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REPORT ON THE 8TH INTERNATIONAL CONFERENCE, JÜLICH, F.R.G., 2ND-6TH MAY 1988

by

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PLASMA - SURFACE INTERACTIONS IN CONTROLLED FUSION DEVICES

Report on the 8th International Conference
Jülich, Federal Republic of Germany, 2-6 May 1988

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The Eighth International Conference on Plasma-Surface Interactions in Controlled Fusion Devices was held in Jülich, Federal Republic of Germany and was organised and sponsored by Kernforschungsanlage Jülich GmbH. The meeting was attended by nearly 300 scientists who presented about 180 papers including 17 invited papers.

This series of conferences, which started in 1974, provides a major bienniel forum for research in the pure and applied disciplines of surface and plasma physics. The first few meetings in this series were concerned mainly with fundamental surface studies, but in the more recent meetings the emphasis has shifted progressively towards in situ measurements in fusion devices and their interpretation in terms of plasma physics. This trend was continued in the present meeting. The majority of papers dealt with the plasma boundary in tokamaks. Only a few papers were concerned with other confinement systems or with fundamental processes.

This report is intended as a short survey of the conference for readers who are not necessarily specialists in this field. It must inevitably be highly selective of the many excellent papers which were presented. For more detailed information readers are referred to the conference proceedings, which, as for earlier meetings in this series, will be published as a special volume of the Journal of Nuclear Materials. There will be a separate review on the Plasma Boundary Theory Meeting which was held in Augustusburg during the week before the PSI Conference.

Plasma Edge Structure and Improved Confinement

In the first invited paper, S. A. Cohen (PPPL) reviewed the role of plasma surface interactions and the edge plasma in achieving H-modes. He pointed out that the improved confinement of the H mode is accompanied by several undesirable effects; uncontrolled density rise, impurity accumulation and high transient heat fluxes. However the divertor-like configurations are being chosen for many future machines, including ASDEX-U, CIT, INTOR, ITER, JIT AND NET) and it is therefore important to understand the role of the plasma boundary in these configurations.

M. A. Mahdavi (GA) described two different types of Edge Localised Modes, (ELMs) which occur in DIIID. One type has large amplitude ("giant" ELMs) and results in significant energy and particle losses, whereas the second type has much smaller amplitude and higher frequency ("grassy" ELMs) and does not result in significant energy or particle loss. The main factor which determines the type of ELM appears to be the distance separating the separatrix from the walls or limiter. As the distance is increased, the grassy ELMs are replaced by giant ELMs. Density and temperature profiles in DIIID before and after ELMs were compared. The gradients remained unchanged, but there was a significant loss of particles. The density inside the separatrix decreased and the scrape-off density increased about 1ms after an ELM. This was interpreted as being consistent with diffusive transport across field lines rather than parallel transport along field lines.

Plasma wall interactions in JET with different limiter and X-point configurations were reviewed by P. E. Stott (JET). An extensive data base for the scrape-off layer has been compiled and scalings with the core plasma parameters have been established. S. K. Erents (Culham) presented the results of probe measurements in JET with the newly installed carbon belt limiters. He showed radial profiles of density, temperature and floating potential with well identified changes in slope which were interpreted as locating the last closed flux surface.

Ion cyclotron heating in JET has been applied at powers up to 17 MW and several effects are seen which indicate a direct interaction with the scrape-off layer plasma. Particularly noticeable is the rapid time scale on which the scrape-off layer broadens when the heating pulse is applied.

This is faster than the time scale for energy and particles to be transported out from the core plasma. Direct heating of the scrape-off layer by ion cyclotron heating is also observed in Alcator C and TEXTOR. Results presented from Alcator showed density and temperature profiles broadening with ion cyclotron power and it was estimated that about 20% of the power went directly into the scrape-off layer. Results from TEXTOR showed strong effects on the density rise, instantaneous electron heating, modification of profiles etc during ion cyclotron heating. The scrape-off layer effects in Alcator C were found to be independent of the position of the ion cyclotron resonance layer, whereas experiments in DITE with electron cyclotron heating claimed that the boundary effects did depend on the position of the resonance layer.

U. Samm (KFA) reviewed plasma edge physics in the TEXTOR tokamak with poloidal and toroidal limiters. The e-folding length of the density profile close to the limiter is similar in both configurations, but the variation as the distance from the limiter is increased is less with the toroidal limiter than with the poloidal limiter. Samm drew attention to the steepness of the heat flux profiles in the boundary layer which means that considerable attention has to be given to the accuracy of blade location in the limiter design. The plasma interaction with the toroidal limiter shows a strong toroidal modulation which was interpreted as being due to the toroidal field ripple. Although the ripple is small, its effect is enhanced by the very steep profiles in the plasma scrape-off layer. Experiments in the T10 tokamak on the scaling of temperature in the scrape-off layer show that temperature varies inversely as the square of the mean density. This is consistent with earlier measurements in JET. R. Budny (PPPL) discussed the "q-mode" in TFTR which occurs at specific values of edge q. The mode is characterised by an increase in $\int ndl$ and a decrease in the $D\alpha$ light. This q-mode shows some of the aspects of a limiter H-mode. Its effect is interpreted as being due to magnetic islands distorting the scrape-off layer. This leads to an increase in the carbon influx. There is a decrease in the recycling coefficient and an increase in the particle confinement time.

Impurities

Impurity production and transport at limiters were discussed in an invited paper by G. F. Matthews (Culham). He presented results from DITE with a specially designed "impurity control" limiter where the surface in contact with the discharge is curved away from the discharge so that sputtered impurities are directed away from the discharge rather than towards it as in a conventional limiter. This geometry differs from a pump limiter which retains a section of surface facing the discharge in order to handle high power density. The geometry of the impurity control limiter results in a knife edge located in the region of highest power flux. The DITE results show that the limiter geometry plays an important role in determining the penetration of impurities into the plasma. Whilst this technique may not be useful in designing limiters which have to handle high power loads, it may have applications in the design of divertor plates for future experiments such as ITER.

The results with the DITE impurity control limiter show that in helium discharges Z_{eff} is reduced to 2.5 compared to 3.5 with a conventional limiter and the total radiated power falls by a factor 2. However, the improvement in deuterium discharges is much less marked; Z_{eff} does not change significantly and the radiated power falls by only 20%. The DITE measurements show that the carbon influx from the limiter in helium discharges is consistent with physical sputtering of carbon by helium together with self sputtering by carbon itself. In a deuterium discharge the measured influx of carbon is a factor 2 larger than in a helium discharge, whereas if physical sputtering by the deuterium plus self sputtering were the only release mechanisms, the influx would be expected to be smaller by a factor 5. A similar discrepancy in carbon influxes in hydrogenic discharges has been observed in other tokamaks including JET.

Chemical sputtering of carbon in hydrogenic plasmas leading to the formation of hydrocarbons has been previously proposed as a candidate mechanism for the enhanced influx of carbon. A paper by W. D. Langer (PPPL) described a model for carbon and methane production incorporating an improved data base for the ionisation of hydrocarbons into a modified version of the DEGAS code to model the transport processes which are significantly more complicated for hydrocarbons than for hydrogen due to the wider variety of molecular interactions. Measurements in DITE by G. F. Matthews (Culham) indicate that the mean energy of the carbon atom influx from the limiter is $\sim$ 1 eV. This is not consistent with the low energies ($\sim$ 0.1 eV) expected for ionisation of methane production by chemical sputtering. Spectroscopic measurements in DITE which were reported by S. J. Fielding (Culham) also give no indication of significant methane formation at the limiter. It appears from these results that chemical sputtering is not responsible for the enhanced influx of carbon in hydrogenic plasmas. This interpretation is consistent with data from several experiments.

An alternative explanation for the enhanced influx of carbon is that oxygen, which in deuterium plasmas is found in roughly equal concentrations to carbon, plays an important role in the release of carbon either by physical sputtering or via the formation of carbon monoxide. V. Phillips (KFA) described measurements in the scrape-off layer of TEXTOR which show that the impact of hydrogen, oxygen and carbon ions onto a carbon sample results in the formation of hydrocarbons, CO and CO_2. The chemical formation of CO due to the impact of the oxygen ions was observed to be 2-3 times larger than the formation of the hydrocarbons. There was no significant formation of H_2O molecules.

K Behringer (JET) reported that oxygen concentrations are very low in helium discharges in JET, and are well correlated with the residual deuterium flux, suggesting that a chemical mechanism is involved in the production of oxygen impurities. However a different behaviour in TEXTOR was reported by F. Waelbroeck (KFA), where it was found that the oxygen concentration in helium discharges was almost as large as in deuterium. To account for these results Waelbroeck proposed that physical rather than chemical processes determine the rate of oxygen release from carbonised walls, whereas with metal walls, oxides form and are reduced by hydrogenic fluxes.

G. M. McCracken (Culham) discussed impurity production at the tokamak wall. Again there seems to be a clear contrast between helium and hydrogen discharges. In helium the discharge interacts mainly with the limiter, but in hydrogen there is a strong interaction with, and impurity influx from the walls. McCracken proposed a complex mechanism where hydrogen reaches the wall by charge-exchange, releases carbon monoxide which is ionised in the scrape-off layer allowing oxygen ions to reach the limiter where they release carbon by sputtering. However the experimental data is sparse and there are some inconsistencies between different experiments. Further study is required in order to measure the fluxes to the wall and to conclusively identify the dominant release mechanisms. A paper by H. Verbeek (Garching) et al reported measurements in ASDEX of the neutral particle flux to the walls in the low energy range 10 eV to 1 keV and the associated impurity production. When the mean plasma density was increased, the flux of neutrals increased but their mean energy fell.

Measurements of the physical dimensions of the carbon limiters in JET after exposure to ∿ 3000 tokamak discharges show that net erosion occurs on the leading edge of the limiter, and net deposition occurs at larger radii. These results are consistent with a model of the scrape-off layer where erosion occurs in regions where the incident particle flux is sufficiently energetic to exceed the sputtering threshold, whilst deposition occurs at larger radii where the flux is less energetic. This processs also helps to clean up the limiters by eroding any metallic contamination from previous discharges and redepositing it at larger radii where it is buried under subsequent carbon layers. J. Roth (Garching) has measured the sputtering yields of the re-deposited layers and found them to be similar to the yields for bulk materials. However measurements reported by R. Behrisch (Garching) using a carbon collector probe show that erosion and re-deposition occur at the same radii sequentially during a single discharge. It appears that strong erosion occurs on the leading edge of the probe during the early part of the discharge and there is re-deposition onto the eroded area during the latter part of the discharge.

Several papers discussed the transport of impurities in the scrape-off layer. In ASDEX an influx of iron ∿ 4 x 10^{18} atoms s^{-1} was measured from the wall, released mainly by charge exchange sputtering, and an influx of copper (∿ 2 x10^{19} atoms s^{-1} in ohmic plasmas rising to ∿ 10^{20} atoms s^{-1} with 2.4 MW NBI) from the divertor plates, released mainly by deuterium ion sputtering. About 50% of the iron returned to the wall, about 45% went to the divertor shields and only 10% reached the divertor plates. In contrast 80% of the copper went to the divertor shield and very little returned to the plates. Measurements of carbon fluxes in the scrape-off layer were reported from TEXTOR. The peak deposition rate was ∿ 2 x 10^{16} atoms cm^{-2} s^{-1} and the measurements were consistent with the carbon being transported predominantly along magnetic field lines without any significant poloidal transport.

Impurity accumulation in ASDEX in regimes with good energy confinement was reviewed by G. Fussmann (Garching). Accumulation occurs in the H-mode and is also observed in discharges with pellet refuelling or counter neutral beam injection. Improved particle confinement makes control of the density more difficult and can become a severe problem in high recycling conditions - for example with carbonised walls or large areas of carbon tiles. The simultaneous improvement in impurity confinement also leads to critical problems. Accumulation of high Z impurities in the core leads to strong radiation cooling, whilst high concentrations of low Z impurities seriously dilute the deuterons. G. Fussmann pointed out that an improvement of confinement is of benefit only if impurity influxes can be kept to very low levels. These observations are generally consistent with the predictions of neoclassical transport theory, but there are also some discrepancies. There is also disagreement with other experiments, notably JET where K. Behringer (JET) reported that impurity accumulation is rarely seen. Likewise M. A. Mahdavi (GA) reported from DIIID that there is no impurity accumulation, and in fact on some occasions the impurity concentration falls during H modes.

Hydrogen Recycling and Wall Pumping

An invited paper by J. Ehrenberg (JET) reviewed the recycling of helium and hydrogen in tokamaks with carbon walls. He drew attention to the different recycling behaviour seen in TEXTOR and JET and pointed out that this could be due to either material or temperature differences between the two experiments. Strong pumping of discharges limited on carbon tiles on the inner wall has been observed in several tokamaks including JET, TEXT, TEXTOR, TFTR, PDX and ASDEX and is widely used in these experiments as an operational tool for density control. An interesting observation in JET is that although the discharge is strongly pumped whilst on the inner wall, when it is moved back onto the outboard limiter, it quickly regains the same density as a discharge which has always remained on the outboard limiter. Ehrenberg reminded us that there is a continuous exchange of particles between the discharge and the surrounding surfaces which contain a very large reservoir of gas.

Disturbing the steady state conditions of these surfaces, for example by helium discharge cleaning which depletes the hydrogen reservoir or by hydrogen discharge cleaning which adds to it, will lead to corresponding changes in the recycling behaviour of the discharge. Ehrenberg discussed the interpretation of experimental data in terms of a recycling model and concluded that gas is retained in the wall by diffusive-like processes.

Experimental data for the ion-induced release of hydrogen from carbon by low energy (300 - 500 eV) helium ions was presented in a paper by R. A. Langley (ORNL). These data extend earlier results by other authors to energies relevant to the scrape-off layer and to conditioning discharges. The depletion depth is considerably shorter than would be expected if helium - hydrogen collisions were the dominant detrapping mechanism and suggests that helium - carbon collisions may be the dominant process.

In DIIID, reduced recycling, improved density control and a modest improvement in energy confinement were obtained by conditioning the carbon divertor tiles with helium glow discharge cleaning before each tokamak discharge. This procedure made the H-mode regime easier to obtain, particularly at low heating power. DIIID also reported an improved confinement regime in low q ($2 < q < 2.6$) discharges with no additional heating ("Ohmic H-mode"). Energy confinement times were improved by up to 50%, and the Dα light emission reduced by $\sim$3.

N. Hosogane (JAERI) described the effects of changing the JT-60 walls from metal (titanium carbide coated molybdenum) to carbon. With the metal walls there was a high recycling in the divertor chamber with a compression ratio (divertor pressure divided by torus pressure) of the order of 45. The pressure in the divertor and in the main torus increased with the square of the mean density. The particle exhaust by the divertor was effective at densities up to 6×10^{19} m^{-3}. With metal walls Z_{eff} was in the range 1.5 to 2 and 10% of the input power was radiated, showing the ability of the divertor to control impurities. With carbon walls the radiated power went up to 20% in the divertor configuration and to 35% in the limiter configuration. The H-mode has been achieved in the outside X-point divertor configuration but the threshold heating power is high (> 16MW), the H-mode duration is relatively short and there is only a modest (∿ 10%) increase in energy confinement.

The effect of wall temperature in the range 150 to 300°C on recycling was discussed in results from JT-60. The higher wall temperature was effective in reducing recycling, improving density control and improving recovery after a disruption.

Divertors

Recycling and neutral gas transport in the vicinity of the divertor X-point in DIIID were discussed by S. Allen (GA). The neutral gas transport was modelled by the DEGAS code, giving good qualitative and reasonable quantitative agreement with experimental measurements of the $H\alpha$ light emission and neutral gas pressure. The $H\alpha$ light emission in DIIID is poloidally asymmetric. It is larger on the inboard side of the X-point than at the outboard side. A similar asymmetry in the $H\alpha$ emission, and also in the radiated power was reported for JET. P. J. Harbour (JET) pointed out that this is consistent with the magnetic geometry of the scrape-off layer and with the power flowing from the core of the discharge into the scrape-off layer being strongest at the outboard mid plane. Measurements with probes close to the JET X-point have shown that the electron temperature is lower (∿ 10 eV) and the density higher (∿ 9×10^{19} m^{-3}) at the inboard region than at the outboard region (30 eV and 3×10^{19} m^{-3}). Thus there is a net flow of electric current through the scrape-off layer from the outer to the inner region, and an electric current density ∿ 10 A cm^{-2}, comparable to the ion saturation flux in the divertor, has been measured.

K. McCormick (Garching) reported that the scrape-off layer density and scale length in ASDEX remain constant during the H mode when the mean core density increases. Density profiles in ASDEX and JET both show that the density gradient inside the separatrix increased and the scrape-off density decreases during the H mode transition. Several papers from the ASDEX group reported the changes in plasma behaviour following modifications to the divertor geometry and material. The new arrangement appears to have a detrimental effect on achieving the H-mode but has resulted in improved confinement in ohmic discharges. These results indicate that confinement is strongly coupled to conditions at the plasma boundary.

Pump Limiters

An invited paper by G. M. Goebel (UCLA) et al reported the results of the ALT II pump limiter in TEXTOR. The limiter is a toroidal belt of 8 segments of inconel blades covered with carbon tiles. Only 2 of the 8 blades are pumped and a pumping speed ∿ 5000 ℓs^{-1} is achieved with getter and turbomolecular pumps. The exhaust efficiency is < 1% and is independent of the mean plasma density. It is estimated that if all 8 blades were pumped the efficiency would be ∿ 5%, and that this could be further improved by fitting additional scoops and pumps. The heat flux on the limiter is non uniform toroidally due to toroidal field ripple. It is also poloidally assymetric with the flux to the ion drift side exceeding that the the electron drift side by a factor 2-3. Results from the DITE pump limiter reported that best performance is obtained in helium discharges where ∿ 6% of the particles leaving the discharge are collected by the pump limiter.

Preliminary resonant helical divertor experiments were reported from JIPPTII. A limiter blade is inserted into a coherent magnetic island, and most of the energy is observed to be concentrated onto the tip of the blade.

Wall & Limiter Conditioning

A recent trend in many tokamaks has been the progressive introduction of large quantities of carbon in the form of limiters, divertor plates and protective tiles. For example TFTR and JET now contain several tonnes of carbon. In many tokamaks a large fraction of the wall area is now covered in carbon tiles or as a deposited carbonised layer. Whilst this has had the beneficial effect of reducing high metallic impurities, the high porosity of carbon and its ability to retain large amounts of hydrogen and water have necessitated revised techniques for conditioning the walls and limiters.

A paper from JT-60 described typical cleaning and conditioning procedures following the installation of new carbon tiles. The torus was first baked at 300°C for 3 days, followed by 18 hours of glow discharge cleaning, 36 hours Taylor discharge cleaning at 280°C. After this the recycling coefficient was less than unity and effective density control was obtained, but further conditioning was needed at regular intervals during subsequent tokamak discharges to maintain the density control.

An invited paper by H. F. Dylla (PPPL) reviewed the experience of first wall conditioning in TFTR. He described the conditions necessary to produce the enhanced energy confinement regime (the so-called "supershots") which had reached ion temperatures up to 22 keV in 1986 and up to 30 keV in 1987. Two factors are important; balanced neutral beam injection which heats the discharge and provides deep refueling of the core, and control of recycling. The key to controlling recycling in a tokamak with carbon walls and limiters is extensive helium discharge conditioning. H. F. Dylla reported that helium is more effective than hydrogen in removing oxygen from carbon surfaces and moreover strongly depletes the hydrogen absorbed in the near surface layers leading to a strong pumping action in subsequent hydrogen discharges. These conditioning discharges contain large amounts of carbon ($Z_{eff} \sim 6$!). W. R. Wampler (Sandia) has measured the release of deuterium from carbon during bombardment by low energy helium and carbon ions, and found that the amount of deuterium which can be removed ($\sim 2 \times 10^{20}$ D m^{-2}) is close to the pumping capacity produced by the supershot conditioning procedure in TFTR.

Carbonisation, pioneered first in TEXTOR, has become well established as a means of reducing high Z impurities in metal walled tokamaks, and has also found application in some other confinement geometries. Carbonisation of T-10 was carried out at low wall temperature (∿ 100°C) and effectively reduced the metallic influx (chromium) but increased the hydrogen influx. In common with the experience in other tokamaks, the first discharge after carbonisation was dominated by a large influx of hydrogen, which was reduced to a negligible level only after several days of operation. Carbonisation continues to be applied routinely in TEXTOR and long term samples analysed after many months of operation showed films 10 - 35 µm thick with under-stoichiometric concentrations of carbide and an excess of ∿ 10% carbon near to the surface. Several papers discussed the properties of these amorphous hydrogenated carbon films, including measurements of the trapping, permeation and release of hydrogen.

A new development was the boronisation reported from TEXTOR by J. Winter and F. Waelbrock (KFA). Several other papers discussed the chemical vapour deposition process and the properties of boron carbon films. A layer of boron and carbon was deposited on the walls at a temperature of 300 - 350°C by a glow discharge in a mixture of 0.8 He + 0.1 B_2H_6 + 0.1 CH_4. The average film thickness was 30 - 50 nm and the composition measured by AES was 50% boron and 50% carbon. Subsequent tokamak discharges had low radiated power (P_{rad} fell from 80% to 30%) and a strong increase in the conducted power loading of the limiters which rose by a factor ∿ 3.5. The main change appears to be a marked reduction in oxygen concentration which fell by a factor of ∿ 8. There was a corresponding reduction in the CO and CO_2 concentrations measured in the scrape-off layer. The concentration of carbon in the discharge fell by a factor 2. The coating also resulted in considerably reduced recycling from carbonised walls. ICRH could be applied with little or no density rise compared to before boronisation when ICRH resulted in a considerable increase in density. The improved conditions persisted for more than 200 discharges including many at high powers of ion cyclotron heating (> 2MW). This new and potentially valuable technique will no doubt find application in other tokamaks.

Hydrogen in Metals & Material Properties

An invited paper by W. Moeller (Garching) reviewed the trapping and transport of hydrogen in carbon and carbonised layers. He discussed the implantation of hydrogen in the near surface layer and identified the release mechanism as molecular formation in the deposition zone followed by diffusion back to the surface. The local saturation and mixing model, which is based on the assumption of a maximum hydrogen concentration that the material can accommodate, gives a simple but adequate description of the amount of implanted hydrogen as a function of the implantation energy. Saturation of the implanted layer occurs in a relatively short time and leads to recycling. This is supported by measurements of deuterium concentrations measured by R. Behrisch (Garching) in carbon probes exposed in JET. The measured deuterium is well correlated with the amount of deposited carbon (in the ratio D:C between 0.24 and 0.33 which is close to the expected saturation values). These concentrations are up to two orders of magnitude smaller than the deuterium fluence calculated from scrape-off layer parameters. Clearly at the low energies typical of the scrape-off layer the deuterium rapidly reaches saturation, and the total concentration is determined by the codeposition of carbon. Measurements of the codeposition of carbon and deuterium in TFTR reported by S. J. Kilpatrick (PPPL) showed that the D:C concentration was in the range 0.28 to 1.15, with most values around 0.4 to 0.6 which is close to the expected saturation value.

R. Causey (Livermore) discussed the retention of tritium in graphite and its consequencies for tokamak reactors. Carbon is the leading material in present day fusion experiments because it has low Z and good thermal properties, but its drawbacks are high porosity and affinity for hydrogen. He described four processes leading to tritium retention; surface saturation, porosity, co-deposition and transgrannular diffusion and trapping. Co-deposition is the most important process, but the other mechanisms will also be significant in TFTR and CIT, whereas the effect of the saturated layer and porosity will be insignificant in ITER due to the proposed high operating temperature. Thermal desorption or glow discharge cleaning are efficient for removing the tritium from co-deposited layers, but temperatures in excess of 1000°C will be needed to remove the bulk deposition efficiently. R. Causey also briefly reported some recent experiments where tritiated samples of carbon were exposed to air, and some 50% of the tritium was released immediately as water. Measurements of deuterium and tritium distributions in JET and their implications for the tritium inventory were discussed in papers by P. Coad (JET) and D.H. Goodall (Culham).

Other Confinement Systems

Although the majority of papers at this meeting were concerned with tokamaks, there were a few which reported studies in other configurations. Plasma wall interactions in reversed field pinches were discussed in papers by A. Matsuoka et al (Nagoya) and by M. Bagatin and S. Ortolani (Padua). The initial operation of the ATF torsation was reported by P. Mioduszewski (ORNL) and the edge plasma in the L2 stellarator was discussed by M. S. Berezhetskij (IGP, Moscow). The effects of carbonisation and carbon tiles were compared in a paper by the Heliotron E group who found that carbonisation of the whole wall reduced the iron flux by a factor between 10 and 30 whereas carbon tiles on the walls in the separatrix areas made little improvement. These results suggest that the dominant release mechanism in this device is due to wall sputtering by charge exchange neutrals.

Studies of plasma surface interactions in the Tandem Mirror Gamma were reported by Y. Nakashima et al (Tsukaba). Electron cyclotron resonance cleaning discharges had significant effect on the wall recycling, and reduced light impurity spectral intensities by up to an order of magnitude.

New Machines & Future Developments

Preliminary results were reported from several new machines, including the Tokamak de Varennes, TORE-SUPRA and the torsatron ATF. The main emphasis in these papers was on the choice of materials for walls, limiters etc and the cleaning and conditioning procedures which had been applied. These machines have clearly benefitted from the experience of other groups. These have carbon as a limiter and wall tile material, and apply various prescriptions for cleaning and conditioning. TORE-SUPRA has followed the "standard" prescription of baking, glow discharge cleaning in hydrogen, carbonisation, and glow cleaning in helium.

The final invited paper was given by P-H Rebut (JET) who reviewed the experience with wall materials in JET and then presented an outline proposal for a future large ignition tokamak based on JET's experience. The outline design presently being considered has linear dimensions 2-3 times larger than JET (plasma minor radius $\sim$ 3m, major radius $\sim$ 7.5m, elongation $\sim$ 2) with a toroidal magnetic field $\sim$ 4.5T and current capability up to 30 MA. A single null divertor configuration will be used to exhaust helium and to take advantage of H-mode confinement in widening the margin for ignition. However the design parameters have assumed L mode scaling and that the confinement is degraded by α particle heating. The additional heating requirements are relatively low $\lesssim$ 50 MW). The fusion power will be between 0.5 and 4 GW depending on the plasma density and dilution due to helium and impurities (a Murakami limit of $\sim$ 15 and $Z_{eff} \lesssim 2$ are assumed). The torus wall will be water cooled stainless steel protected by poloidal rings of radiatively cooled carbon tiles. The tile temperatures will be determined primarily be nuclear heating and the front surfaces are expected to reach 1500°K. The most serious materials problems will be encountered in the divertor. Although the average power density is relatively low ($\lesssim$ 2 MW m^{-2}), peak loads will be about 5 times higher ($\sim$ 10 MW m^{-2}) and will be accommodated by sweeping the X-point ($\lesssim$ 10 Hz) across a larger tile area.

Conclusion

In the limited space of the review I have tried to cover the main topics which were discussed, but it has not been possible to refer to all of the many excellent papers which were presented. This was a very successful conference and there was much fruitful discussion. Many papers dealt with wall conditioning techniques and the continued emphasis on this topic reflects its importance in fusion experiments with high heating powers. Most experiments now have carbon rather than metal walls and limiters in order to reduce high Z impurities, but the strong affinity of carbon for hydrogen has lead to the need to develop new conditioning procedures - in particular helium discharge conditioning, in order to control recycling. The subject of plasma wall interactions has developed and matured considerably over the past decade. The sophistication of measurement techniques and interpretation methods has developed considerably, and workers in this field have made substantial progress towards the detailed understanding of the effect of the material surfaces on confined fusion plasmas. The next conference in this series will be held in Bournemouth, United Kingdom from 20th to 25th May 1990.