $(1 - g_n)$ of the surface layer is replaced by hydrogen diffusing from the bulk, where g_n is a function of shot number n. We then expect that after n discharges, the equilibrium ratio $T_n = D_\alpha/(H_\alpha + D_\alpha)$ is given by $T_n = (1 - f)\, g_{n-1}\, T_{n-1} + f$. From experimental values of T_n we derive that $g_n = 0.73\,[1 - 0.8 \exp(-0.28\, n)]$ giving the fit to the experimental data shown in Fig. 2. The model predicts that after a series of discharges in deuterium T_n will rise asymptotically to the value 0.66, and that doubling the filling pressure leads to an asymptotic T_n of 0.8. Further if we increase the time between shots we would expect more hydrogen to diffuse from the bulk and replace deuterium on the surface. This all agrees very well with the experimental data.

Finally we note that the two recycling processes reflection and particle induced desorption will give rise to fluxes with different energy distributions. At incident energies less than 1 keV the reflected particles will have energies close to their incident values and will have a high probability of penetrating into the centre of the plasma, whereas the particles released from the wall would be expected to have energies less than 10 eV and will undergo charge exchange or ionisation in the outer regions of the plasma. These results confirm the earlier [2] interpretation of the radial profile of the H_α emission as resulting from approximately equal influxes of low and high energy neutral atoms.

We gratefully acknowledge helpful discussions with Drs J. Hugill and J.W.M. Paul and assistance from the DITE operating team.

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HIGH DENSITY DISCHARGES WITH GETTERED TORUS WALLS IN DITE

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Abstract: The limiting density and energy containment time in DITE are improved by a factor > 2 by gettering the torus wall with titanium. This is explained by a reduced influx of low-Z impurities which normally cause contraction of the current channel by cooling the plasma edge.

Electron densities exceeding 10^{20} m^{-3} have been reached in several tokamaks, notably Alcator [1] and Pulsator [7], by feeding hydrogen gas into the discharge. This leads to a decrease of Z_{eff} and an increase of the energy containment time τ_E. In similar experiments in DITE the maximum mean electron density which we had obtained was $\bar{n}_e = 2.3 \times 10^{19}$ in a discharge with $I = 180$ kA, $B_T = 2.7$ T and $q_a = 4.6$ at the limiter radius, $a = 0.27$ m. The best value for $\tau_E = 7.8$ ms was obtained at $I = 67$ kA, $B_T = 2$ T, $\bar{n}_e = 1.7 \times 10^{19}$ m^{-3} and $q_a = 9.3$. We were prevented from reaching higher densities by disruptive instabilities. We believe that these disruptions are caused by contraction of the current channel when the plasma edge is cooled by an influx of light impurities, chiefly oxygen, desorbed from the torus wall by the recycling plasma. A similar influx of oxygen was observed on Pulsator [7].

To test this hypothesis that the density is limited by the influx of light impurity we have evaporated titanium onto the torus wall. Gettering has previously been shown to reduce both the recycling and the oxygen concentration [3]. In DITE we use a single Varian Ti-ball source which getters some 30 - 40% of the torus wall. The source is evaporated continuously between discharges (for 10 - 20 minutes) and withdrawn from the torus ~ 30 s before a discharge. The evaporation rate of 2×10^{-2} g/discharge is sufficient to pump a quantity of gas several times larger than that introduced.

With the torus wall gettered and an increased feed of hydrogen gas, we have extended the density limit significantly and, for a discharge with $I = 150$ kA and $B_T = 2.7$ T, we have obtained a mean density $\bar{n}_e = 7 \times 10^{19}$ m^{-3}, central density $n_e(o) \approx 1.1 \times 10^{20}$ m^{-3}, $\beta_p \approx 0.6$ and $\tau_E \approx 25$ ms. Taking data from a good number of discharges at different currents, the extension of the stable operating region in a plot of I against $\bar{n}_e$ becomes apparent.

(200 kW), which changes the electron temperature profile [9], supresses the m.h.d. activity and allows the density to rise smoothly.

The gettering reduces but does not eliminate the oxygen influx which presumably comes from ungettered parts of the torus. During an early stage of the gettered discharge when the density is comparable to an ungettered discharge, the intensity of the O V line (2781 Å) is down by a factor ≃ 9. There are bursts of increased oxygen influx during the density pauses (Fig. 4) and we suppose that with ungettered torus walls these would be larger and would cause disruption at a lower density limit. Even in the gettered torus, the higher density limit is still set by disruption preceded by a sharp rise in oxygen flux. Were this eliminated by some means, there seems no reason why the density limit could not be improved further, at least until ionisation of hydrogen, hydrogenic bremsstrahlung, charge exchange and conduction to the limiter produced a cooling effect equivalent to the radiation by light impurities. However, preliminary results with two getter sources on opposite sides of the torus do not indicate a substantial improvement compared to the results obtained with a single getter.

In general our results are consistent with models of disruption in which ohmic heating is insufficient to prevent cooling of the plasma edge with consequent contraction of the current channel and m.h.d. instability [8].

Acknowledgements: We are indebted to the DITE operating and engineering teams for operation of the machine, and thank R.J. Bickerton and J.W.M. Paul for valuable discussions.

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