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Contents

HYDROGEN ISOTOPE ANALYSIS OF THICK LAYERS DEPOSITED IN TOKAMAKS

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ABSTRACT

Predictions can be made of the tritium retention in future tokamaks such as ITER based on analyses of the D retention in redeposited films in existing tokamaks. However, although amounts of H+D up to the saturation level are frequently observed, measurement is invariably by Ion Beam methods such as NRA and ERDA which only analyse to a depth of the order of a micron, whilst it is only the total content of very thick layers that is of relevance to ITER. This paper compares these near-surface data with methods developed to determine the composition throughout thick C-H films (~100 microns) such as Neutron-induced Elastic Recoil Detection Analysis (n-ERDA) and SIMS and Nuclear Microprobe analysis of specially prepared cross-sections.

1 INTRODUCTION

The primary mechanism for hydrogen retention in large tokamaks is codeposition with (and/or implantation into) material eroded from areas of plasma-facing components (PFC) with high incident fluxes and redeposited in regions of lower fluxes. If the PFCs are made of carbon in the form of graphite the saturation level of H-isotope trapping in redeposited layers at <270C has been shown to be given by H:C≅0.4:1 (1). In a long pulse, high power machine such as the planned **I**nternational **T**hermonuclear **E**xperimental **R**eactor (ITER) redeposited films up to millimetres in thickness may accumulate at the deposition-dominated wall areas. If the machine is fuelled by a 50% deuterium (D)/50% tritium (T) mixture, then T may be trapped at up to 0.2 times the amount of C in these thick layers, and retention of this magnitude would be unacceptable both from radioactivity and cost considerations.

In the post-mortem analysis of PFCs from JET and other tokamaks, similar amounts of H and D are generally observed in the near-surface region: since JET is normally fuelled with D the reason for the prevalence of H is unclear (2). However, as a result a saturation level of H-isotopes in the near-surface region may correspond to an analysed retention of D of about 0.2 times the amount of C, and D at this level has frequently been observed in surveys of the PFCs in JET (3,4). Most of these measurements have been made using the **I**on **B**eam **A**nalysis (IBA) variant **N**uclear **R**eaction **A**nalysis (NRA), and with this technique usually only the outermost 1 micron (approximately) of the surface is analysed. Redeposited layers up to 130 microns thick have been measured in JET by sectioning the films on the flanks of the discrete limiters used until 1986 (5), and it is clearly important for the retained D inventory to know whether or not the D concentration throughout the film is the same as that seen by NRA in the outermost micron. A **S**econdary **I**on **M**ass **S**pectroscopy (SIMS) profile was made at a different point on the limiter where the film was 24 microns thick which showed that the D (and H) concentrations appeared to start high at the surface, but then fell by about an order of magnitude within the bulk of the film (5). However, the SIMS technique, which consists of sputtering material from a surface using an ion gun and analysing the ion content of the sputtered material entering a mass spectrometer, cannot be considered to be quantitative except in certain well-defined situations. Firstly the sputtering yield for an impurity element in a surface can vary over orders of magnitude depending on the surface roughness, the composition of the substrate and the binding configuration of the impurity. Secondly the fraction of material sputtered as ions and detected by the spectrometer varies by many orders of magnitude for different elements, and thirdly the composition profiles into the surface can be severely distorted due to differential sputtering, knock-on and shadowing effects.

Thus JET data (which give a similar picture for H-isotope retention to other tokamaks) generally show high surface (~1 micron) concentrations of retained H and D, and provide an example of lower concentrations into the bulk of a thick redeposited film. This paper describes the assessment of techniques for determining the H-isotope content of thick (>10 micron) films and their application to the analysis of the same thick redeposited films from the 1986 JET limiters.

2 EXPERIMENTAL RESULTS

(a) Preparation of samples

The ideal situation would be to be able to make an analysis in situ, or at least on a complete component after removal from the tokamak. However, since the limiter tiles removed from JET after the 1986 operations were each 450 x 120 x 77 mm, the only technique able to analyse a complete tile was IBA using a large target chamber specially constructed for analysing JET components. In order to investigate other methods it was therefore necessary to prepare smaller samples: samples were cut from the flanks of one of the limiter tiles as shown in Figure 1. Samples cut from the same part of the profile of the tile (eg samples 3, 8 and 11) are assumed to be equivalent. Since the films are very thick, it is possible to profile through the film by analysing a cross-section of the film, if the spatial resolution of the technique is good enough, and this can be enhanced by producing a taper section which improves the resolution by up to an order of magnitude by increasing the apparent thickness of the film. Thus it can be seen that sections were prepared from samples cut adjacent to the conventional coupons. However it should be noted that preparation of sections may affect the results subsequently obtained by smearing material across the surface or leaching out certain components by reaction with the potting resin or polishing solution. (A possible method of preparing a section through a thick film without metallographic polishing is ion beam slope cutting (6,7). The area to be analysed is the side wall of a crater formed by ion bombardment, the line of the wall being defined by a sharp-edged screen. However development of the technique from films a few microns thick (7) to films of the order of 100 microns has yet to be demonstrated.)

(b) NRA analyses of tile samples and an implanted standard

The samples cut from the JET limiter tile were analysed by NRA to obtain the surface (~1 micron) concentration of D using the D(^{3}He,p)^{4}He reaction. The results are given in the first column of Table 1. To check the quantification some graphite samples were also implanted to saturation with 5 keV deuterons over a 5 mm diameter region, which according to TRIM calculations should provide a surface containing 6.10^{17} deuterium atoms cm^{-2} within the outermost 0.15 microns. One of these standards analysed by NRA and by other techniques is included in Table 1 and the NRA result (which was duplicated in different laboratories) is shown to be in good agreement with the calculations.

(c) Heavy Ion Induced Elastic Recoil Detection Analysis

Another of the IBA family is **E**lastic **R**ecoil **D**etection **A**nalysis (ERDA) wherein an ion beam is incident at glancing angle and atoms may be ejected from the surface after an elastic collision with the incident ion (that is, most of the incident energy is transferred to a recoil in the collision). The detector for the ejected particles is placed at glancing angle in the forward direction. In the most common form of this technique a helium ion beam is employed at energies up to 3 MeV. Each of the H isotopes can be separately analysed by this method, and the depth of analysis is about 1 micron. The technique is much more dependent on surface roughness than NRA, but is usually the only way to obtain an idea of the H (ie protium) surface concentration. However, if very much higher incident energies are employed the analysable depth increases, and if ions of a heavier element are used the range of masses detected is also increased: this is the technique known as Heavy Ion ERDA (8,9). Ejected ions are detected using ionisation chambers wherein an ion from the sample passes through the chambers in series. The maximum value of the energy loss dE/dx, i.e. the Bragg peak height, of the detected particles in the detector gas depends on their atomic charge number Z. By suitable adjustment of the detectors, the atomic number and energy of each ion can be measured simultaneously. From the number of ions detected as a function of energy, for each element in the energy loss versus energy plots, can be calculated the depth distribution of that element into the surface.

Figure 2 shows depth distributions for the masses 1, 2, 12 and 16 (H, D, C and O, respectively) through the outermost 2 microns of the surface of sample 8 from the 1986 JET limiter tile. Profiles can be derived to about 10 microns for the H isotopes under these Heavy Ion ERDA conditions, but it can be seen in Fig. 2 that the H, D and O are mostly restricted to the outermost $^1/_2$ micron of the surface. Note, however, that the H continues at ~20% of its peak value beyond 2 microns, whereas the D concentration falls to zero. Integrating under the D depth profile and using a surface density for graphite of 10^{19} atoms cm^{-2} gives a concentration of 3.10^{17} D atoms cm^{-2} on sample 8. As seen in Table 1 this is lower than the NRA value, but factors of two between these methods have been seen previously (10) and may be due to a difference in the calibration of the Heavy Ion ERDA technique.

(d) Neutron-induced Elastic Recoil Detection Analysis (n-ERDA)

ERDA with primary ions can be seen from the previous section to be potentially very powerful, but the depth attainable is limited by the need to use glancing angles (to approach the forward scattering conditions necessary for maximum momentum conservation, and which also imposes severe practical limitations on the sample) and by the penetration of the primary beam. These limitations are eased if **neutrons** incident on the rear of the sample are the primary source. Fast neutrons will pass through samples a few millimetres thick without significant energy loss or attenuation, and the maximum escape depth for the recoil particles (i.e. normal to the surface) can be utilised (11). For graphite samples total H isotope concentrations can be absolutely determined from comparison with $TiH_{1.87}$ and $TiD_{1.97}$ standard samples for films 300 - 400 microns thick using 14 MeV neutrons, with variations in concentration with depth visible with a resolution for D analysis of ~30 microns: using 2.5 MeV neutrons these figures become ~50 and ~5 microns, respectively. In these experiments a 14 MeV neutron source was employed, and a three detector telescope using silicon sensors was used to simultaneously measure energy loss and energy for each particle. One disadvantage of the method is that the neutron flux at the sample obtainable from an accelerator used as a neutron generator is much lower than the ion flux that can be achieved, so counting times are much longer (typically ~ an hour) for reasonable statistics and the absolute sensitivity of the technique is also lower than for the ion beam techniques.

The total amounts of H and D present throughout the thickness of the films (since they are well within the detection range for 14 MeV neutrons) are listed in the right-hand columns of Table 1. It can be seen that according to n-ERDA the total amounts of D in films up to 120 microns thick are not much greater than those detected in the outermost micron by NRA, although there was good agreement in the analysis of the D standard. n-ERDA also showed larger quantities of H than D in the films. In order to shed light on these somewhat surprising results, the data were deconvoluted to provide depth profiles through the thickest film (sample 4), and these experimental profiles were compared with profiles simulated by Monte Carlo methods for a number of distribution scenarios. The results for D are shown in Figure 3. It can be seen in the figure that the data are a good match to a distribution with 33% of the D at the surface and the remainder tailing in approximately 70 microns into the film, but clearly do not match the other model distributions in the figure. Likewise Figure 4 shows the experimental profile for H, and in this case there is a good match with a distribution with a constant level for 70 microns from the surface followed by a concentration decreasing from half that value to zero over the next 50 microns.

The distributions in Figs 3 and 4 are merely indicative and in reality there may be a wealth of fine structure, since the inherent resolution of the n-ERDA technique is rather poor. However, uniform concentrations of either H or D throughout the film are precluded, and there is a genuine difference between the distributions of the two isotopes: much more detailed information on the distribution in the outer part of the film would be obtained using 2.5 MeV neutrons. Assuming the best-fit profiles to be correct, the H and D contents of the outermost 1 micron would be 1.10^{17} and 2.7×10^{17} atoms cm^{-2}, respectively.

Thus the n-ERDA data suggest the D is concentrated at the surface, and are not inconsistent with the NRA results, although the expected amount in the outermost micron is about half the NRA amount (as was the Heavy Ion ERDA result). Note also that the H content of the outermost micron is ~ one-third of the D content (as indeed was shown by Heavy Ion ERDA on the adjacent sample), so that a more surface specific technique would suggest there is **more** D than H in the film whereas in fact there is almost an order of magnitude **less**.

(e) Nuclear Microprobe analysis of sections

The Nuclear Microprobe produces a focussed ion beam with a minimum diameter of about 5 microns. Thus in principle it is possible to produce NRA profiles through a thick film with a resolution of about 5 microns by analysing a section through the film in a Nuclear Microprobe. Indeed, this resolution can be improved to about 1 micron by producing a taper section through the film. At the maximum resolution the beam current becomes too low for analysis in a reasonable time, but since the film extends uniformly in one direction (supposedly) the beam can be extended parallel to the film surface without degrading depth resolution. In this investigation the bombarded area was thus oblong, 15 microns wide (which is thus the resolution across the section) and 100 microns long, allowing good statistics in about 60 secs. Figure 5 shows a plot of D peak intensity (in arbitrary units) versus distance across the redeposited film section. This section was a taper section of a 60 micron thick film polished at 5 degrees to the surface of the sample: the film appears 240 microns across, so the tapering improves resolution by a factor of 4. (The factor of 11 that might be expected geometrically does not appear to be realised). The sample was taken from a different part of the 1986 limiter, though from a similar section of tile to that shown in Fig.1.

The Nuclear Microprobe analysis shows a peak of D at the surface, the width of which is approximately equal to the beam width, so the actual width of the D-rich layer in this taper section must be <<15 microns, and therefore in normal section must be of the order of a micron or less. Integrating under the surface peak and under the rest of the depth distribution suggests about half of the D is in the surface peak, a result similar to the n-ERDA analysis of another area of film.

(f) SIMS profiling and analysis of sections

As mentioned in the Introduction, a SIMS analysis of a similar limiter tile from 1986 showed lower H and D levels within than at the surface (5), but there are many possible errors associated with the measurement. However, many of the errors associated with sputter profiling disappear if SIMS is used to image the cross-section, as signal intensities from all points in the section should be directly comparable. Furthermore since the primary ion beam used can be focussed to << 1 micron the potential resolution makes the technique complementary to the Nuclear Microprobe. A number of sections, including sample 12, from limiter tiles were examined by SIMS, but the results were disappointing. When the whole cross-section was viewed good secondary electron images were obtained, and ions of impurity elements such as Cr and Ni could be mapped. However the D and H distributions were distorted and could not be used to compare the quantities of each isotope across the film. It was possible to see that there was generally an aggregation of H and D at the surface, and occasionally accumulations at defects within the film or at the film/substrate interface. It was also clear that on the micron scale the composition parallel to the surface, as well as through the film, was variable.

Conventional SIMS was performed (i.e. by bombarding the the outer surface) on samples 1 - 5 and the D standard. Figure 6 shows the signal intensities in the mass peaks 1, 2 and 12 (H, D and C, respectively) versus bombardment time for the D standard. The maximum D signal level is about a factor of 7 lower than the C signal, so this should correspond to the saturation ratio for D:C of 0.4:1 (1). The D level falls off after ~300 secs, which according to TRIM code predictions should correspond to a depth of ~150 nm. Figure 7 shows a similar spectrum recorded from the tile sample 4. Again the maximum D signal is about a factor of 7 lower than the C signal, so since the matrix is again essentially carbon, this should also indicate the saturation level for D in C. Note, however, that this is only for <100 secs at the start of the profiling. The beam current density was about twice that used in Fig. 6 (hence the C signal is 10^4 rather than 4.10^3) so the amount sputtered away in this time (again assuming similar behaviour to the standard) is ~100 nm. The D concentration then stabilises at about a factor of 5 less than its earlier value.

The steps up and down in signal levels seen in Fig. 7 after ~600 and ~1000 secs are due to deliberately raising the beam current density by a factor of two and then returning it to the initial value. The signals from elements present in the substrate should also double, but impurities originating from the vacuum system should not respond in this manner. In particular H is always present in the system. From the behaviour of the H signal in Fig. 7 it can be seen that about half of the H at that time is really part of the film whilst the rest may be contamination. By comparison with Fig. 7 and profiles from other samples analysed at that time, it seems probable that most if not all of the H seen in Fig. 6 comes from contamination. It should be noted that the relative intensities of the H and D signals cannot be taken as a measure of their relative quantities in the film, since the ion sputtering characteristics and detection efficiencies may differ.

3 DISCUSSION

All the analyses of these redeposited films on samples cut from the flank of one of the discrete limiters used in JET in 1986 agree that the D is peaked within the outermost micron (approximately) of the film, and that there is perhaps a similar amount in total in the remaining thickness of the film. Thus there is no serious discrepancy between any one technique and others. None of the techniques offers a non-destructive method of analysing the large components likely to be used as PFCs in ITER, and these data highlight the problem that **surface** analysis by NRA (which can be done non-destructively) cannot be used to predict **bulk** composition.

n-ERDA can provide a quantitative analysis simultaneously for each of the isotopes H, D and T through films up to some hundreds of microns thick (and would give the ratios H:D:T in the outer part of films in the millimetre range, should they occur). The method does rely on neutrons penetrating through the sample without significant losses, but the resulting limitations on sample composition and thickness have not been fully assessed. Samples of graphite a few millimetres thick as in this work present no problem, so it may be possible to analyse through certain first wall components, or to arrange for special components with the outer few millimetres detachable in areas where rapid film growth is expected. If samples have to be cut out for analysis, then cutting out samples to a rough thickness tolerance is all that is required for n-ERDA as well as the surface layer examination techniques like Heavy Ion ERDA and SIMS, whilst that is only the first step in the preparation of the sections necessary for Nuclear Microprobe analysis. There is also a risk that the polishing process may introduce anomalies into the film analysis, though there was no evidence of such problems in this investigation: ion beam slope cutting (6,7) may offer an alternative preparation method. Smearing effects during sectioning would, however, be expected to be too great to allow second order measurements such as bulk diffusion to be made using either technique. The Nuclear Microprobe could also measure T depth profiles for films deposited from D-T plasmas by using a different NRA reaction, but, like n-ERDA, does not have the sensitivity to measure the T in films deposited from D-D plasmas. Measurement of H by ERDA is also possible in principle, but would be very difficult in practice due to the glancing angle geometry required.

The samples used in this work are the only known examples of very thick (~100 microns or more) material redeposited in a tokamak, and it was hoped that they would contain significant D levels throughout the film to provide a better test for the analysis options. The fact that the SIMS analysis previously carried out on the tiles (5) showed reduced H and D levels within the film means that the localisation of the D to the surface in these analyses several years later is unlikely to have occurred merely with time. The discrete limiters regularly reached temperatures in excess of 1000C at the erosion zones to either side of the centre of the tile during plasma pulses, and temperatures in the redeposition zone must also have regularly exceeded the 400C at which the film starts to degas (12): a number of the plasma pulses also terminated in disruptions which can cause large transient heat loads. Thus thermal outgassing of the samples seems a plausible reason for the low total D content of these films, and it may be possible for high D levels to exist throughout a thick film provided the temperature is always kept low enough.

4 CONCLUSIONS

The H, D and T contents of films up to hundreds of microns thick can be simultaneously measured quantitatively by n-ERDA. For thick film analysis a source of 14 MeV neutrons is required, whilst better resolution in depth distributions is obtained using 2.5 MeV neutrons. It is intended to develop a n-ERDA analysis facility capable of providing both energies in the near future.

Metallographic sectioning can also be used to provide D depth profiles through thick films with the Nuclear Microprobe. These tests show that the depth resolution obtainable is a few microns using taper sections, which is equivalent to about 1 micron in a normal section through the film. Of course considerable effort is required to produce the sections, but the polishing process does not appear to have a deleterious effect on the profiles. T depth profiles could also be measured for films deposited from D-T plasmas.

These thick (up to 130 micron) redeposited films had a total D content no larger than thin films found elsewhere in JET, and the D concentration within the surface was at least an order of magnitude less than in the outermost 1 micron. It is believed that this is due to thermal outgassing of the films when the limiters were heated to ~1000C by the JET plasma during high power discharges and/or as the result of disruptions.

5 ACKNOWLEDGEMENTS

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Microprobe analysis, B Farmery (Sussex University) with NRA analysis and Dr A Chew (Loughborough Consultants) with SIMS analysis is gratefully acknowledged. This work was supported by NET in the context of the European Home Team contribution to ITER (ITER Task T62 of the 1994 Comprehensive Task Agreement).

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TABLE 1 Comparison of the analyses (all in units of 10^{17} atoms cm^{-2}) of H-isotopes in carbon samples by different techniques.

	NRA	HIERD	NERD			
Sample Number			Outer Micron		Total in Film	
			H	D	H	D
1 or 6	4.7					
2 or 7	5.4				19.0	6.2
3 or 8	5.0	3.0			72.0	8.0
4 or 9	4.8		1.0	2.7	65.0	8.5
5 or 10	2.6				87.0	5.3
D-standard 2	5.1 (5.3)				b/g	7.5

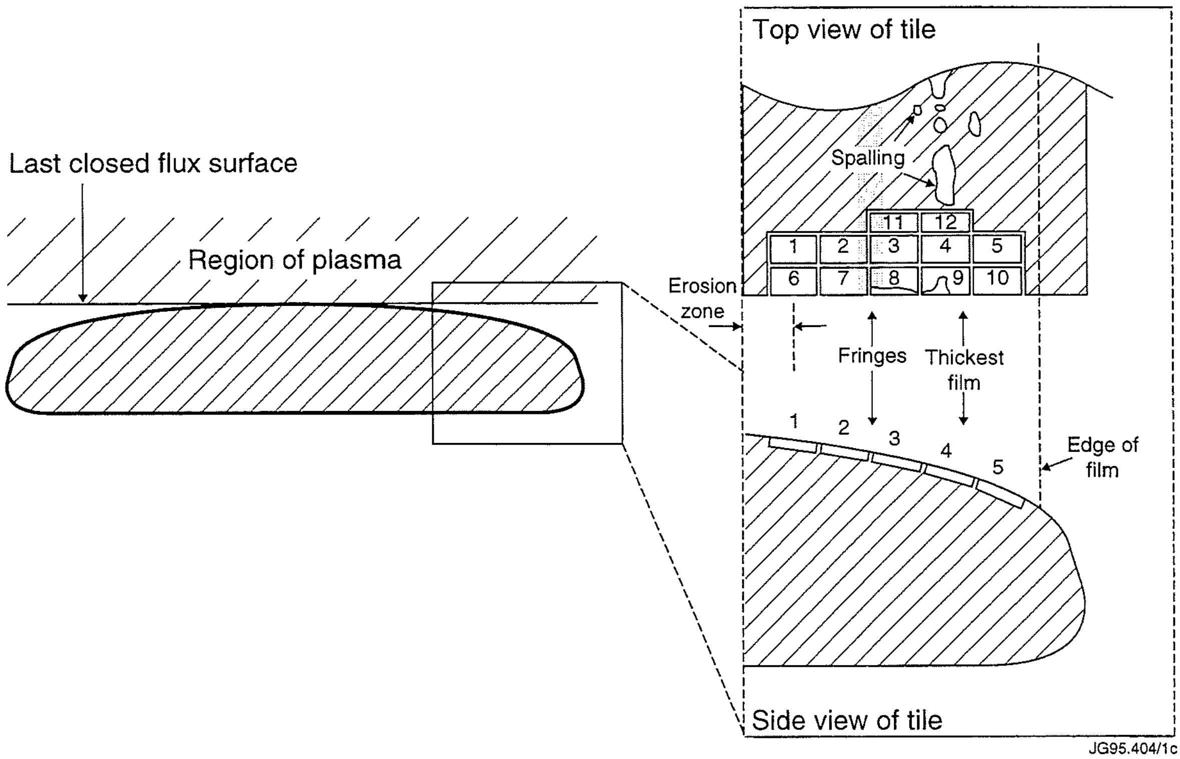

Fig.1: A diagram showing the original locations of the samples cut from a JET limiter tile used in this study, and the position of the tile relative to the JET plasma.

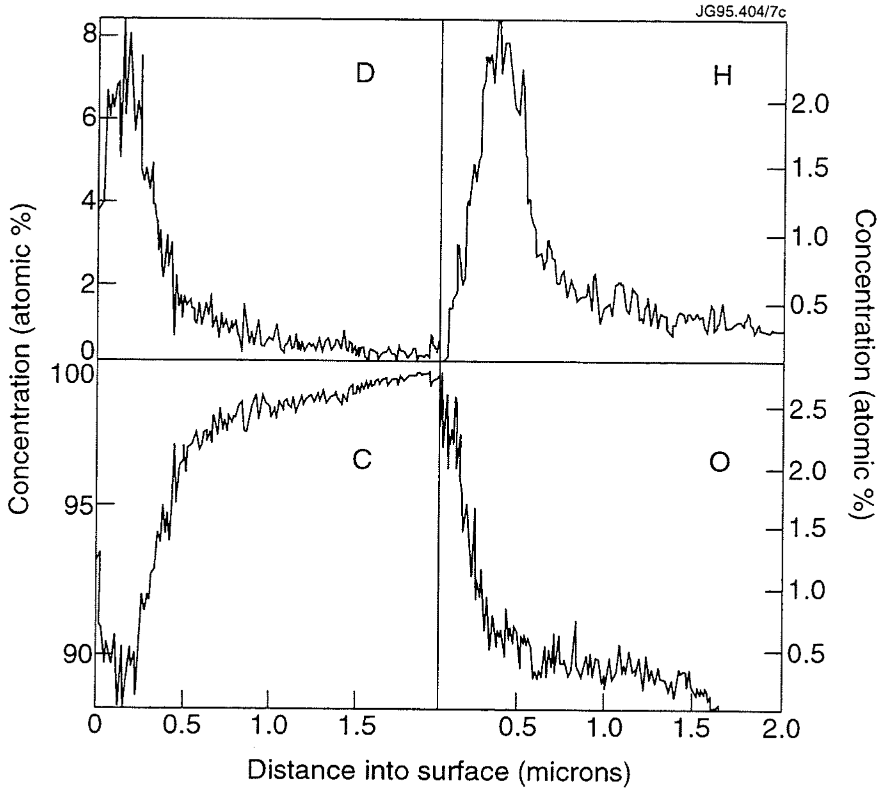

Fig.2: Depth distributions for masses 1, 2, 12 and 16 (H, D, C and O, respectively) determined by Heavy Ion ERDA in sample 8.

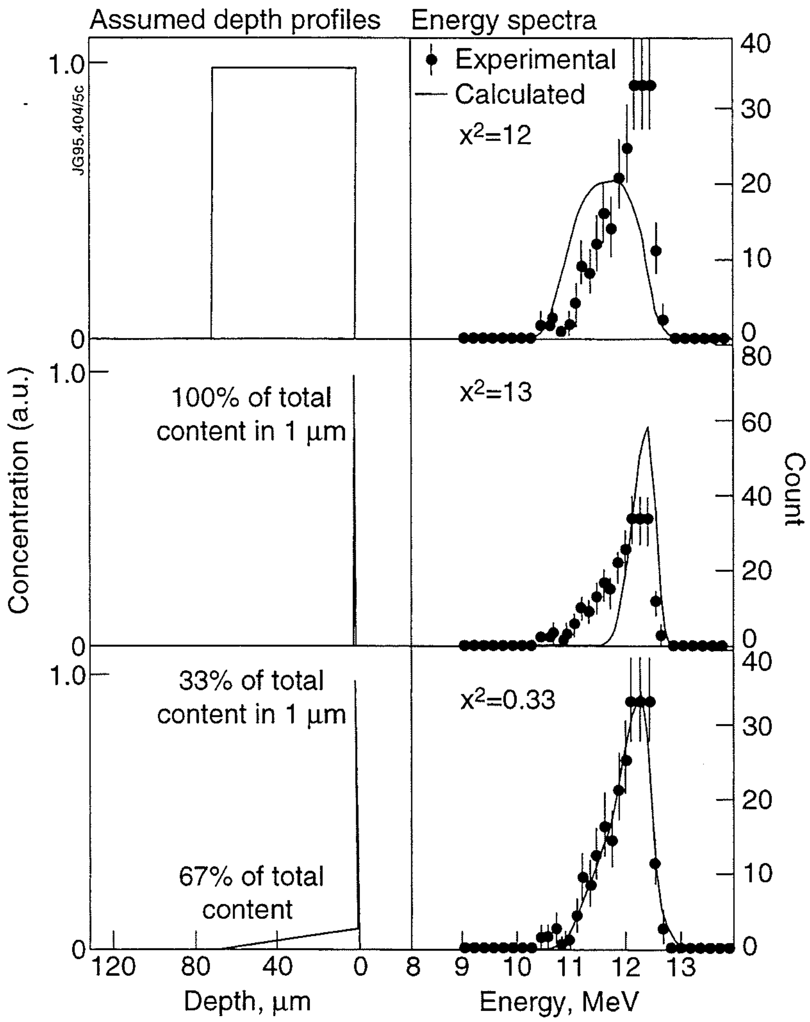

Fig.3: The n-ERDA spectrum for D from sample 4 compared with the calculated spectrum expected for each of three different D depth distributions in the film.

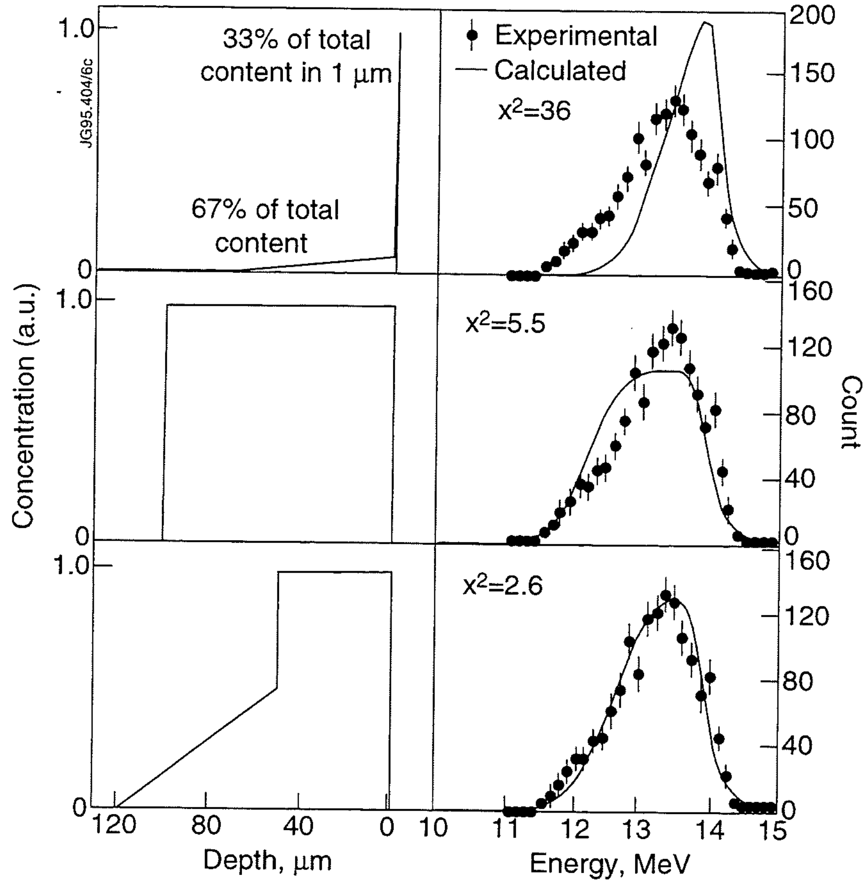

Fig.4: The n-ERDA spectrum for H from sample 4 compared with the calculated spectrum expected for each of three different H depth distributions in the film.

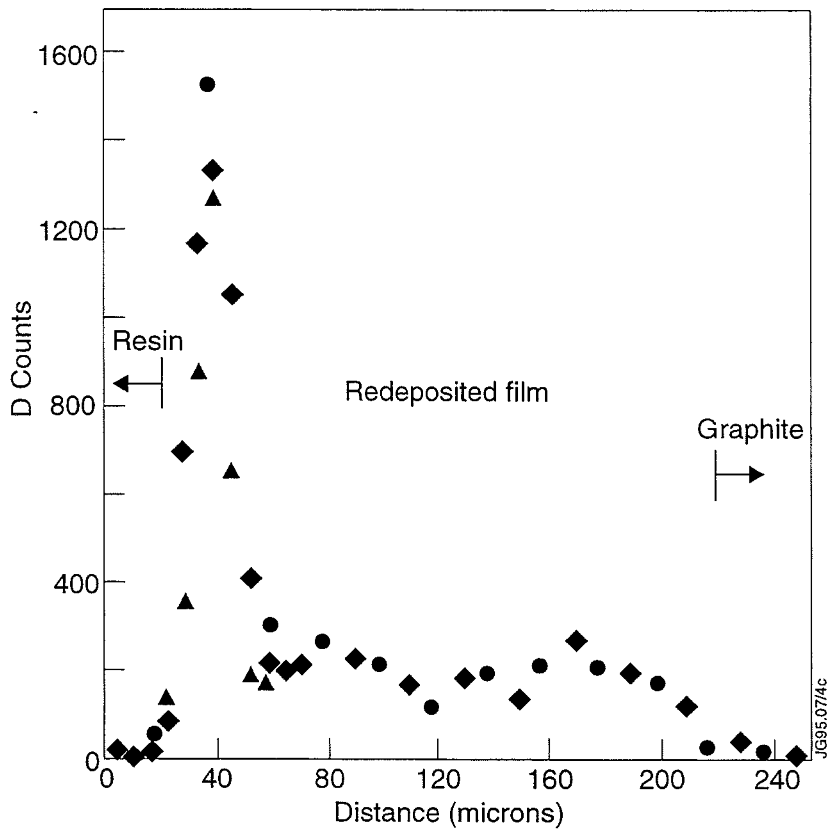

Fig.5: The D peak intensity versus distance across the taper section of a redeposited film obtained by NRA using a Nuclear Microprobe.

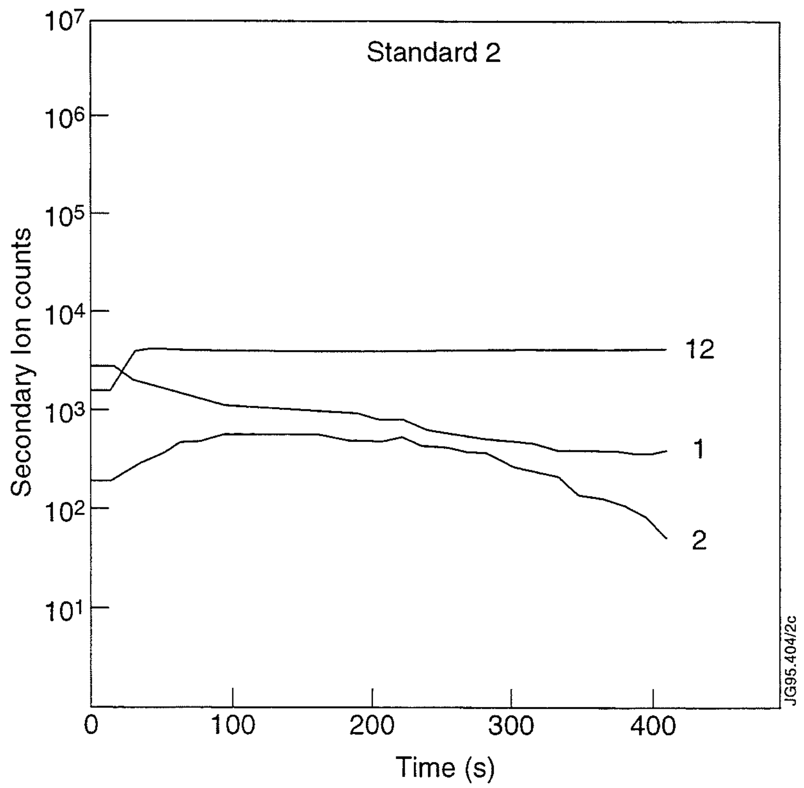

Fig.6: Signal intensities for masses 1, 2 and 12 (H, D and C, respectively) versus sputtering time (i.e. depth) into a D-implanted graphite standard.

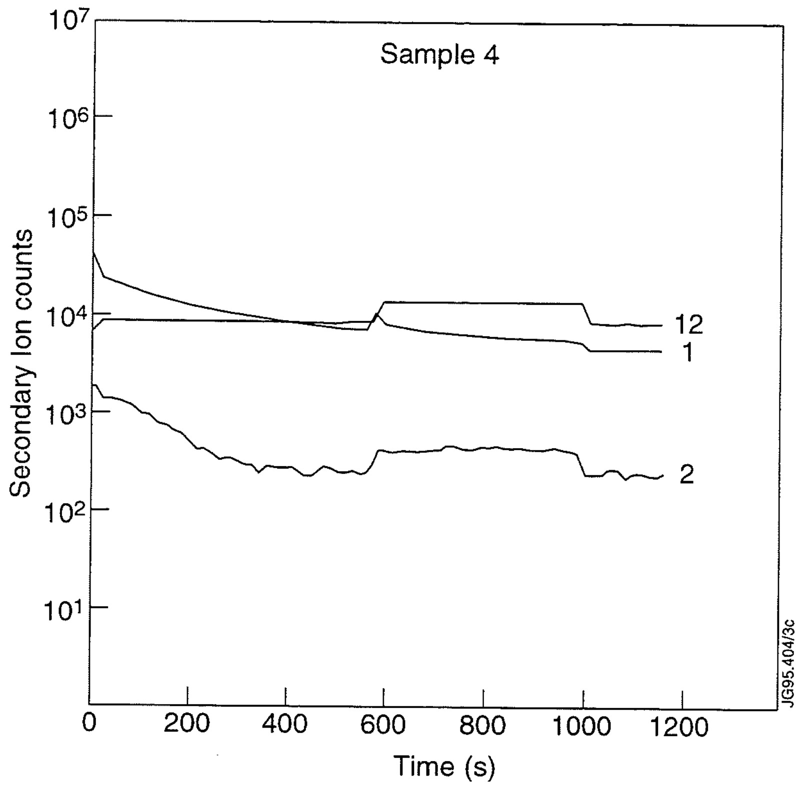

Fig.7: Signal intensities for masses 1, 2 and 12 (H, D and C, respectively) versus sputtering time (i.e. depth) into sample 4.

THE EXPERIENCE WITH JET'S COMBINED DC/RF GLOW DISCHARGE CLEANING (GDC) SYSTEM.

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The JET Tokamak was fitted with four new electrodes of novel design each powered from individual computer controlled DC and RF supplies. Details of enhancements and problems from 15 months experience with the system, are outlined. Experiments were performed to assess the effect of RF on the glow discharge characteristics, and to establish stable glow at low pressure and high voltage. For JET combined RF/DC GDC had no significant advantages over pure DC GDC, provided highly stable DC current control was obtained. In fact, the mechanically weak electrode inductor spiral required to allow RF posed a distinct disadvantage. The electrodes were converted to simple plates, following damage caused by halo currents during Tokamak plasmas disruptions. The performance of these electrodes is assessed. Future developments in the JET GDC system, are outlined.

INTRODUCTION.

Glow discharge cleaning has always played an important role for vessel conditioning in JET following intervention or leaks[1] and for maintaining good vacuum conditions. This includes helium glow for desorption of hydrogen species from the carbon and beryllium tiles so as to reduce uncontrolled gas recycling contributions to tokamak plasma fuelling. The JET vessel (189 m^3) was fitted with four new electrodes of novel design[2], each powered from individual computer controlled DC and RF supplies for the JET pumped divertor operation phase. Each electrode consisted of, a pair of flat inconel plates (~250 cm^2) forming 1000pF of capacitance to the vessel wall and a centrally mounted spiral coil making a series 1uH inductor. The combined output of a DC power supply and a RF generator was coupled into a coaxial line feeding the electrode/antenna which formed a LC resonant circuit. The electrodes were mounted symmetrically at the top of the JET vessel(Fig1). The main advantages which were expected using combined DC/RF GDC (also known as RG cleaning[3]) over a pure DC system were lower glow striking pressure and lower sustainable glow pressure.

THE EXPERIENCE WITH THE NEW JET GDC SYSTEM.

GDC has been used routinely between February 94 and June 95, for vessel conditioning in support of pumped divertor tokamak operations. Gas pressures in the 10^{-3}mbar range and currents of 3A to 4A per electrode gave optimum performance. The most effective scenarios were:

◊ Following interventions or large air leaks, a period of vessel baking at 320°C, 24 hours of deuterium glow, followed by approximately 48 hours of helium glow;

◊ During JET operations, when the vessel is kept at 250 ^{0}C, regular overnight pure helium glow following a regeneration of the in-vessel cryo-pump helium loop and prior to beryllium evaporation.

A computer control sequence was developed and commissioned to make the running of GDC a simple and highly automated operation. The sequence ensures that the many systems on the JET Torus are in the correct state for GDC, switches on the power supplies and triggers the initial gas inlet to initiate and sustain the glow. The overview display (mimic) is shown in Fig. 2.

The problems experienced with the initial system, which have lead to enhancement or modification, are detailed below:

- *Leakage current in JET coils.*

Magnetic fields confined the glow discharge to a small area of the Torus if any poloidal, toroidal or divertor coil were subject to leakage currents (<200A). Checks were added to the GDC control sequence to ensure all coils were fully isolated and earthed prior the start of a glow.

- *Danger of electrode spirals over heating.*

The heat load on the electrode significantly increases as the pressure is reduced into the 10^{-4} mbar range. Red to white hot electrode spirals were observed at low pressure when discharge currents were increased above 2A (Fig 3). The plate part of the electrode remains cool due to good thermal contact with the wall, but the coil with limited thermal contact heats up. A fault caused a DC power supply to drive it's maximum current of 20A in one instance. This condition, if combined with low pressure, could melt the electrode. To guarantee that such conditions were avoided, independent hard wired current trips had to be installed limiting the current to 6A per electrode.

- *Discharges within the vacuum feedthrough.*

A coaxial double electrical feedthrough makes the connection through vessel ports to each electrode. The feedthrough interspaces, normally at atmosphere, were pumped down to rough vacuum for leak testing and, inadvertently, not vented prior to GDC. Glow and small arc discharges occurred within the interspaces causing heating, sputtering of the copper conductors and opening of leaks. The feedthroughs were repaired by remaking the electrical connections and filling with silicon rubber. A solid interspace will be used in the future.

- *Instability of the DC power supplies.*

Each of the DC power supplies (20A, 1500V) is based on full bridge series and parallel resonant power converters operating at resonant frequencies of 100kHz and 20kHz respectively . They have a voltage control mode which typically limits the output voltage when glow is not present and a current control mode for supplying glow current. The analogue control circuits use proportional/integral feedback loops. The current control was stable when driving a dummy resistive load, but when driving a glow discharge a full wave modulation at between 0.5 and 1kHz regularly occurred. The unstable DC supplies were effectively used for GDC[4] (glow pressure > 2×10^{-3} mbar) over a period of 9 months. The

RF sustained the glow when the DC current dipped to zero. The problems were slow to be identified because the data acquisition used for monitoring filtered out the modulation.

It was not possible to obtain a satisfactory low pressure high voltage glow without stabilisation of the DC power supplies. They were stabilised by applying analytical and simulation techniques to reposition the poles and zeros of the current control loop. With highly stable DC supplies the sustainable glow pressure could be reduced and hence GDC at much higher DC voltage performed.

RG cleaning was done with helium on JET at less than 1×10^{-3} mbar and a glow voltage of up to 750V. The benefits of higher voltage glow were:

◊ A more uniform current density over the whole of the Torus giving higher current densities in the important divertor region;

◊ A generally greater cleaning efficiency (eg. for CO and CO_2).

However, the increased energy and hence penetration potential of helium ions caused the carbon tiles to become saturated with helium which had an overall detrimental effect on plasma operation.

- *Interactions between Tokamak plasmas and the inductor spiral of the GDC electrodes.*

High current disruptions, with uncontrolled upward movement of the plasma, occurred during high performance Tokamak operations. Investigation confirmed that in these circumstances the electrodes were not fully protected from the plasma by the surrounding carbon tiles and that during some disruptions large currents (>500A) were flowing through parts of electrode spirals. This caused large bending moments on the spirals and one was bent to the extent that it protruded into the vessel past all protective tiles. Tests showed that with stable DC supplies

RF assistance did not help the glow discharge (see below). Thus the inductor spirals were removed from all electrodes leaving a flat plate which could be used only for DC GDC.

THE EFFECTS RF ON GDC.

The original JET RG cleaning system[5] had an unstable DC glow characteristic with 100% modulation at 300Hz. Hence, most JET experience of RG cleaning had been with unstable DC supplies. Once the control loops of the new supplies had been stabilised the real effects of RF on the glow discharge were assessed. A test vessel (1.5m^3 inconel) was connected to a set of JET GDC power supplies to allow extensive testing.

Does RF assist in the maintenance of glow at low pressures?

Glow discharge could be sustained at low pressures ($<1\times10^{-3}$ mbar) with pure DC. The glow voltage/pressure characteristics with and without RF (Fig. 4) show how the voltage required to maintain constant current glow significantly increases as the pressure is reduced. At 1000V DC steady conditions prevailed provided the pressure was sensitively controlled. At higher pressures RF reduces the DC voltage required to drive a constant current. However, we observed, as the pressure is reduced there is a cross over point beyond which the RF increases the required DC voltage. Consistent results were obtained on the Torus.

It has been extensively reported that RF helps sustain glow at low pressure [6] [7] [8] [9]. Our experience with stable DC supplies, does not support this. The difference in results can possibly be explained by the differences in the geometry of electrodes and vessels. The experience of D111-D was that RF assistance did not appreciably affect the pressure range over which glow could operate [9]. The experience of JET is that RF assistance offers no advantage for the maintenance of glow at low pressure.

Does RF reduce the striking pressure required to start a glow discharge?

On the test tank, the gas pressure was slowly increased to determine the minimum neutral gas pressure to initiate a glow discharge (strike pressure). The strike pressure for the pure RF discharge, the pure DC discharge and the RG discharge were determined for various DC voltages and RF power levels. The strike pressure/voltage characteristic for the RG discharge closely followed that of the pure DC discharge, the RF power level having negligible effect. The strike pressure (5×10^{-2} mbar He or 2.5×10^{-2} mbar D_2) for a pure RF discharge with 150W was approximately the same as for DC or RG discharge with 1200V DC.

A puff of gas is used to initiate glow on the Torus. Glow consistently strikes if the momentary peak pressure reaches 1.5×10^{-1} mbar in helium with 1200V DC, with or without RF. Glow can regularly be struck at lower pressure, but occasionally fails. When the Torus is particularly well conditioned higher pressure is required to strike glow.

The reductions in strike pressure for the RG discharge over the pure DC discharge observed by F. Waelbroeck *et al* [6] have not been observed at JET with stable DC supplies. However these reductions were quite small (33%) at higher DC voltages (>1000V). At JET RF was used to best effect when the RF discharge was initialised prior to adding the DC component. Nevertheless RF (>150W) did not give a lower striking pressure than could be obtained with 1200V pure DC.

THE SIMPLE PLATE ELECTRODE.

Six months experience has been gained of DC only GDC with simple plate electrodes (Fig. 5) attached to the wall of JET. No disadvantages have been experienced, in comparison with the RG cleaning system, with respect to cleaning rates, glow stability or striking pressures. The simple plate electrode has proven to be very effective and offers a number of useful features. Namely, it is very compact, robust, and has high glow power handling capability (>10kW) without active cooling, due to good thermal contact with the wall.

MODIFICATIONS FOR THE FUTURE.

DC only glow with simple plate electrodes will continue to be used at JET. A new gas introduction system is being installed which will enable the flow of different glow gases to be computer controlled as part of the glow control sequence. This will allow glow to be initiated in Deuterium (with lower strike pressure and less effect on cryo-pumps) and continued in Helium. Glow with gas mixtures could also be done. Further operational advantages may be gained with a lower strike pressure. The addition of an electron gun [11], to assist the initial ionisation, is thought to be the most effective way of achieving this.

CONCLUSIONS

A new glow discharge cleaning system has been used effectively in support of JET pumped divertor operation. The experience has led to modification and enhancements to the system's control sequences and hardware, the most significant being the stabilisation of the DC power supplies and removal of the mechanically weak electrode spirals required to couple RF.

On JET, combined RF/DC GDC gave no advantages over pure DC GDC once the feedback control loops of our DC power supplies were stabilised. Stable DC only GDC could be performed at pressures below 1×10^{-3} mbar. At low pressures RF increases the DC voltage required to sustain a constant current glow.

JET will continue to use the DC only flat plate electrode geometry due to its effectiveness, simplicity and robustness.

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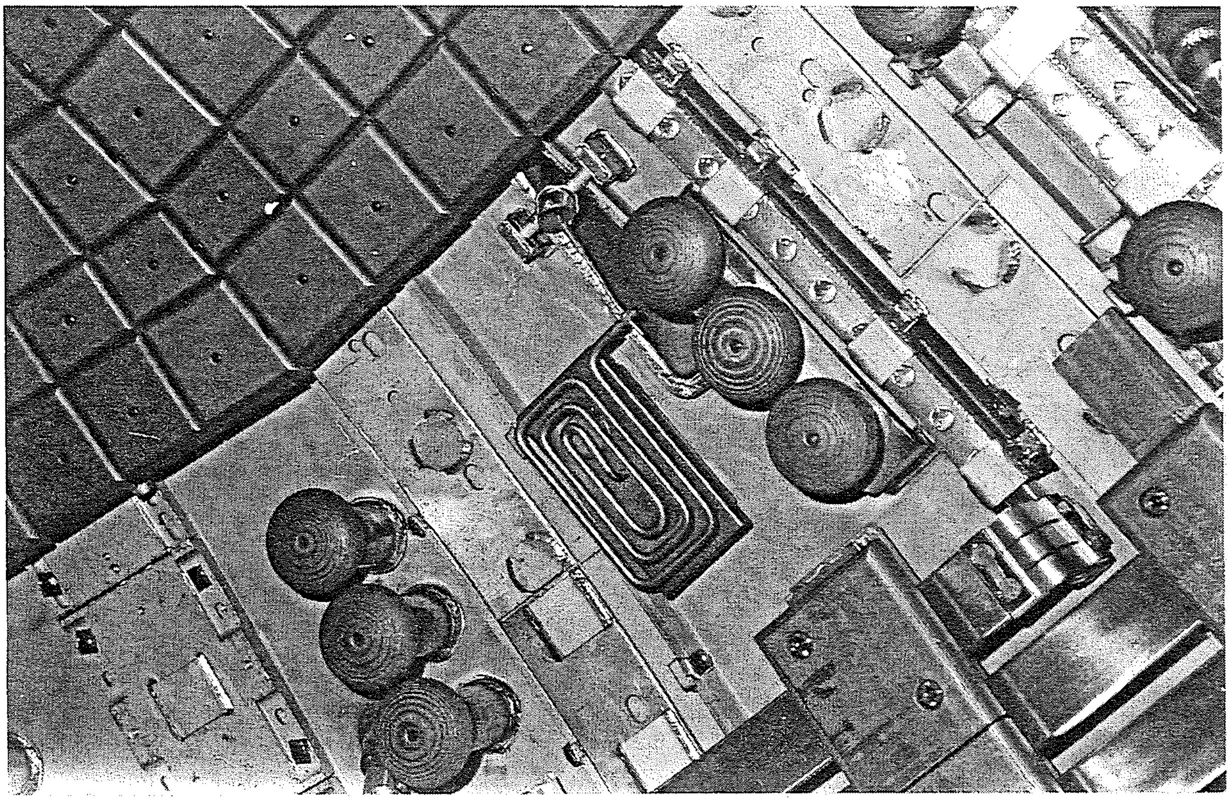

Fig.1: GDC electrode with inductor spiral attached to the upper wall of the JET vessel.

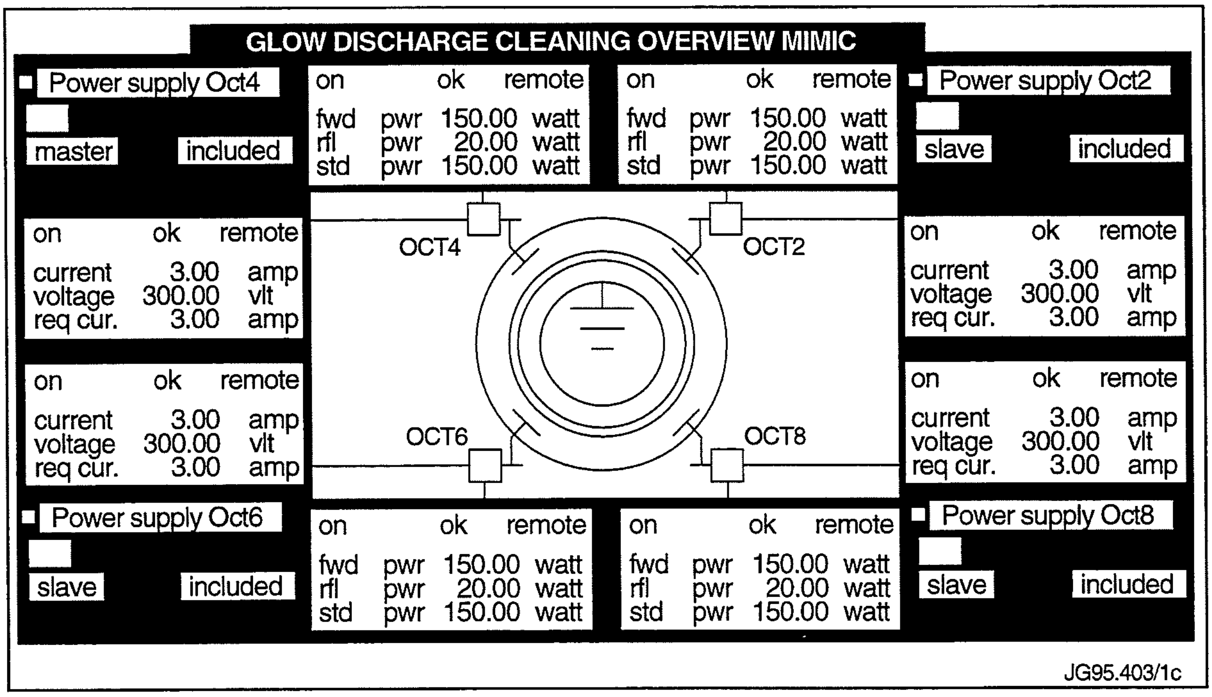

Fig.2: Overview "mimic" of the GDC system.

Fig.3: Heating effect on an electrode of a low pressure deuterium glow (glow current 5A, DC voltage 1000V, pressure 7×10^{-4}mbar.)

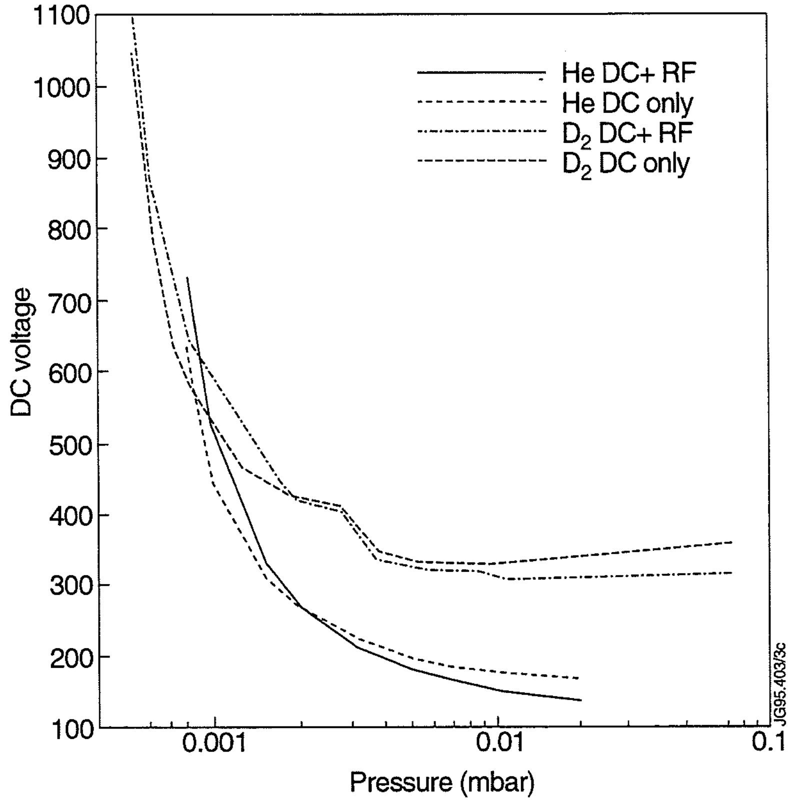

Fig.4: Voltage/pressure characteristic for a 1A glow discharge, with and without RF.

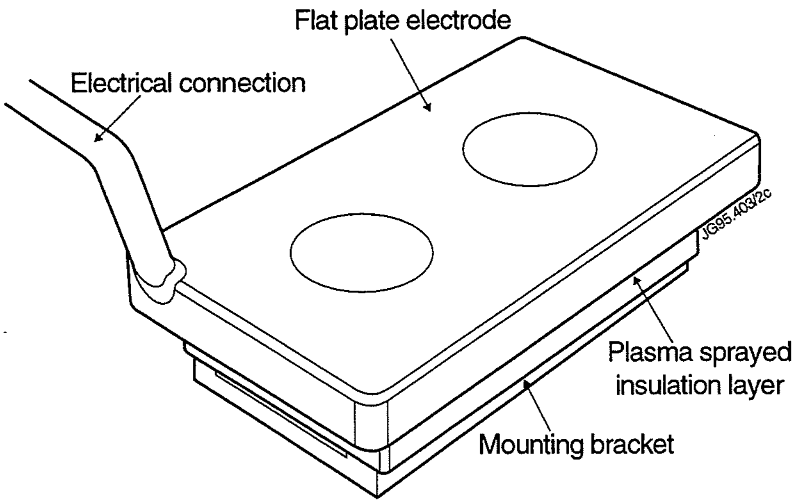

Fig.5: Simple plate electrode.