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PERFORMANCE OF CARBON TILES AND IN-SITU CARBON COATINGS IN JET AND TEXTOR

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SUMMARY

JET started initially with metallic walls (Nicrofer 7612LC) and four graphite limiters. Gradually more and more graphite protection has been added and it has now reached 50% wall coverage. The inboard wall was covered with graphite tiles early in JET's operation to protect the wall from damage and two toroidal belt limiters have been introduced to increase JET's power handling capacity. Carbonisation has been used as an additional tool to achieve certain benefits. Carbonisation has been developed at TEXTOR as a method to simulate for a short time an all carbon machine and as a means to control density and impurity production. This paper reviews the benefits of the extensive use of graphite for protection and limiters and of the deliberate application of thin carbon layers. Attention is given to the changes in the material under plasma exposure, and the damage due to the plasma contact and the machine operation under these conditions. The role of the parameters of the scrape-off layer in the explanation and prediction of the plasma wall interaction is emphasized.

INTRODUCTION

It was recognized early that the thermonuclear regime in tokamaks can only be reached when the impurity level expressed as Z_{eff} is sufficiently low i.e. $Z_{eff} \lesssim 2$. Z_{eff} is the effective charge: $Z_{eff} = \frac{\sum nZ^2}{\sum nZ}$ (over all species). High Z_{eff} leads to dilution of the fusion fuel mixture of D and T and to high radiation losses. Materials with a high Z tend to radiate from the hot core and low Z materials tend to radiate from outer layers. Therefore there is a general tendency to choose limiters and first wall material with a low Z so that radiation losses from the hot core plasma can be kept to a minimum and a reduction of edge temperatures is obtained by radiating power near the plasma boundary. Typical allowable concentrations are: O or C 10^{-2}; Fe or Ni 10^{-3}; and W 10^{-4}.

Although carbon in the form of high density, fine grain, high purity graphite has a low Z and good thermal shock resistance and allows a very high surface temperature, there were originally reservations about using it on a large scale because of problems foreseen with steady state cooling; gas desorption and the predicted high erosion due to chemical sputtering. These problems have proven to be a minor importance in a high current long pulse tokamak such as JET. Other examples of large tokamaks using graphite as limiter and first wall protection are DIII-D; TFTR; and recently JT-60.

The protection tiles and limiters in JET have been designed for a typical power load ≤ 5 MW m^{-2} over a period of 10 seconds. For example the two belt limiters with 10 m^2 effective area will take the anticipated full 40 MW during a 10 second JET discharge. In selected areas an occasional high power load of ≤ 20 MW m^{-2} for about 1 second can be tolerated.

The graphites chosen for application in JET are Le Carbon Lorraine 5890 PT (from the start) and Ringsdorff EK986 (also used from a later date). Detailed data on the physical, mechanical and thermal properties of these graphites are given in reference 1. For some applications where a very high power load might occur carbon fibre re-inforced material has been selected based on tests that have proven that the power handling capability is at least a factor of 3 higher. The carbon fibre re-inforced material is Dunlop DMS678 or Le Carbon Lorraine A05G. Technical details concerning the application of these graphites in JET are given by Dietz[2] and Pick[3].

Carbon coatings applied by running a RF assisted glow discharge in a mixture of hydrogen and methane at elevated wall temperatures have been used in JET and TEXTOR to simulate an all carbon-wall machine. As an additional benefit this type of discharge helps to remove O and Cl by the additional chemical processes leading to the formation of CO, CO_2, CCl_2 etc. The thin layer deposited in this way covers metallic deposits and small droplets resulting in a temporary reduction of these metals: the carbon film can be removed by a glow discharge in hydrogen or deuterium. Carbonisation has also been used to increase the limits of high power coupling to plasmas in TEXTOR but this effect although initially positive appears to be negligible in JET.

Carbonised layers are not only formed by deliberate actions but occur spontaneously in tokamaks where limiters and other protections are made of carbon: these layers seem to have the same structure as the carbonised films. The carbon films show the same sputtering properties as carbon irradiated by high hydrogen fluxes.

REASONS FOR THE USE OF INCREASED PROTECTION

The JET vacuum vessel originally had unprotected Nicrofer 7612LC walls of a complex structure and four graphite limiters of a mushroom shape[4]. Some components were designed to withstand high heat loads and serve as protection for bellows and vacuum walls. In this stage of the experiments the metal concentration in the discharge was quite high especially for low density discharges. Inspection of the vessel wall showed that there was extensive damage on the inboard wall (Fig 1) and that small splashes of inconel from these events could be found everywhere in the machine[5] and most importantly on the carbon limiters[6]. The analysis of the damage shows that most of it had been caused by very high energy run-away electrons such as will be generated in the aftermath of a disruption (photo neutron activation). Later a similar effect was observed when discharges were required with a large elongation: these discharges are intrinsically unstable and rely on an active feedback system. Disruptions occur in the vertical direction when the system exceeds its stability limits[7]. As counter measures first the inboard wall was covered by extensive graphite protection for ± 1.2 m from the midplane and later eight poloidal rings of graphite tiles were added on the octant joints to protect the upper/lower wall (Fig 2)[3]. At each opportunity limiters and other structures were extensively cleaned so that no small droplets were left.

Carbon fibre reinforced tiles have been fitted near the inner midplane where high localised heat loads were expected during disruptions and in areas where possible neutral beam shine through would strike the inner wall. None of these tiles have failed due to these operational scenarios, though some have been replaced as a result of normal erosion effects.

Carbon protection against events combining high heat loads and very localised deposition of beams of high energy runaway electrons is highly successful mainly because of the good thermal shock resistance and the fact that the mean free path for stopping high energy electrons (50 MeV) is very long (10-20 cm). It means also that thin protective carbon layers (in the direction of the beam) will not work and that metal structures under this protection would show very localised melting.

When an area of carbon protection is used as a limiter, as happens when the discharge is run at the inboard wall for some time, then it has become increasingly important to align the tiles to the best accuracy possible. Since the power scrape-off layer is in the order of 10 mm any object misaligned with respect to the magnetic field lines will receive a much higher heat load this anticipated. In JET the inner wall was initially misaligned in some areas[3]. Replacement in such areas by carbon fibre reinforced tiles has shown better performance under high heat load but the temperature can still be high enough for sublimation to occur.

The JET limiters were initially uncooled. At the end of 1986 after removal the post mortem analysis showed that the heat load occurring during that campaign had caused some surface cracking. Power levels achieved during that period were 10 MW NB and 7 MW RF for several seconds. The total wetted area of the 8 limiters was approximately 1.5 m^2 and this was slightly exceeded the anticipated limits of performance. In order to allow the full anticipated power load of 40 MW for 10 seconds the surface area had to be increased, therefore new belt limiters have been installed with a nominal surface area of 20 m^2 [9-10]. The excess heat is removed between pulses by radiation to a water cooled structure. Initial experience at a level of 20 MW for several seconds shows only mild heating and no detrimental effects.

THE USE OF CARBONISATION

The carbon layers deposited by means of the carbonisation process are in the form of hydrogenated films (a-C:H). The films are deposited by running an RF assisted glow discharge in a mixture of D_2 and up to 20% CD_4 (or in H_2/CH_4, depending on the film required). They are hard, homogenous and semi-transparent and have good adhesion properties provided the surface is cleaned by glow discharge cleaning (GDC). The mean layer thickness is predictable from the throughput of gases, the discharge current (1-10 μA/cm²) and the duration. The layer contains H or D to 40 at % depending on the gases used for deposition and on the wall temperature. Due to the complicated construction of the vessel wall strong non-uniformities may occur[11].

Carbonisation in JET is usually done in H_2 + 12% CH_4 for 6-48 hours at a current density of 2μA/cm² and at a pressure of $\sim 5 \times 10^{-3}$ mbar[12]. The uniformity on the vessel wall is not measured, but the mean thickness is normally about 10-100 nm depending on the deposition time. The vessel temperature is usually 300°C.

During the cleaning and coating operations some CO_2 is removed (CO removal is negligible), but this had never led to significant reduction of oxygen in normal discharges. The JET vessel was frequently carbonised in 1985 but only rarely since then, because it appeared to be unnecessary for good coupling and high deposition of power from the ICRH heating system, and carbonisation has always given start up problems. Often GDC in D_2 is used to promote isotope exchange with the H trapped in films formed from H_2/CH_4.

The procedure for carbonisation used at JET have been copied from TEXTOR, where the process was pioneered, and where the coatings are much more controlled, and are characterised in great detail. At TEXTOR a mixture of D_2 + CD_4 is normally used and the current density is $j \sim 10$ μA/cm²; pressure[13] 10^{-3} mbar; liner temperature T_L = 150°C; thickness 100 nm[13]. It has been shown that overnight baking to 350°C removes a large fraction of the trapped $H_2(D_2)$. In contrast to JET the removal of oxygen is reported to be very efficient in TEXTOR leading to $Z_{eff} \approx 1.5$ with carbon as the dominant impurity. TEXTOR relies on carbonisation to obtain good coupling of the RF power to the plasma and a low influx of metal impurities during ICRH.

A specific application of the carbonisation technique in JET is the coverage of the Faraday screen of the RF antenna[14]. The screens are fabricated from pure nickel, and much of the nickel found in the plasma (where it is the principle metallic impurity) has been found to originated from the screens. The influx depends on the applied power and the mode of operation, although the exact mechanism is not known. Attempts to reduce the Ni influx by means of the application of a carbon layer to the screens has proven successful however the erosion rate is so high that the effect is quickly lost. Thin carbon coatings on pure nickel at 300°C lead to a layer containing carbides and in the absence of magnetic fields the change in μ_r gives noticeable effects on the skin depth (which disappear again when high magnetic fields are applied due to saturation).

CHANGES IN MATERIAL PROPERTIES RESULTING FROM PLASMA EXPOSURE

All materials, whether they are solid graphite or a carbon film deposited by the carbonisation process will change their surface properties following plasma exposure: sputter yields, hydrogen retention, secondary emission coefficient, back-scattering, surface morphology, etc are all modified.

The virgin carbon material has a low total erosion yield of $\sim 10^{-3}$ (from laboratory experiments in low flux hydrogen ion beams) which after exposure to the large fluences on a representative limiter surface increases to about 10^{-1} [15]. This value is taken at ∿ 700°C which is a surface temperature frequently observed on the JET limiter. Distinct changes in surface morphology also occur, for example it is found that small voids (∿ μm in diameter) open up as in the course of the exposure. Measurements on material exposed in JET show that the secondary emission coefficient is slightly higher than for unused carbon[16].

JET limiter surfaces in direct contact with the charged particle flux have consistently shown a metal coverage in the range of 10^{17} at/cm^2. It appears to be an equilibrium distribution established in a small number of discharges and the result of an erosion/deposition process to be treated later. The coverage must not be understood to be a uniform layer but as a mixture of carbon and metal. Sometimes very small droplets resulting from agglomeration are recognisable in the voids[6]. At high limiter temperatures the metals contamination of the surface starts diffusing into the bulk.

In JET specific damage has only occurred occasionally. A hole found in one limiter at the midplane (figure 3) has been attributed to a repeated deposition of energy from beams of run-away electrons. Post mortem examination showed ^{7}Be as a result of photoneutrons. It was not clear why jus this single point was damaged, but the limiter was later found to be 6 mm more inward than the others.

Damage to the protection tiles of the inboard wall has been attributed to a measurable misalignment and their alignment has subsequently been improved.

In the X-point operation of JET the protective rings of carbon tiles in the poloidal direction were used as divertor plates. At the intersection of the separatrix with the tiles, which were equipped with a shallow roof top profile, a very high heat load was observed (10-20 MW/m^2). In early X-point experiments the angle of incidence of the magnetic field lines was under-estimated and the tiles were exposed on their side faces (heat load up to 100 MW/m^2). This has led to damage and has been corrected by increasing the inclination of the roof top (figure 4) and aligning the tiles in the horizontal plane to within ± 2 mm[17].

In addition to this damage very localised deformation of some tile supports was observed. The deformation is attributed to currents flowing in the scrape-off layer of X-point plasmas due to different electron temperatures in inboard and board of the divertor region. Currents in the order of 1kA are required to explain the deformation.

It is important to note that the surface properties of metal components of the torus also change (even in the absence of carbonisation) because the surface composition changes. Even surfaces in the shadow of limiters where the CX neutral flux is supposed to be dominant have been shown to be covered by a carbon deposit in JET as well as in TEXTOR.

In JET small inconel and carbon samples have been used as a monitor of the wall conditions and the poloidal and toroidal distributions of the deposits have been measured. Deposits are principally of carbon and show a maximum at the outer midplane[18]. The toroidal distribution is normally uniform and can be affected by specific incidents[19]. The carbon deposit shows also a fairly constant C/H or C/D ratio of around 0.25, which points to a co-deposition process[20]. Although deposits were found on all wall samples erosion was found from the disappearance of a ^{13}C marker at 250 nm under the surface of a carbon sample[21]. The amount of erosion was dependent on the poloidal angle.

In TEXTOR the depth of the carbon deposit has been analysed as a function of distance in the scrape-off layer[22]. The observation is consistent with a chemical process where CD_4/CD_3^+ plays an important role.

THE INTERACTION OF THE PLASMA WITH THE LIMITERS

In JET the plasma in the scrape-off layer and its interaction with the limiters has been investigated in great detail. The parameters of the scrape-off layer have been measured as a function of the main independent plasma parameters I_p and $\bar{n}_e$. For the situation with discrete limiters and in the steady state condition at the current flat top the scaling of $n_e(a)$ and $T_e(a)$ is given in figures 5A and 5B[23]. The behaviour can be understood reasonably well in terms of a simple analytical particle and energy balance. The data have been used to describe the erosion and redeposition of carbon from the limiter surfaces.

Erosion is caused by the flux of charged particles, hydrogen and impurities such as C and O. Particles impinge on the surface with an energy increased by the space charge potential $\sim 3\ kT_e$ and for the impurities by their higher charged state eg. C^{4+}. The radial profiles of the particle flux I_S are mostly close to exponential:

$$I_S(x) = I_S(a)\ e^{-x/\lambda_I}$$

The erosion is counteracted by a deposition flux of impurities diffusing radially out from the confined plasma. The impurities are deposited (assuming 100% sticking efficiency) according to:

$$I_{imp}(x) = I_{imp}(a)\ e^{-x/\lambda_{imp}}$$

λ_I and λ_{imp} might be different because the transport coefficients $D_\perp$ are not necessarily the same.

Thus there is always a competition between erosion and deposition. If we assume only physical sputtering then an energy threshold occurs at a low energy, and since $T_e(x)$ is also exponentially decreasing we find deep in the SOL at high x only deposition, while net erosion occurs nearer to the plasma surface. This is shown in figure 6 and valid for OH discharges in the steady state flat top[24].

A JET limiter analysed for erosion/deposition is shown in figure 7. Isotope markers of ^{13}C were implanted in the surface to provide a depth reference. The areas of erosion and deposition were very distinct and erosion occurred to a depth of 200µm. Deposition occurs on the edges ie. at a distance > 2 cm into the SOL. The erosion/deposition pattern matches the one of figure 7 closely, and the total erosion calculated for 10^4sec discharge time (with a total flux $5x10^{21}m^{-2}s^{-1}$, and an effective carbon sputter yield by H, C, O, $\sim$ 0.1 including carbon self-sputtering and a 1% oxygen concentration) yields a total carbon fluence of $1.5.10^{25}$ m^{-2}, which is $\sim$ 0.19 mm.

The layered structure on the edges as observed on all limiters at the post mortem examination shows a very high deuterium content. Other investigations in the laboratory and in JET show consistently that carbon deposits contain up to 40 at % hydrogen. The amount of hydrogen/deuterium found ($\sim$ 10^{22} m^{-2}) suggests a layered structure saturated with hydrogen/deuterium, which was later confirmed[25]. In JET ratios of 0.2-0.4 have been found depending on the previous use of helium discharges. The co-deposition of C and H has been experimentally and convincingly demonstrated on a time resolved collector probe with a silicon sample exposed in JET in the scrape-off layer of a 5 MA OH discharge[26]. The exposure time was about 1.3 sec and the C/H ratio was $\sim$ 0.25, whilst the an e-folding length for each element was 12.3 mm (figure 8). The deuterium concentration found was comparable with the flux of deuterium in the SOL predicted (by the extrapolation) from Langmuir probe measurements. The co-deposition of hydrogen and carbon leads to appreciable inventories in excess of 10^{24} particles for a typical operational period.

The erosion process described here is also responsible for the removal from the limiter of the carbon films deposited on occasions by carbonisation, and for the cleaning up of the limiter surfaces when they are covered by metals diffusing out of the confined plasma uniformly. (For example after shots with high nickel contents, such as can be produced by RF heating). The removal of a carbon coating (10 nm thickness) is shown in figure 9 where the normal equilibrium nickel concentration drops after carbonisation but reappears slowly after approximately 40 discharges. Thicker coatings (1000 nm) have a lifetime in excess of 200 discharges[27].

The erosion process gives rise to an influx of impurities: carbon from the limiter surfaces and metals from the deposits on the surface. Since carbon is the bulk material the sputtering data can be applied to obtain the influx in a quantitative way. For metals this cannot be achieved since it is not a uniform layer. In JET sputtering from the walls due to CX neutrals can be neglected. Using the measured parameters of the SOL and physical sputtering, the total carbon influx can be calculated (figure 10) as a function of the main plasma parameters. A survey of the carbon concentrations in the centre of the plasma shows a similar behaviour[28]. A direct comparison with the measured influx for I_p = 2MA gives a discrepancy which might be due to the localised measurement or to the extra contribution of oxygen sputtering.

The importance of this good agreement between the observed erosion/redeposition and general behaviour of the carbon influx and the calculations is that the interaction can be extrapolated to higher currents and to conditions other than OH once the scaling of SOL parameters is established. The high carbon concentration in JET comes as a result of the high edge temperature, and a decrease of the influx can be obtained by working at high density.

In TEXTOR the carbon concentration is lower than in JET which might be attributed to a lower edge temperature. The behaviour with density is more complicated since the sputtering by CX-neutrals plays an approximately equal role to the sputtering from the limiter. Carbon concentrations in the plasma increase slightly with an increase in density[29].

EFFECTS OF THE WALL AND LIMITERS ON THE PLASMA

Plasma start-up depends very much on previous history and in this respect TEXTOR has shown that reproducible starting conditions can be obtained. In JET there are various possible modes of operation; ICRH in different gases ^{3}He, ^{4}He, D_2 etc, X-point operation with D° injection; inner wall operation with D° injection; etc together with possible GDC overnight. Even though the wall temperature is fixed at 300°C, the various modes of operation constitute various initial conditions which do not lead to a highly reproducible wall condition.

Additionally, carbonisation has always led to start-up problems in JET due to degassing. Plasmas run into high density disruptions or into radiation barriers limiting the plasma current to 100 kA and short pulses without a flat top. Conditioning by GDC in He or starting-up in He helps to overcome this difficulty. These problems are a consequence of the complicated interaction of carbon and hydrogen, no doubt involving chemical reactions.

TEXTOR has well documented examples of the interaction between plasma and wall during start-up due to different treatments after carbonisation. Figure 11A and 11B show two examples one with a low liner temperature (150°C) and one with a high liner temperature (350°C)[30]. In the first case the density comes to a flat top (overall recycling $\approx$ 1) while in the second case the recycling is <1 showing that hydrogen can be trapped in the carbonised layers. In both cases the trap can be filled by a short GDC in D_2.

During discharges non saturable wall pumping is observed in JET and TEXTOR as well as other tokamaks. It is not clear whether this is only due to the presence of graphite wall protection, possibly in combination with carbon layers, since the mechanism has not been identified. Wall pumping, ie. removal of particles, is observed while the plasma is left in contact with the main limiters or in a stronger form when the contact area is changed by moving the plasma.

In JET the plasma was moved to the inner wall, back to the limiter and again to the inner wall (figure 12A); in TEXTOR only one move was made to the inner wall (figure 12B). (Note that TEXTOR has no extended coverage of the inner wall but just one discrete carbon bumper limiter). Increases of elongation bringing the plasma closer to the top/bottom of the wall have an identical effect in JET to moving to the inner wall. Figure 13 shows the line integrated density for three plasma shots; firstly, a plasma which remains in contact with the cooled belt limiter throughout the flat top, secondly a plasma which is moved to the inboard wall during the flat top, and thirdly a plasma which made contact with the top/bottom of the vessel by increasing the elongation during the flat top. For each pulse the gas feed was closed after the current rise.

The overall mechanism of wall pumping can be simulated by assuming that the total particle content is constant and that the densities in the two reservoirs, plasma and wall, are proportional to their confinement or residence times. In

JET the residence time of the wall needed to model the results is about 1 second[31].

The wall pumping mechanism is used to quickly decrease the density at the end of a high power additional heating pulse to prevent a density-limit disruption. The pumping speed (particle removal rate) is several times 10^{21} particles/second.

The extensive graphite wall protection and limiters are considered to be a positive benefit for the different modes of operation of JET. In particular the extensive use of graphite has removed all metal impurities from the plasma, at least for OH discharges, leaving only carbon (the contribution of which can be predicted from physical sputtering, and therefore decreasing with increasing n_e) and oxygen and chlorine. The behaviour of oxygen and chlorine in JET can not be explained, and they can not be removed by the GDC or carbonisation.

All modes of operation have been accessible, including the hot ion mode which is obtained by running the discharge on the inboard wall keeping the density down by the temporary strong pumping effect: this effect can be enhanced by conditioning with He-discharges; and X-point operation combined with NB heating which has brought the benefit of an increase of τ_E by a factor 2. In both modes the plasma could not be heated by RF since the distance to the antenna was too large. High RF power can only be coupled to the plasma when the plasma is touching the belt limiters, but unfortunately at higher power material is released from the Faraday screen. Carbonisation has no influence on the coupling.

In TEXTOR the contact with the limiter is less dominant that in JET. Contributions to the hydrogen/carbon influx directly from the wall in JET are less than 0.1 times those from the limiter whereas in TEXTOR they are comparable to those from the limiter. Therefore carbon influx and concentration does not decrease with increased n_e since the CX-neutral contribution is high. Oxygen is effectively removed by GDC and $Z_{eff} \stackrel{>}{\sim} 1.5$ as compared to JET where $Z_{eff} \stackrel{>}{\sim} 2.5$. High power RF heating a TEXTOR can only be achieved after carbonisation: it is unclear why there is a difference to JET.

Both in JET and TEXTOR detailed investigations are being undertaken to study the total gas balance. The co-deposition of C and H generally leaves large amounts of gas trapped in the deposited layers, with obvious consequences for the tritium inventory. Preliminary observations are that in normal JET discharges with a gentle pulse decay 70% of the input gas is trapped, ie not recovered after the discharge; after disruptions about 50-100% is recovered. After a disruption there is a fast release of the gas, whilst after an OH discharge a delay of 20s is observed. He-discharges show a full accountability for the gas inventory (and less oxygen in the plasma because chemical effects are absent).

CONCLUSIONS

1. High density, high purity graphite has proven to be a successful low Z protection and first wall material in a large tokamak.

2. Erosion/deposition rates are predictable once the scaling of the parameters of the scrape-off layer is known. If the plasma limiter contact is the dominant interaction then physical sputtering from a carbon limiter can correctly predict the carbon influx.

3. Protection of metal surfaces is necessary and graphite tiles have shown to be a good material. This is partly because of the good thermal shock resistance and partly because of the natural spreading of the heat load caused by run-away electrons.

4. Graphite limiters can be cooled by radiation between shots. The effective surface area needs to be large enough to prevent too high surface temperatures.

5. Good alignment to the magnetic field configuration is important in areas which are critical in the maximum power load capability.

6. In situ coatings will generally work only temporarily. Erosion rates are predictable once the ion or particle flux is known.

   TEXTOR observes beneficial effects from carbonisation: reduction of oxygen and high power capability for RF heating. These are not observed on JET. Coating will form spontaneously due to deposition in areas where the electron temperature is too low for erosion.

7. Co-deposition of carbon and hydrogen, occurring spontaneously in a predominantly carbon machine, may lead to serious problems for the tritium inventory.

8. He-conditioning presents a powerful method to manipulate the hydrogen in the near surface layer of the solid carbon and carbon films.

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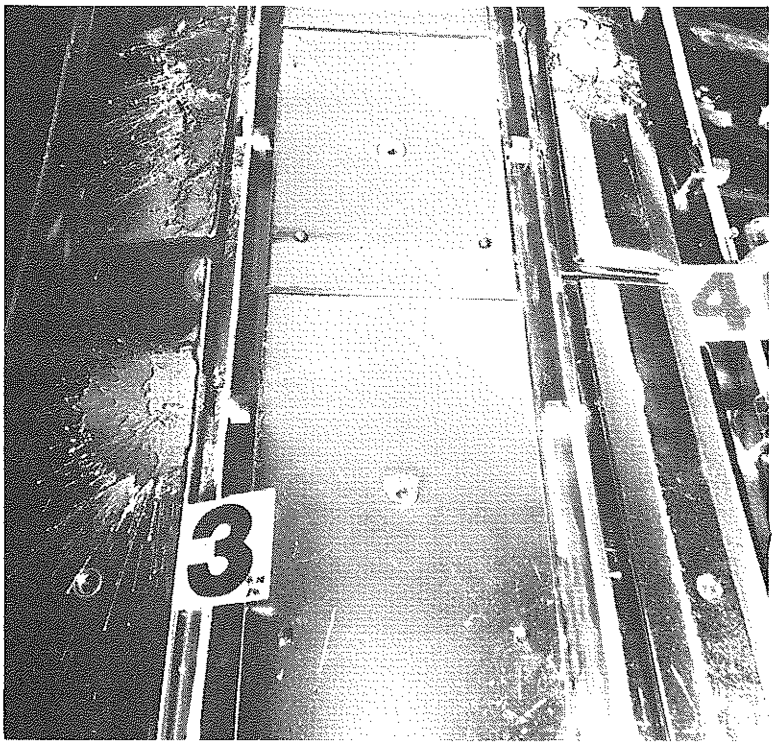


Fig. 1 An example of inboard wall damage as it was found in early operation of JET.

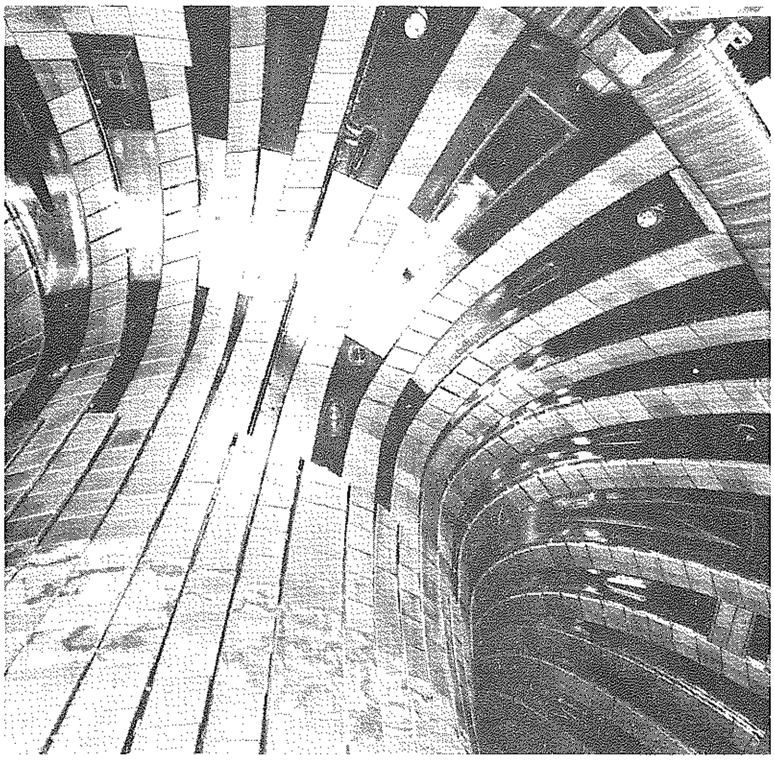


Fig. 2 Inboard wall protection tiles and the poloidal rings of tiles on the octant joints. A row of carbon fibre re-inforced tiles near the midplane and a small part of the belt limiter are just visible. View towards the top of the vessel; situation 1987.

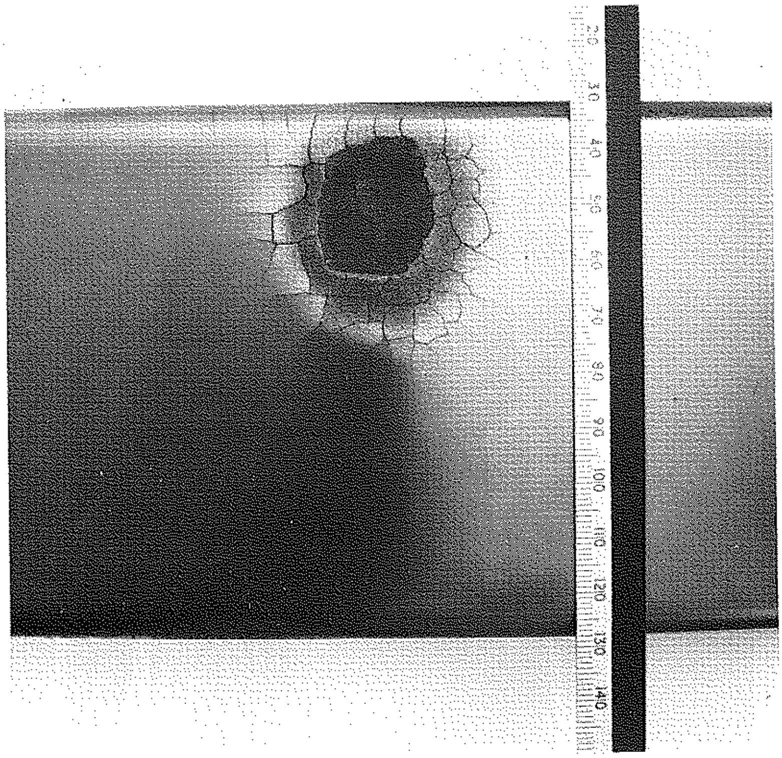


Fig. 3 A hole in one of the JET limiters caused by repeated deposition of a run away electron beam. The geometric midplane was at 33cm.

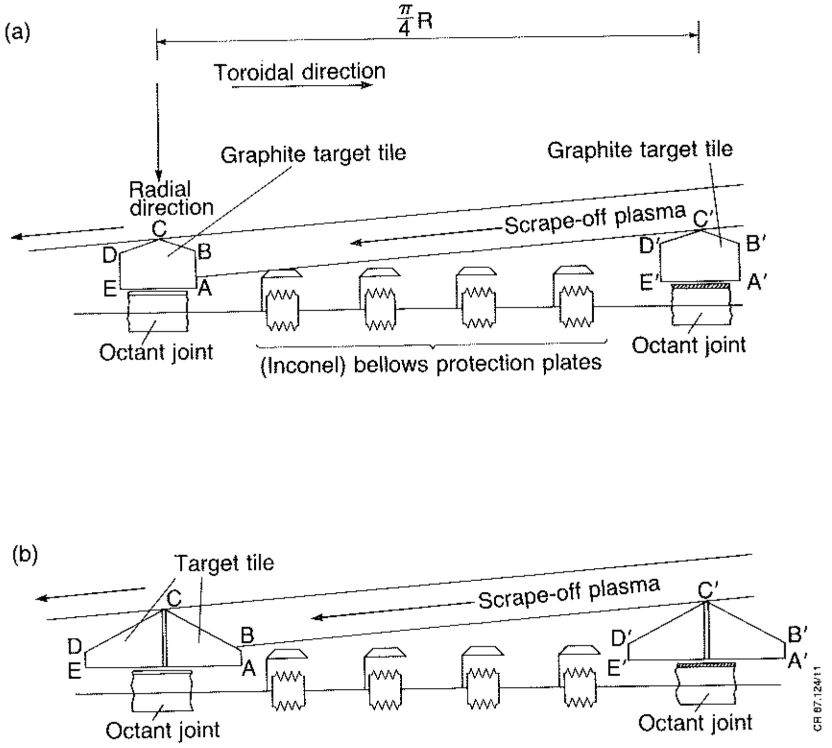


Fig. 4 Schematic configuration of X-point target tiles (a) in early operation and (b) after correction.

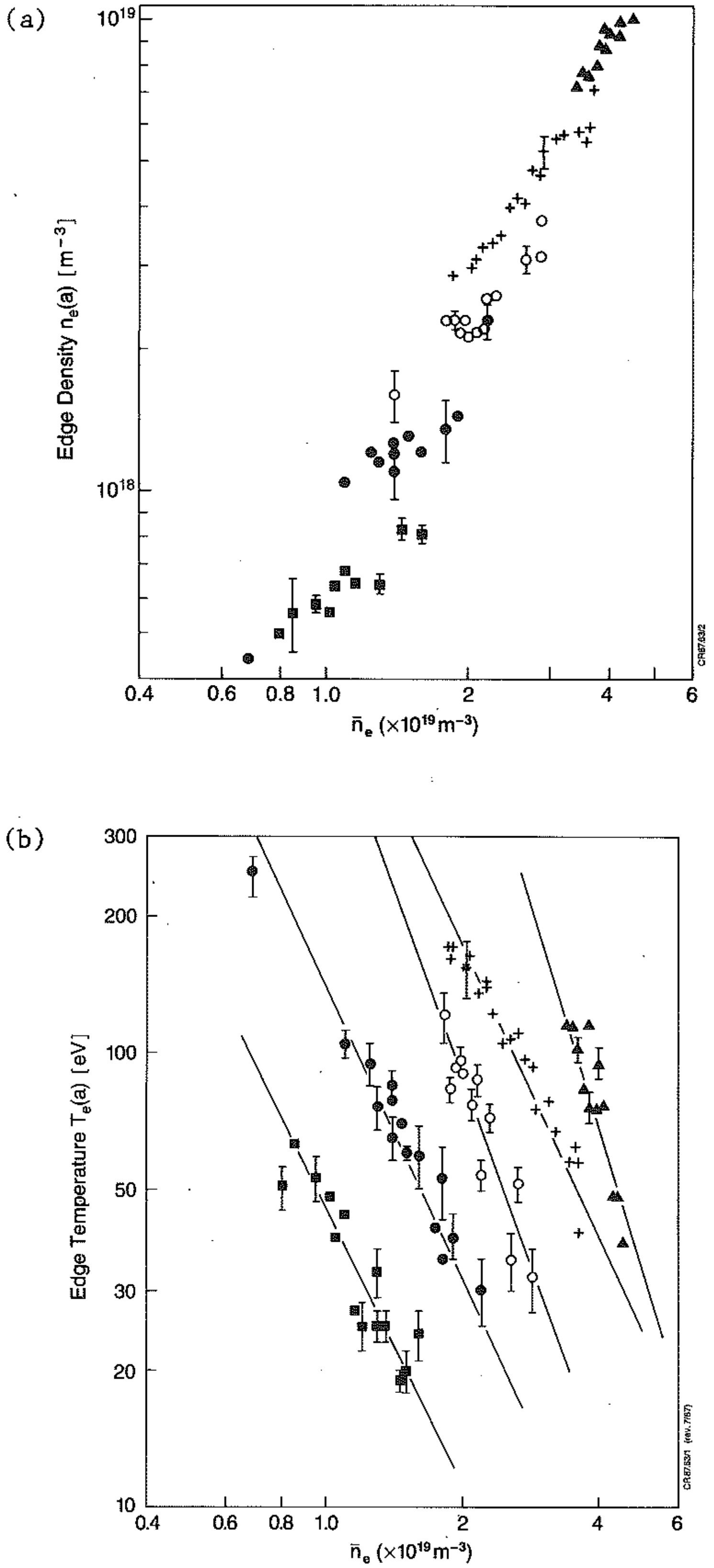


Fig. 5 A) Edge density n_e (a) B) Edge temperature T_e (a) as a function of $\bar{n}_e$ with I_p as a parameter for OH limiter discharges in JET. (from Ref. 23)

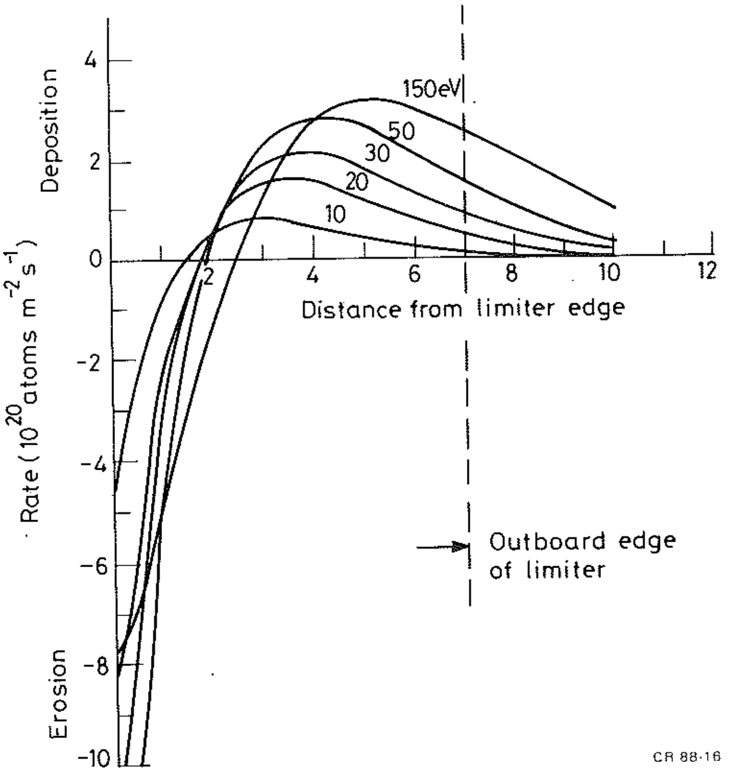


Fig. 6 Net erosion/deposition rate of carbon as function of distance from the last closed flux surface for various edge temperatures. Edge density $5\times10^{18}m^{-3}$; $T_e = T_i$; and $\lambda_n = \lambda_{imp} = 20mm$; $\lambda_T = 40mm$. (from Ref. 24)

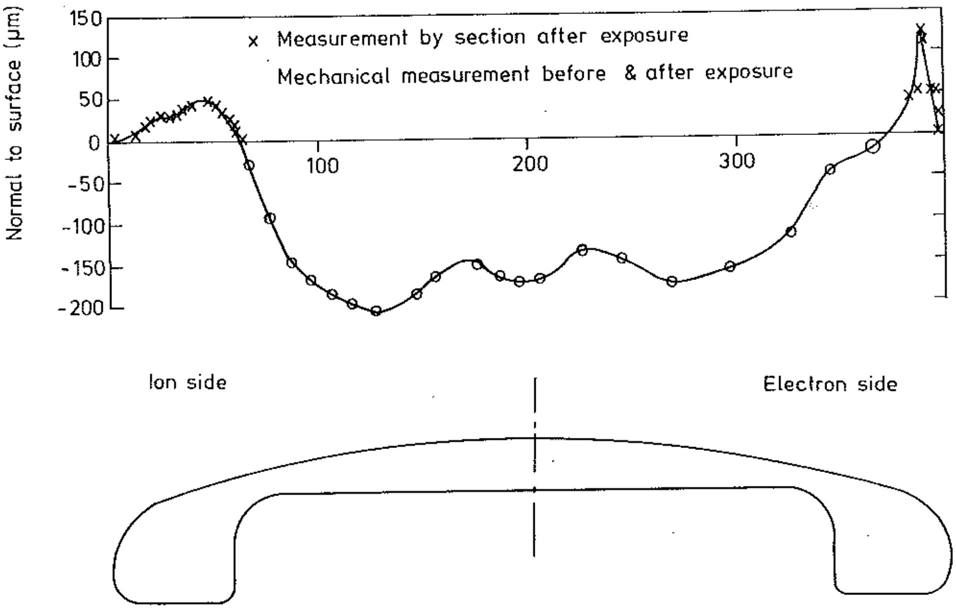


Fig. 7 Erosion measured mechanically on a JET limiter after 1986 operation. Reference level was established from ^{13}C markers in the surface.

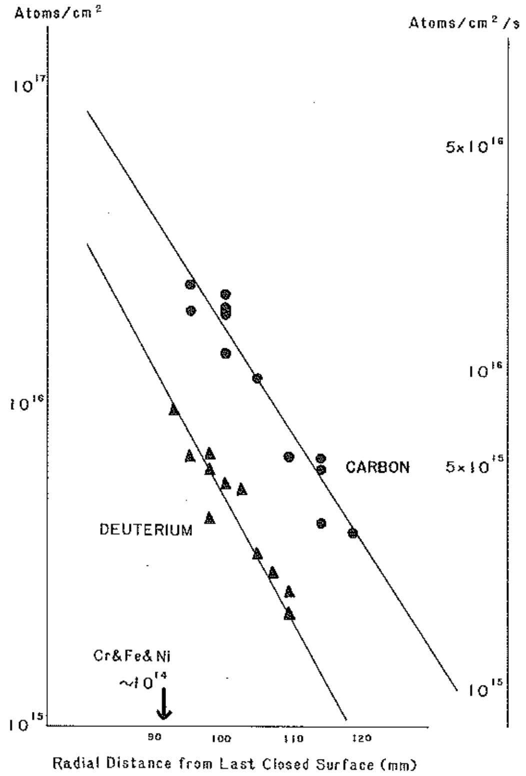


Fig. 8 Surface concentration and inferred deposition rate of carbon and deuterium on a collector probe with Si-samples exposed to a 5MA OH discharge. Results shown are at the flat top of the plasma current. (from Ref. 26)

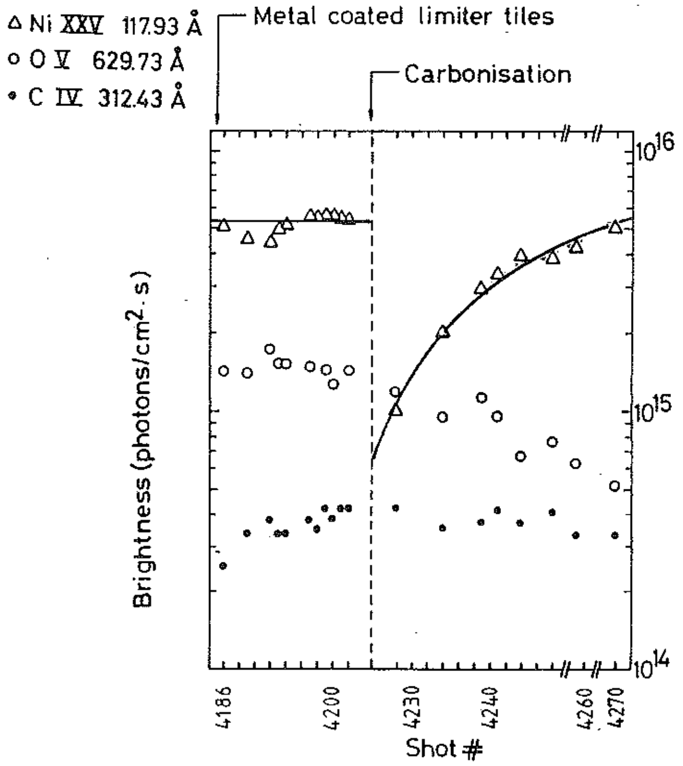


Fig. 9 The decrease of Ni concentration after carbonisation and the slow disappearance of the carbonisation layer. Shown as a function of shot numbers.

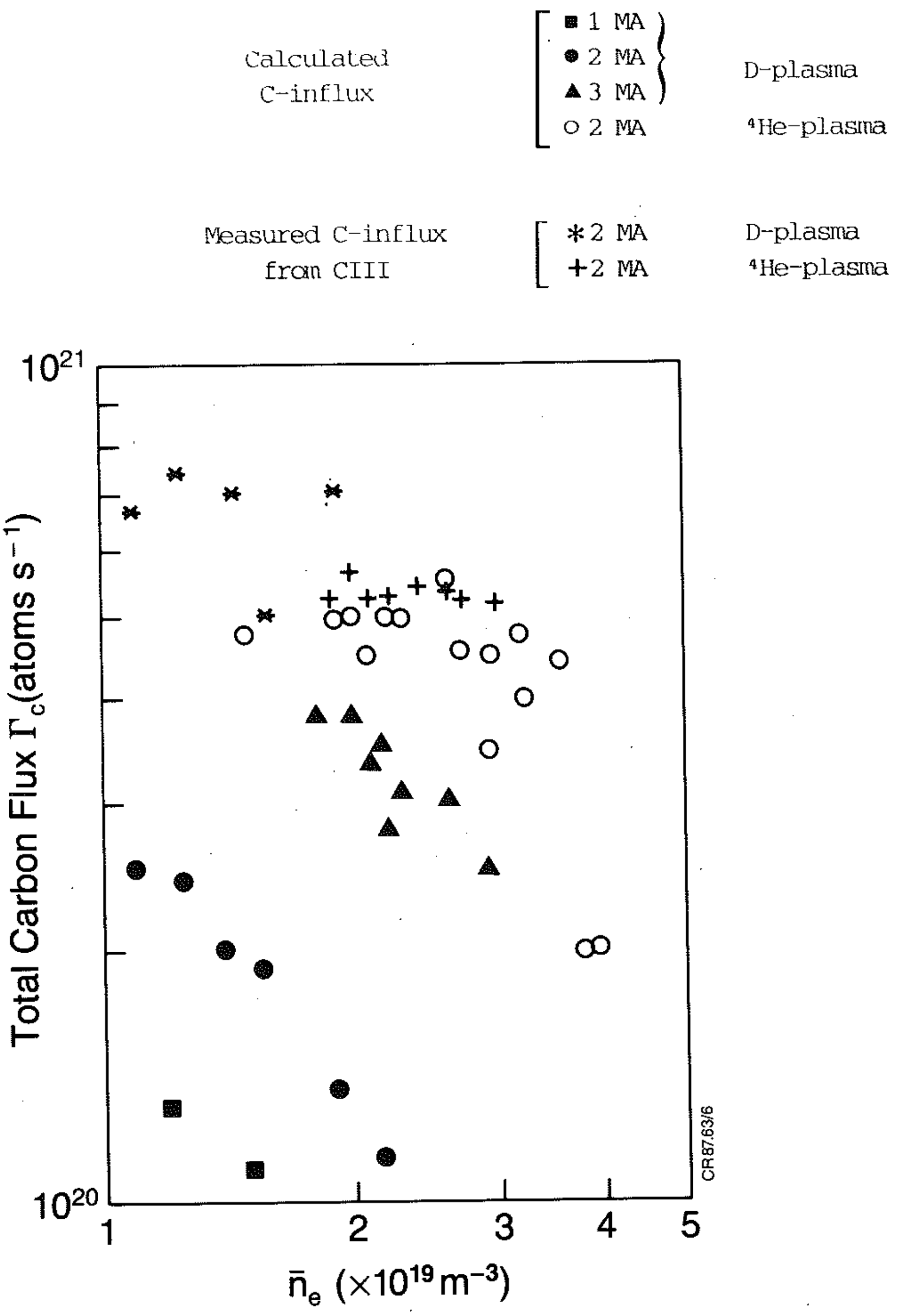


Fig. 10 Calculated and measured influx of carbon from JET limiters as a function of $\bar{n}_e$ with I_p as parameter using measured SOL parameters for steady state OH conditions. (From Ref. 23)

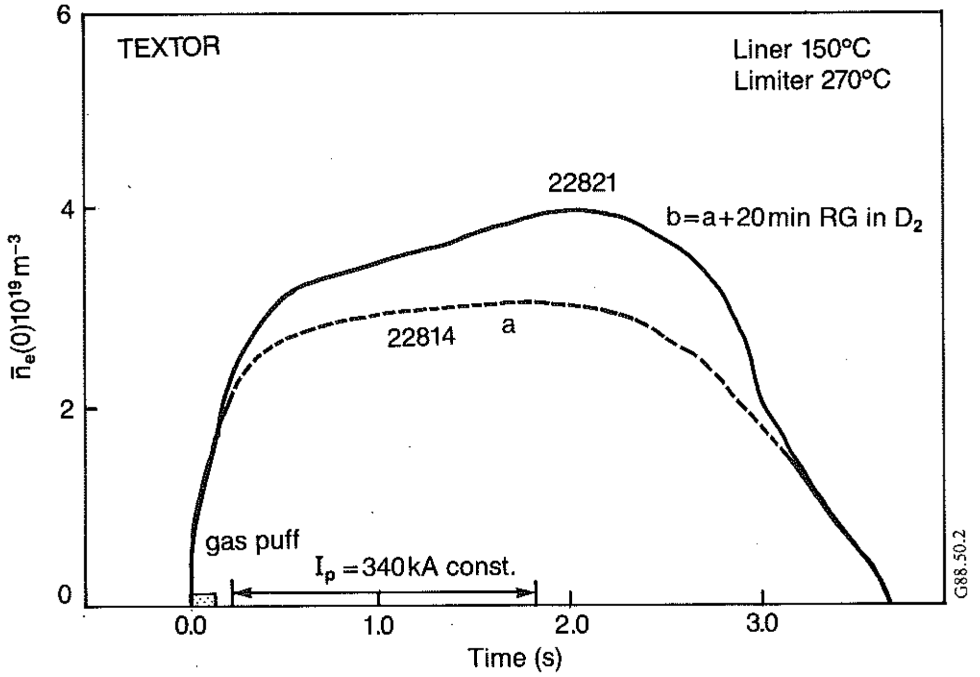
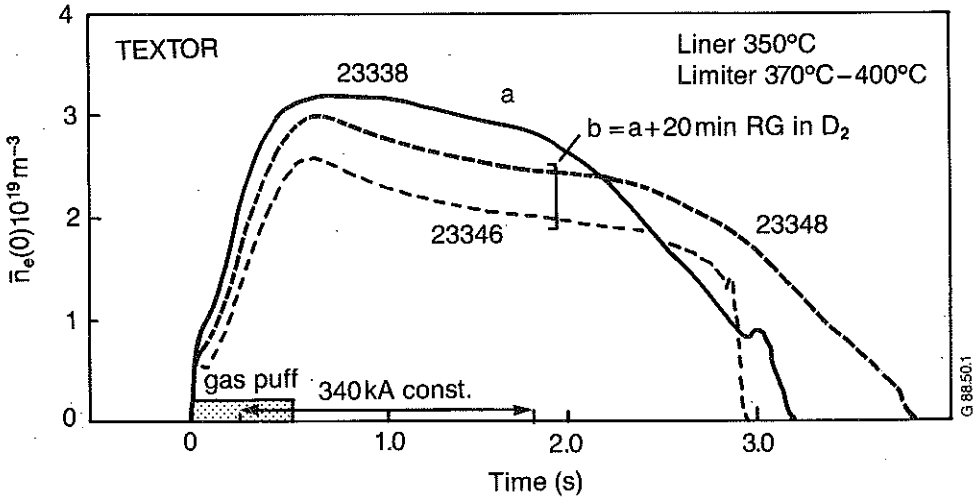


Fig. 11 Density behaviour after carbonisation in TEXTOR:

A) Shot 22814 (a) shows the central electron density after carbonisation at a wall temperature of 150°C and a 350°C bake-out overnight. Shot 22821 (b) shows the loading of the wall due to a 20 minutes RG in D_2. (from Ref. 30)



B) Shot 22338 (a) shows the central electron density after carbonisation at a wall temperature of 350°C and a 350°C bake-out overnight. After 20 minutes RG in D_2 the wall is depleted due to particle induced desorption (shot 23346); in subsequent shots the wall inventory again (shot23348). (from Ref. 30)

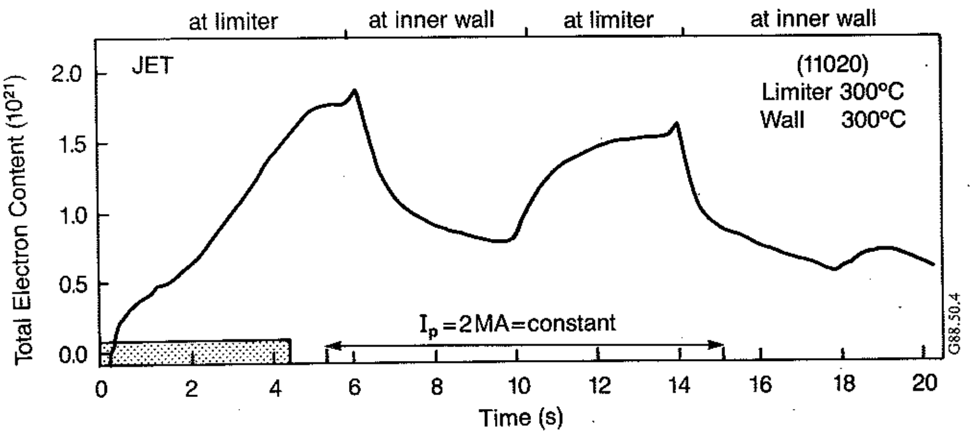
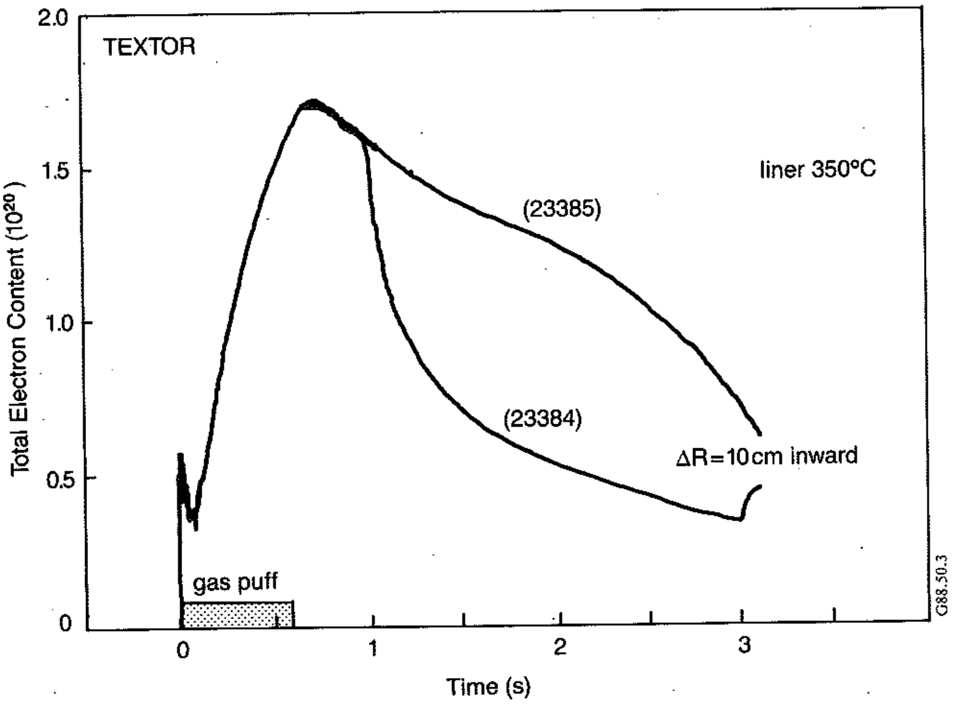


Fig. 12 A) Wall pumping in JET. After formation the plasma is moved from the limiter to the inboard wall and back again. The move is then repeated. (from Ref. 31)



B) Wall pumping in TEXTOR. After formation the plasma is moved to the inboard wall and left there. (from Ref. 30)

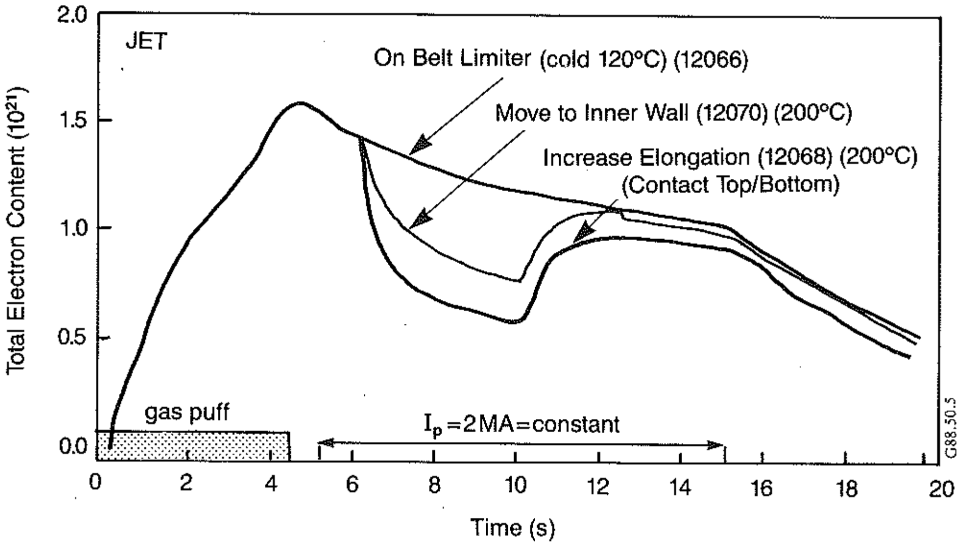


Fig. 13 A comparison of wall pumping by a move to the inboard wall and to the top/bottom by an increase in elongation in JET.