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ABSTRACT

The high density limit and the energy containment time in DITE are increased by more than a factor two by gettering the torus walls with titanium. This effect is attributed to the reduced influx of low-Z impurities when the density is increased with gettered walls. This influx would normally cool the outer regions of the plasma with consequent contraction of the current channel and disruptive instability at the density limit.

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We describe a new regime of operation of DITE tokamak [1] with higher electron densities $\bar{n}_e \approx 10^{20}\ m^{-3}$, longer energy containment times $\tau_E \sim 30$ ms and values of the effective ion charge Z_{eff} close to unity. This regime has become accessible by evaporating titanium onto the torus wall to act as a getter [2].

Prior to the titanium gettering, experiments in DITE tokamak with R = 1.17 m and a = 0.27 m gave a maximum mean density measured across a diameter, $\bar{n}_e = 3.8 \times 10^{19}\ m^{-3}$ for a discharge with $B_T = 2.7$ T, I = 150 kA and $q_a = 5.6$. The longest measured energy containment time was 8 ms for a discharge with higher $q_a \sim 9$, $\bar{n}_e = 1.7 \times 10^{19}\ m^{-3}$, $B_T = 2.0$ T and I = 67 kA. The regions of stable operation in $\bar{n}_e$ and I, described previously [1] for $B_T = 0.9$ and 2.0 T, have been extended to include $B_T = 2.7$ T. These regions for different B_T coincide when plotted in the normalized form 1/q ($\propto$ I) against $\bar{n}_e R/B_T$ as shown by region A in Fig. 1. The density normalization was suggested by the scaling of limiting density, $\bar{n}_e \propto B_T/R$, proposed by Murakami [3] and the limiting values for Ormak with and without gas feed are shown as M2 and M1 respectively in Fig. 1.

When the density is raised by feeding purified H_2 gas into the discharge, we observe an increase in the emission of O II and O V spectral lines which we interpret as evidence of an increased influx of oxygen, although there may be some contribution due to recombination as noted in Pulsator [4]. The source of the oxygen appears to be desorption from the torus wall by the increased recycling of hydrogen ions and neutrals which results from the gas feed [5]. Such an influx of oxygen will cool the outer regions of the plasma, as observed in many tokamaks when light impurities are fed into the discharge, and the consequent contraction of the current channel results in disruptive instability [6]. We believe this mechanism is responsible for the density limit for stable operation shown in Fig. 1.

To test this hypothesis, we have reduced the influx of oxygen by evaporating titanium onto the torus wall. Previous experiments on ATC [7] showed that this procedure reduces hydrogen recycling and the influx of oxygen and other impurities. In DITE we use a single Varian Ti-ball source to getter 30 to 40% of the torus wall. The source operates continuously for the 10 to 20 minutes between discharges and is withdrawn from the torus 30 s before a discharge. The evaporation of 2×10^{-2} g of titanium before each pulse is sufficient to pump several times the amount of gas introduced.

With the torus walls gettered the hydrogen gas feed can now be increased without a large influx of oxygen. The density can then be raised well beyond the previous limits as shown in Fig. 1 by region B, within which the highest density part has not yet been fully investigated. On the same figure we include the data from Alcator [8] and Pulsator [4] normalized in the same way. The points marked 'a' to 'd' in Fig. 1 refer to typical gettered discharges for which we have measured temperature and density profiles giving the parameters listed in table 1.

Table 1 - Parameters of Typical Gettered Discharges

Point on Figure 1	a	b	c	d
Discharge current (I) kA	100	140	160	230
Toroidal field (B_T) T	2.0	2.65	2.7	2.65
q at limiter	6.2	5.9	5.2	3.6
Mean electron density 10^{19} m^{-3}	3.6	4.4	4.3	4.2
Central electron density 10^{19} m^{-3}	5.3	7.0	6.2	6.3
Z_{eff}	1.6	1.4	1.2	1.2
β_{pe} (profiles)	0.28	0.26	0.17	0.12
β_p (diamagnetism)	0.5	0.5	0.4	0.35
Energy containment time (τ_E) ms	10	17	16	19

Oscillograms of the current, loop volts (which gettering reduces by a factor 2) and mean electron density are shown in Fig. 2 for the gettered discharge labelled 'b'. Also plotted are β_p and τ_E calculated from the change in diamagnetic flux and the measured current and loop volts. Radial profiles of electron temperature and density at t = 150 ms are shown in Fig. 3. Similar hollow profiles have been observed in discharges with high concentrations of metallic impurities where, at the discharge centre, the energy loss due to impurity radiation exceeds the power input due to ohmic heating [9]. However, the mechanism of electron cooling has not been elucidated in the present case and may be different. At high density a substantial fraction of the ohmic input can be transferred to the ions if their temperature lags the electron temperature appreciably. We calculate the values of Z_{eff} listed in Table 1, assuming it is uniform across the discharge. The values of β_p derived from diamagnetism are somewhat higher than from the measured profiles but are within experimental errors when a reasonable value for the ion energy content is assumed.

The maximum central density so far obtained in DITE, n_{eo} = 1.1×10^{20} m^{-3} with $\bar{n}_e = 7 \times 10^{19}$ m^{-3}, is in a hydrogen discharge with B_T = 2.7 T, I = 150 kA and q_a = 5.6. Diamagnetic loop measurements give $\beta_p = 0.6 \pm 0.1$ (estimated error) and $\tau_E = 25 \pm 5$ ms. The longest containment time in the current plateau phase of the discharge, $\tau_E \approx 30$ ms, with a corresponding β_p = 0.55, is obtained in a deuterium discharge with B_T = 2.7 T, I = 230 kA, q_a = 3.6 and $\bar{n}_e = 5.5 \times 10^{19}$ m^{-3}. Oscillograms of current and volts for this discharge are shown in Fig. 4 together with values of β_p and τ_E derived from I, V and the diamagnetic flux. During the current decay we are not certain that the inductance remains constant and the corresponding uncertainty in V, β_p and τ_E is indicated by dashed lines.

Although the hydrogen gas influx is constant, the density rise is often interrupted by one or more pauses lasting 10 - 30 ms during which there is increased MHD activity, loss of plasma and an increase in internal inductance. We interpret these effects as evidence of a major re-arrangement of the discharge. A uniform density rise can be maintained through these MHD periods by temporarily increasing the gas feed to compensate the losses but this does not prevent the MHD activity. We also observe that increased power input (200 kW) from neutral beam injection, changes the electron temperature profile [10] and suppresses the MHD activity allowing the density to rise smoothly and to a higher value.

The gettering reduces but does not eliminate the oxygen influx which may come from ungettered parts of the torus. During the early stages of a gettered discharge when the density is comparable to an ungettered discharge, the intensity of the O V line (2781 Å) is reduced to 12%. There are bursts of increased oxygen influx during the density pauses (Fig. 5) presumably resulting from the increased plasma loss. We suppose that with ungettered torus walls the oxygen influx 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. If this could be eliminated by some means, there seems no reason why the density limit could not be improved further, at least until other processes, such as ionization of hydrogen, charge-exchange or conduction to the limiter, produce 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.

Time-resolved measurements of the heavy metal influx at the discharge boundary [11] and spectroscopic data of highly ionized molybdenum and iron lines confirm the substantial improvement in the plasma purity.

In general our results are consistent with a model of the disruptive density limit in which ohmic heating is insufficient to prevent the edge of the plasma being cooled by an influx of light impurities, with consequent contraction of the current channel leading to MHD instability.

We wish to acknowledge discussions with many of our colleagues and in particular with R.J. Bickerton, and we are indebted to the DITE operating and engineering teams for reliable running of the machine.

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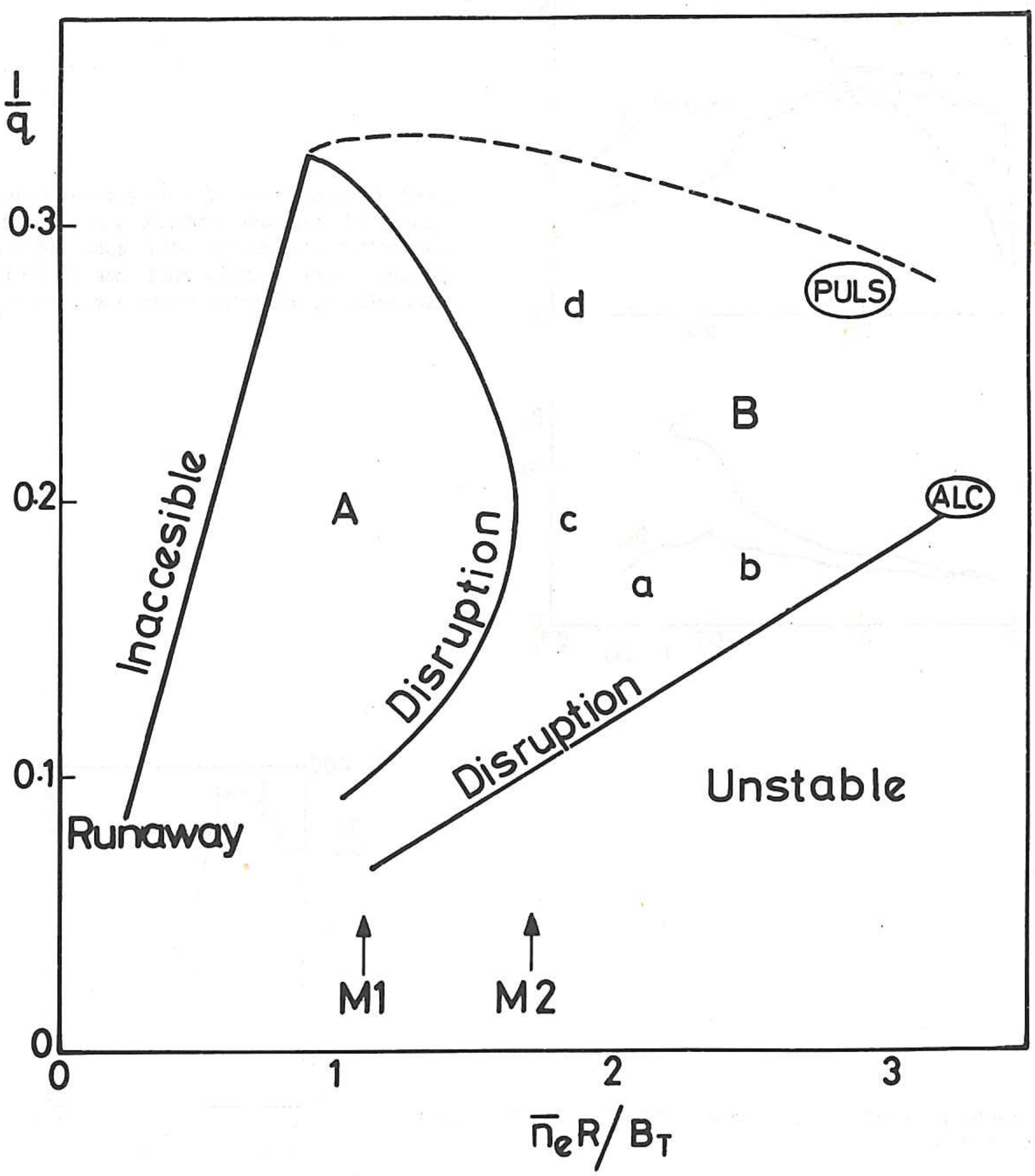

Fig.1 Stable operating region in (I, $\bar{n}_e$) space with normalized co-ordinates $1/q \propto I$ and $\bar{n}_e R/B_T$; region A without gettering and B with gettering. Density limits in ORMAK without and with gas feed marked M1 and M2. High density regimes in Alcator and Pulsator marked ALC and PULS.

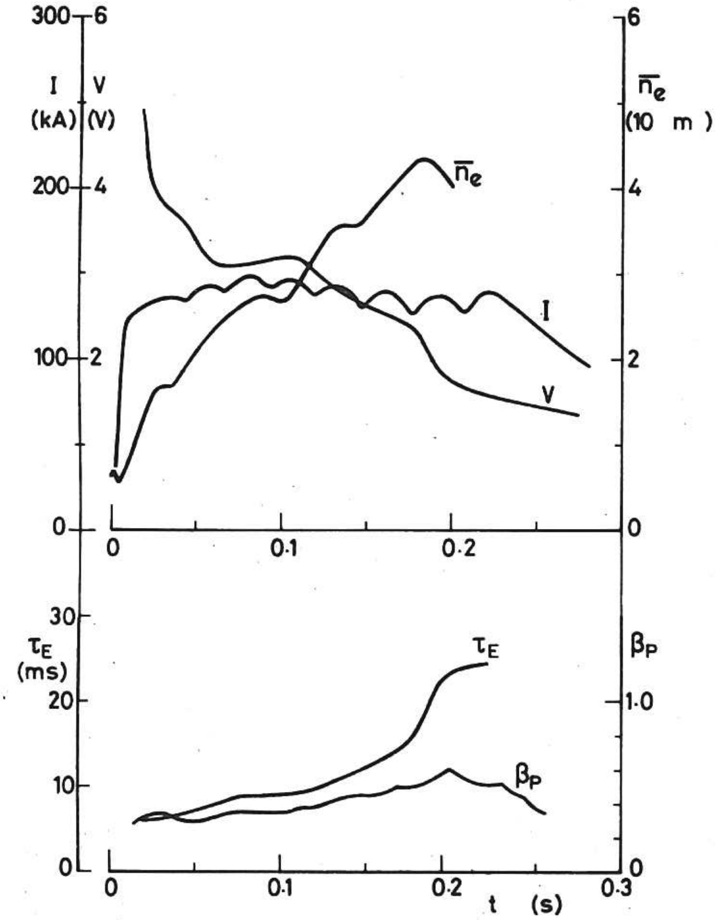

Fig.2 Time development of hydrogen discharge Table I (b). Measured parameters, plasma current I, loop volts V (corrected for dI/dt assuming constant plasma inductance) and mean density $\bar{n}$. Derived parameters β_p and energy containment time τ_E.

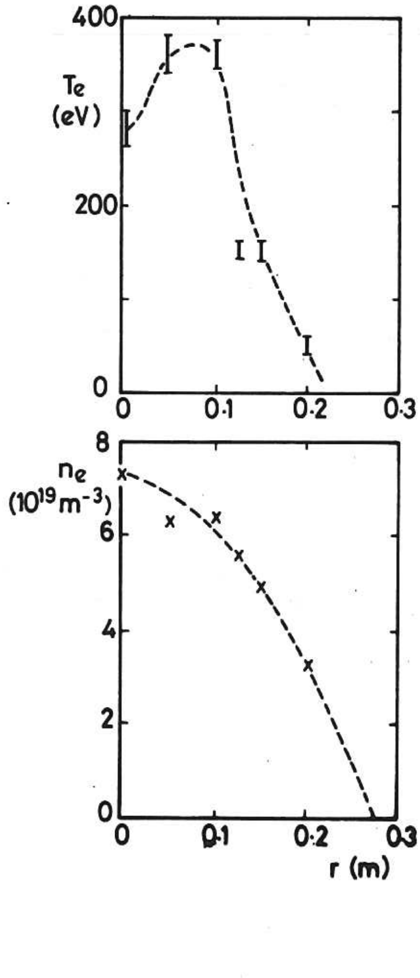

Fig.3 Profiles $T_e(r)$ and $n_e(r)$ for discharge Table I (b) at 150ms from photon scattering.

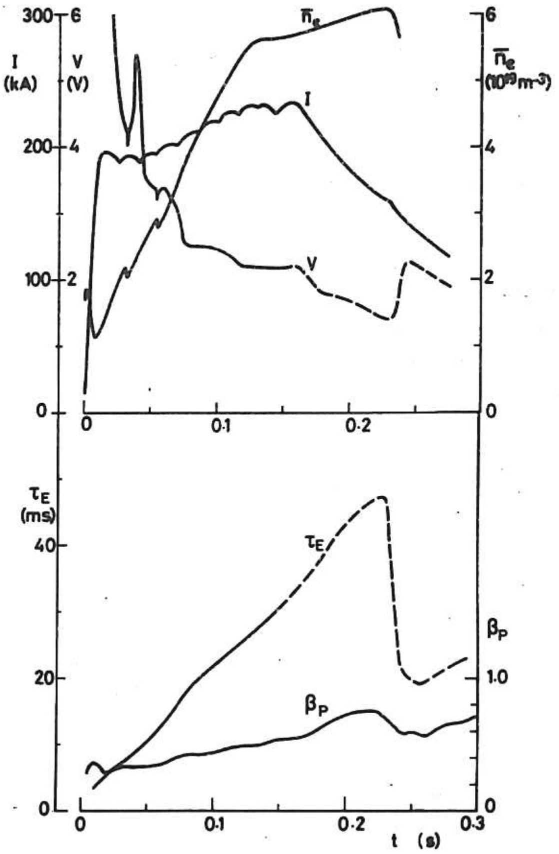

Fig.4 Time development of deuterium discharge with best containment. Measured parameters, plasma current I, corrected loop volts V and mean density $\bar{n}_e$. Derived parameters β_p and energy containment time τ_E.

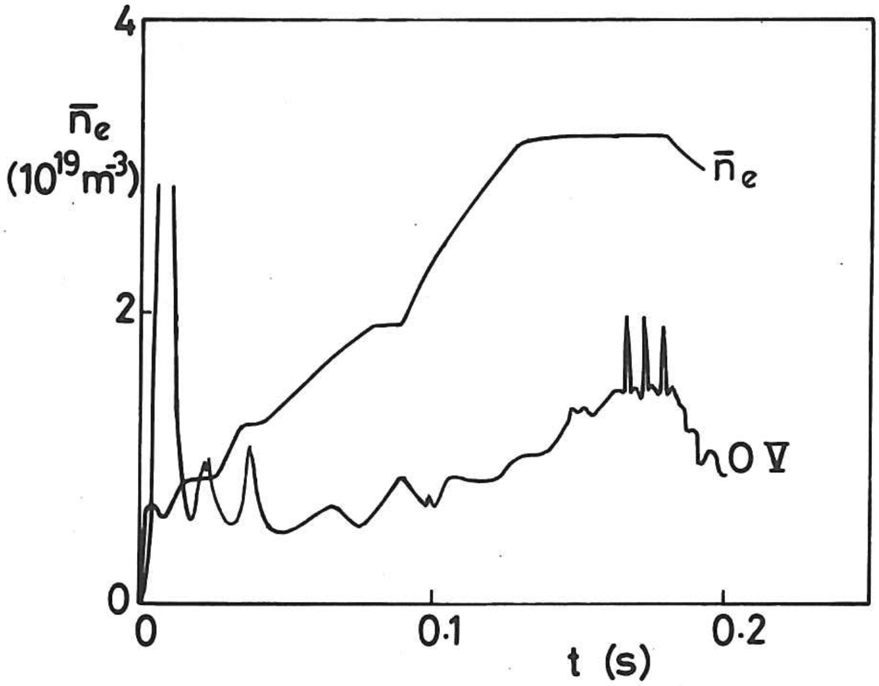

Fig.5 Time development of intensity of O V (2781 Å) emission showing increased influx during pauses in the rising mean density $\bar{n}_e$.