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PISCES PROGRAM
SUMMARY OF RESEARCH 1988

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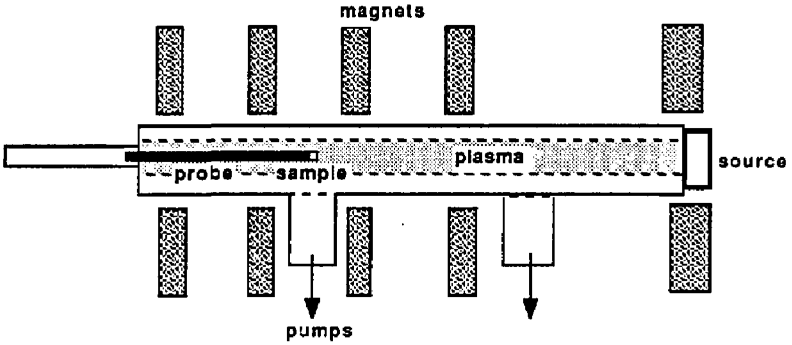
PISCES FACILITY -- UCLA

The PISCES research laboratory at UCLA is devoted to work on plasma edge physics, materials behavior and plasma-materials interactions in fusion devices. The laboratory's first plasma device, PISCES-A, has operated since 1984. A second device, PISCES-B, with a bakeable chamber and line-of-sight ports for sample viewing will begin operation in 1988. Each device has the capability to generate continuous plasma covering the range, $n = 10^{11}\text{-}10^{13}$ cm^{-3}, T_e = 3-30 eV and heat fluxes on samples up to 100-200 $\mathrm{W/cm}^2$. These plasma conditions are similar to the plasma at the edge of a large tokamak.



PISCES-A	-- H, D, He, Ar, etc. steady state plasmas -- 10^{11} - 10^{13} ions/cm^3 (tokamak edge) -- ~10^{18} ions/s-cm^2, maximum flux -- ~10^{22} ions/cm^2, fluence per half day run -- 0 - ~500 eV ion impact energy (bias) -- 2-3 cm typical sample diameter

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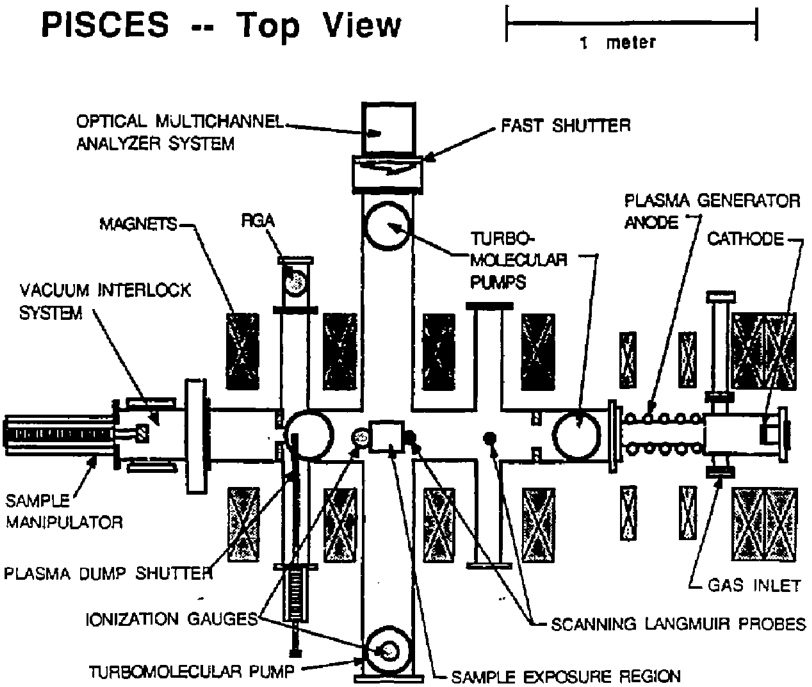

Figure I. PISCES-A, floor layout

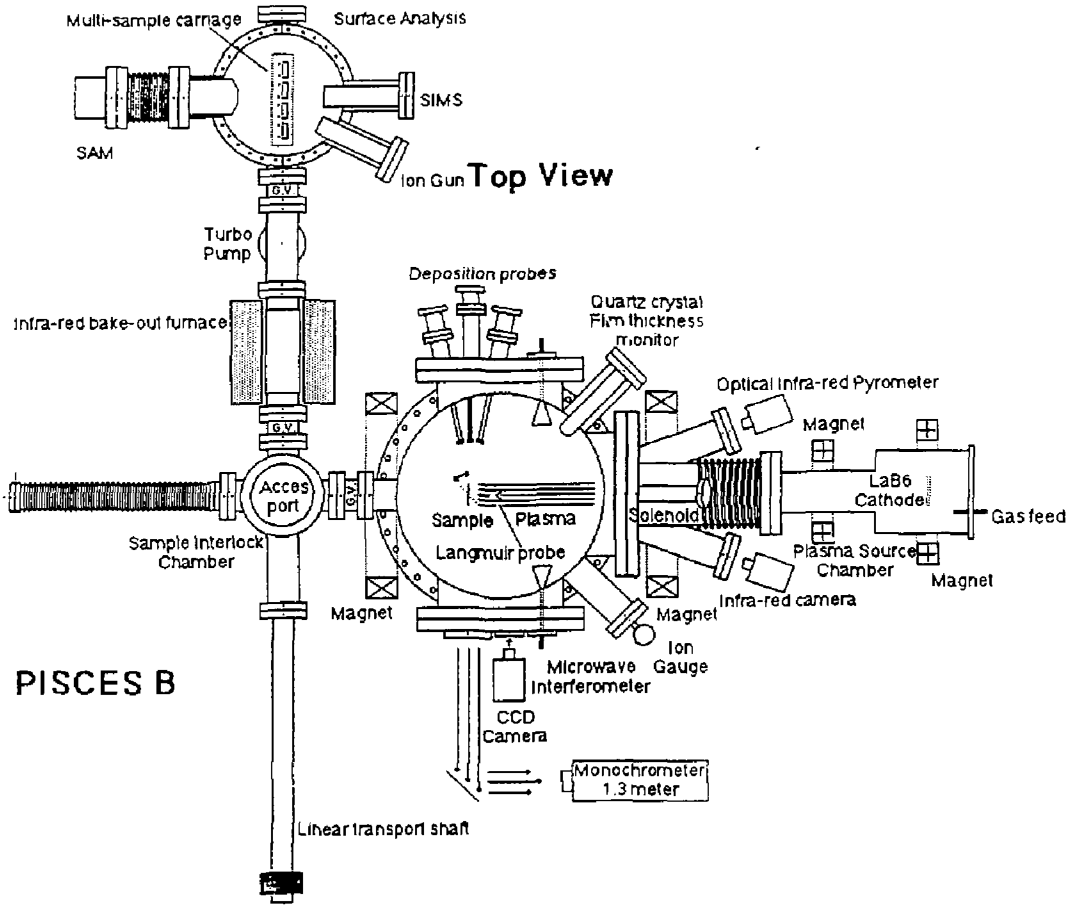

Figure II. PISCES-B, floor layout

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Introduction

The PISCES Program has two complementary parts. The PISCES Materials Program provides information on the behavior of materials subjected to continuous ion bombardment from steady state plasmas. The PISCES Physics Program includes the development of diagnostics that support the materials-related work and the development of novel techniques for controlling plasma boundary layer flow. These efforts are supported by the Development and Technology Division of the Department of Energy' Office of Fusion Energy. Current work in the PISCES Program is summarized in this report by a series of brief descriptions of research. More detailed information on these subjects may be found in References 1 - 13 in the bibliography.

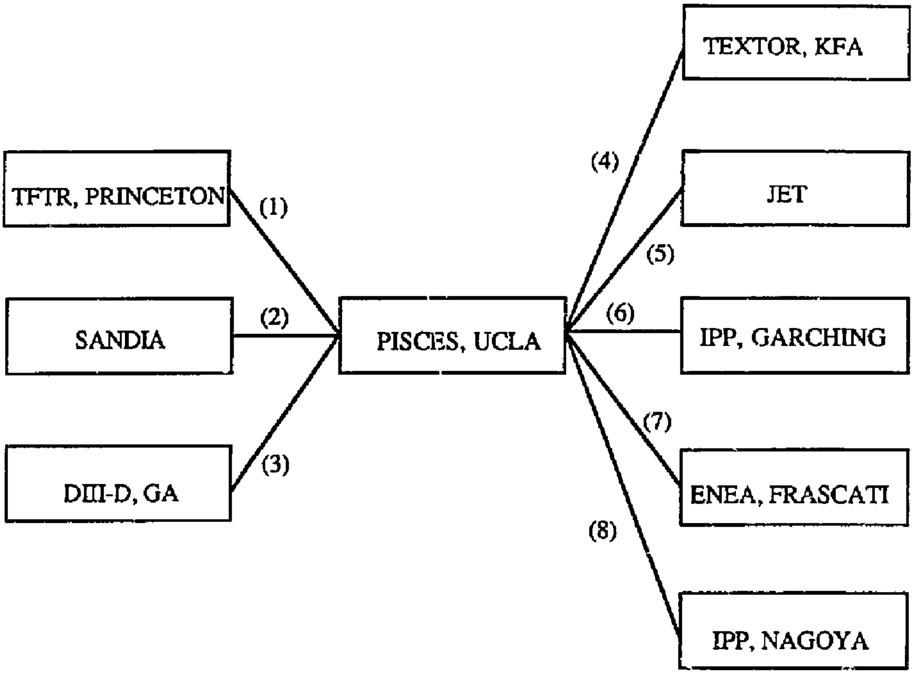
The PISCES Program also informally contributes to and benefits from other programs under Prof. R. W. Conn. Their scopes include the development of hardware for impurity control in tokamaks (Alt-I/Alt-II), the theory and modeling of plasma boundary behavior (PMI Program) and reactor studies such as TITAN and ARIES.

In 1987 and 1988 the major portion of the PISCES materials program has been devoted to investigations of plasma-surface interactions in carbon-based materials because graphite has been widely used in large tokamaks to improve confinement, and considerable effort has been focused on the virtual pumping characteristics of graphite and on the effects of preconditioning the graphite surface. The major efforts in the materials research program in 1988 are: (1) continuing data on the pumping of hydrogen by graphite, including the effects of temperature ramps that simulate TFTR and CIT conditions; (2) studies to exploit codeposition of hydrogen in grooves for possible application to a novel limiter concept; and (3) high temperature recycling behavior (radiation-enhanced sublimation) of graphite. In past years, the PISCES Program has produced considerable data on the erosion and redeposition of graphite, C-C composites and other materials.[14-23] And research in this area will continue in 1989 with erosion and redeposition studies of various graphites including boron-doped graphites from Japan.

PISCES has been used effectively for international collaborations on carbon-based materials and more such collaborations are planned for 1989. Also, the PISCES Program has integrated effectively with the national effort to resolve issues for TFTR regarding tritium inventory in plasma facing components by active participation in the TFTR D-T Physics Group. The accompanying diagram indicates some of these collaborations.

The PISCES Physics Program is developing "novel concepts" by establishing preliminary experimental verification for novel techniques, such as biased limiters, that can be used to modify the boundary layer flows in the edge plasma of tokamaks in order to reduce local particle fluxes and heat loads. This effort includes experimental work on scrape-off-layer particle fluxes and heat loads. This effort includes experimental work on scrape-off-layer simulations in PISCES and on electrically biased surfaces inserted into PISCES plasmas and collaboration on experiments in the Continuous Current Tokamak at UCLA. PISCES plasmas are similar in density and temperature to the edge plasma of a tokamak and plasma edge phenomena driven by wall interactions can be simulated. The steady state operation of PISCES facilitates the detailed study of topics such as plasma neutralization and pumping, ionization and redeposition, and modification of this plasma/impurity transport through externally applied magnetic or electric fields.

Experimental equipment for the PISCES facility includes the existing PISCES-A device, the new PISCES-B device, an AES/SIMS surface analysis station, a scanning electron microscope with EMPA, an outgassing station, supporting diagnostic equipment and a micro-Vax computer (with connection to a VAX) for data processing. There is also additional equipment, including the experimental probes and related data analysis equipment, for experiments in the Continuous Current Tokamak (CCT). References 24-26 give details of the PISCES plasma source.



(1) TFTR-tile erosion exps.-88'
Deposition probe exps.-88'

(2) Graphite pumping exps.-87'
Tungsten erosion exps.-88'

(3) He-conditioning exps.-87'
Graphite tile pumping exps.-88'

(4) Plasma spectroscopy exps.
(A.Pospeiszczyk)

(5) Graphite tile pumping exps.-88'

(6) Deuterium release exps.-87'
High temp. graphite erosion exps.-88'
(J.Bohdansky)

(7) Net-candidate materials erosion exps.-87'
(E.Franconi)

(8) Biased RF-limiter exps.-88'
(T.Shoji)
B-doped graphite erosion-89'
(Y.Horino)

Figure III. Collaborations between the PISCES Program and other fusion programs.

1. Deuterium Pumping by C-C Composites and Graphites*

Wall pumping effects by graphite components such as limiters and divertor plates have been found to play a crucial role in improving plasma parameters in major tokamaks (TFTR, JET, DIII-D and TEXTOR). Except for JET, surface conditioning of these plasma-facing components seems to play a crucial role in obtaining the wall pumping effect. The PISCES Program has developed a plasma-activation process (He-PAP, Ar-PAP) as a surface conditioning technique for low-density graphite materials and produced significantly enhanced retention of hydrogen plasma particles, i.e. pumping, at temperatures between 20 and 480°C. We believe this pumping in PISCES is similar to the low recycling at the edge observed after helium conditioning in large tokamaks.

Graphitic materials exposed in PISCES to the He-PAP conditioning technique include pyro-graphite, 2D-weave, 4D-weave and POCO. Deuterium plasma recycling and chemical erosion behavior have been investigated for these materials under the following conditions: fluxes of about 7×10^{17} ions $s^{-1}cm^{-2}$; exposure time in the range from 20s; bombarding energy of 300 eV; and graphite temperatures between 20 and 120 °C.

Figure 1 shows the surface morphologies after He-PAP. The POCO-graphite and 4D-graphite weave have sponge-like surface morphologies with significantly increased pore openings. Before He-PAP, the surface pores are completely blocked or plugged with machining dusts and/or weakly bound particles. For the pyro-graphite and the 2D-weave, there are no obvious surface pore openings. This is expected for pyro-graphite, which is used as a pore-free reference surface for the deuterium pumping measurements.

He-PAP increases the pore openings connecting with the plasma-facing surface and also removes adsorbed atoms from in-pore surface sites, and thereby reduces the deuterium plasma recycling and chemical erosion rates before the pumping capacity of the surface becomes saturated. We believe a dynamic pumping mechanism operates in porous graphite in addition to the usually cited radiation-produced traps in the lattice, and that a significant population of the particles that would eventually recycle are temporarily stored in pores and released after plasma bombardment is over. This hypothesis is consistent with the leads reproducible pumping observed in JET as well as the He conditioning results in TFTR. PISCES tests also show that deuterium recycling, even at the steady state, is reduced as the surface porosity increases due to materials selection (see Fig. 2). A novel idea for exploiting this phenomenon is described in the next section.

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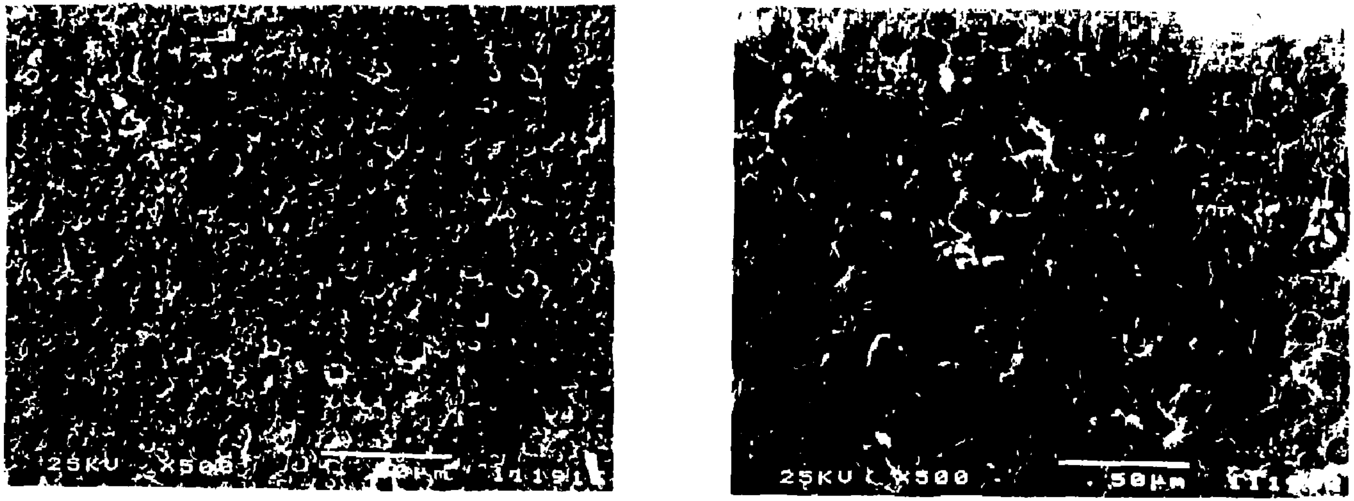
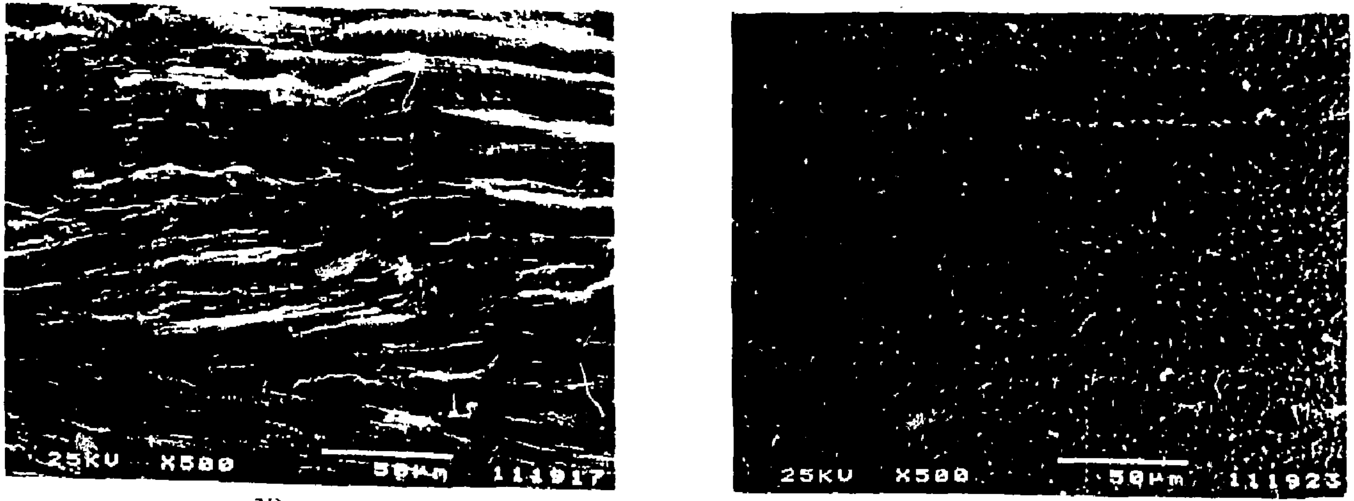
*See also Refs. 1-3



POCO-graphite

4D-weave



2D-weave

Pyro-graphite

Fig. 1: Surface morphologies of selected graphite materials after He-PAP.

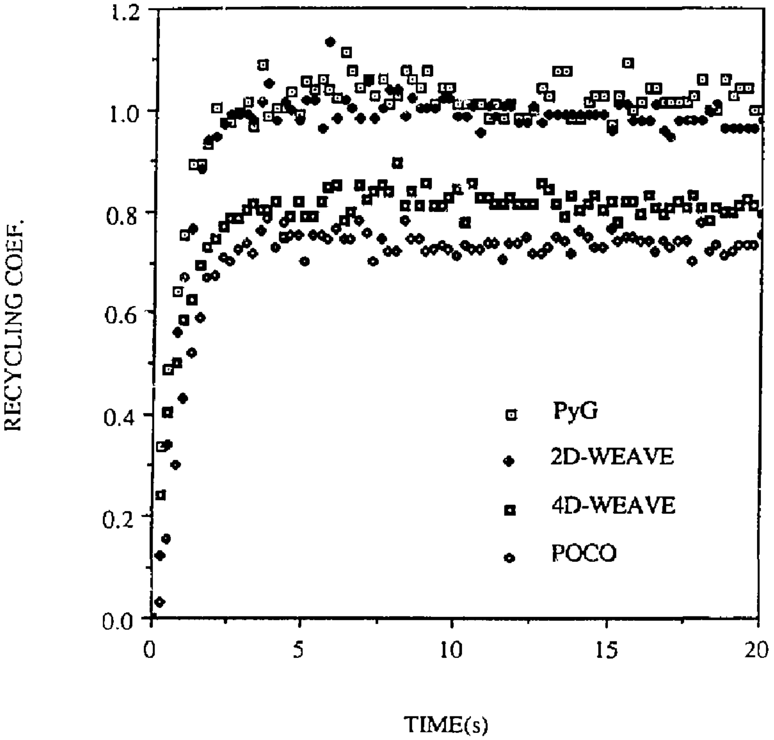


Fig. 2: Recycling coefficients from selected graphite materials under deuterium plasma bombardment at 300 eV. The recycling coefficients are normalized to the steady state value for pyro-graphite as a pore-free reference surface.

2. Reduced Particle Recycling from Grooved Graphite Surfaces*

The beneficial effects from conditioning graphite components in order to control the fuel particle recycling in present-day tokamaks are well recognized. However, these saturable wall pumping effects may not be effective for long-pulse fusion devices like ITER. The PISCES Program is developing a novel idea, based on co-deposition of carbon and hydrogen, that may reduce recycling at the surfaces of components during long pulse operation.

Under deuterium plasma bombardment in PISCES, the particle recycling of a POCO AFX-5Q sample with machined grooves along its plasma facing surface has been investigated. The grooves are 2 mm wide, 6 mm deep and separated by 2 mm. The groove width is about the same as the ion gyro radius in PISCES. The plasma conditions are: fluxes around 7 x 10^{17} ions $s^{-1}cm^{-2}$; exposure time of about 100s; bombarding energy of 300 eV; and graphite temperatures between 20 and 120 ^{o}C.

The results are shown in Figure 3. The recycling level of the grooved surface is continuously lower than a flat surface by 15-20%. No tendency toward saturation for the reduction of recycling was observed. Furthermore, the emission of other impurities, such as physically sputtered carbon and chemically sputtered hydro-carbons is suppressed (Fig. 4).

The lower portions of the groove walls (furthest from the plasma) have a coating with a topology indicative of redeposition and a yellowish color indicative of hydrogenated carbon. Figure 5 shows the surface morphologies. Also, the upper portions of the groove walls seem to be eroded. We believe this non-saturable pumping is due to co-deposition in the grooves resulting from sputtering of carbon from the sidewalls of the grooves along with adsorption of hydrogen and chemically sputtered hydrocarbons on the groove surfaces. Due to the ion gyro-radius, incoming ions can reach only the upper portions of the groove walls and there sputtering takes place. The lower protions of the walls serve as a substrate of for co-deposition of the sputtered carbon and of incoming neutral hydrogen and hydrogen reflected from the groove walls. The surface morphology of the co-deposited film in the grooves is similar to that of the redeposited material on TFTR components, such as the example given in the next section.

Continuous co-deposition could significantly increase the tritium inventory of plasma-facing components in a fusion device. So one must also consider how to remove the co-deposited material, for example, by wall conditioning techniques such helium discharges (see the next section). A desireable next step is to apply the groove/co-deposition concept to toroidal devices (with make appropriate adjustments of groove dimensions and configuration). The PISCES Program is developing a collaboration with GA Technologies for application to D-III-D.

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*See also Refs. 1- 3

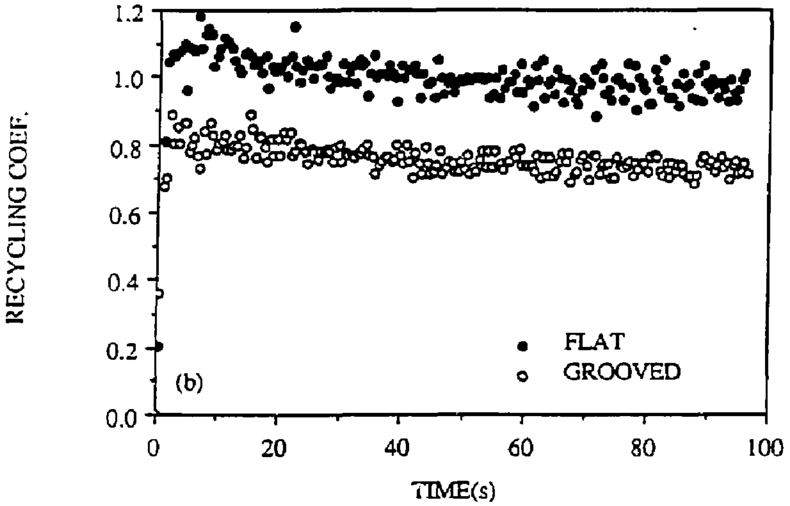

Fig. 3: Recycling coefficients from a flat surface and a grooved surface of POCO graphite under deuterium plasma bombardment at 300 eV. The target temperature changes from room temperature to 120 °C near the end of the exposure.

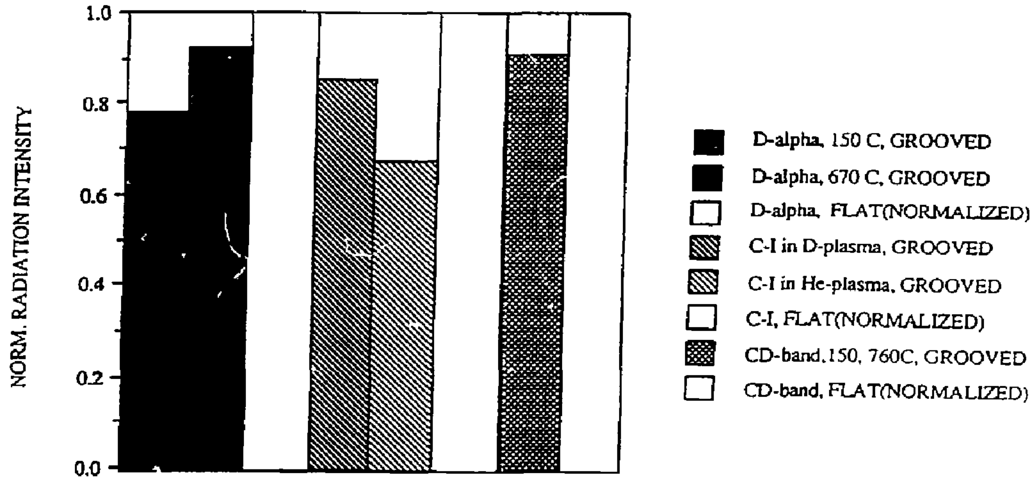

Fig. 4: Spectroscopic measurements of impurity emissions from a flat surface and a grooved surface of POCO-graphite at the steady state.

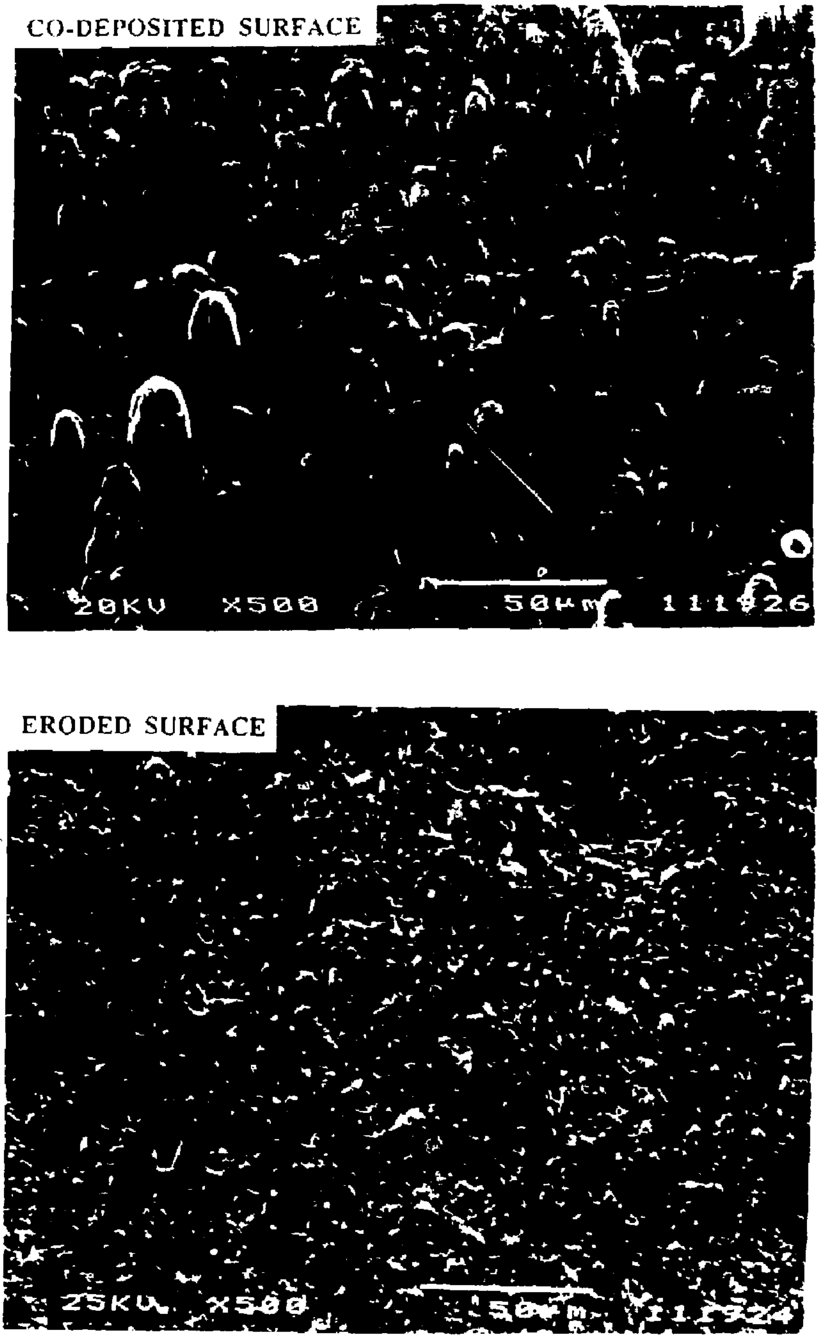

Fig. 5: Surface morphologies of the lower portion (coated by co-deposition) and the upper portion (eroded) of a groove wall.

3. Surface Analysis of Graphite Tiles Exposed in Tokamaks*

The PISCES Program is evalutating the surface morphologies of carbon-based materials from tokamak components as part of a general evaluation of the effects of surface conditioning that includes comparisons with samples exposed in PISCES. This effort began with investigations of tiles from TFTR. Similar surface analysis studies on the graphite tiles from the divertor region of DIII-D and from the inner wall limiter of JET are also now being done.

Graphite tile materials exposed in TFTR have been analyzed with SEM (Scanning Electron Microscope) and EMPA (Electron Micro-Probe Analysis) in the PISCES lab. The samples are from the "redeposition-dominated" region (position: #N3-15) and from the "erosion-dominated" region (position: #N3-7) of the bumper limiter and were exposed to 7166 ohmically heated shots and 2756 neutral beam heated shots in TFTR in 1985-1987. The bumper limiter, with its two tons of graphite tiles, served as the key plasma interactive surface in attaining the S-mode plasma discharges (supershots). The deuterium retention for the redeposited and eroded graphite tiles is 2×10^{18} D-atoms/cm^2 and 3×10^{17} D-atoms/cm^2, respectively, as determined by NRA measurements done at SNLA.

In comparing the surface morphologies of several conditions of graphite (Fig. 6), one finds a porous surface for graphite pre-conditioned in PISCES (Fig. 6a) so that surface pores are fully opened. The PISCES-conditioned sample has an open pore structure somewhat similar to the TFTR-eroded graphite (Fig.6b). However, the TFTR-eroded sample also has polishing scores and its pores appear to be somewhat plugged with polishing dust particles and/or some plasma deposits. In contrast, the TFTR-redeposited sample (Fig. 6c) has features that protrude at an angle and are characteristic of redeposition. Their directionality is associated with the particle motion along the magnetic field lines. Where redeposition dominates in TFTR, the redeposited material typically is sufficiently thick (30 to 60 microns) that one sees no surface pore openings.

In EMPA analysis of the TFTR-eroded graphite and the PISCES-conditioned POCO AFX-5Qanalysis, no detectable surface impurities were observed. Whereas, similar analysis of an as-received TFTR-redeposited sample (Fig. 7) showed small amounts of impurities such as oxygen, iron, chromium and nickel. The compositional ratio of these metallic impurities suggests that they came from Inconel components.

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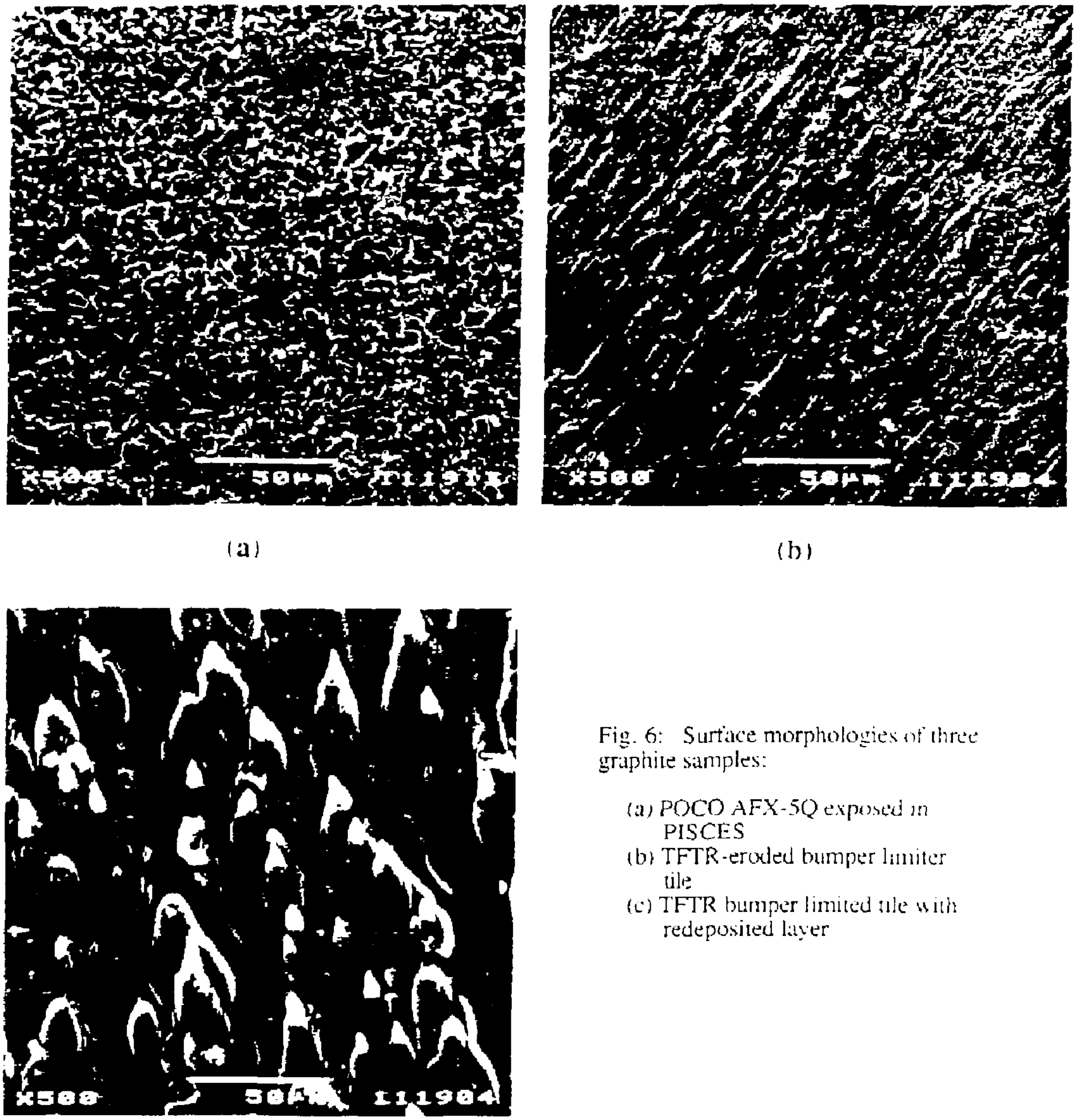
*See also Ref. 4



(a)

(b)

(c)

Fig. 6: Surface morphologies of three graphite samples:

- (a) POCO AFX-5Q exposed in PISCES
- (b) TFTR-eroded bumper limiter tile
- (c) TFTR bumper limited tile with redeposited layer

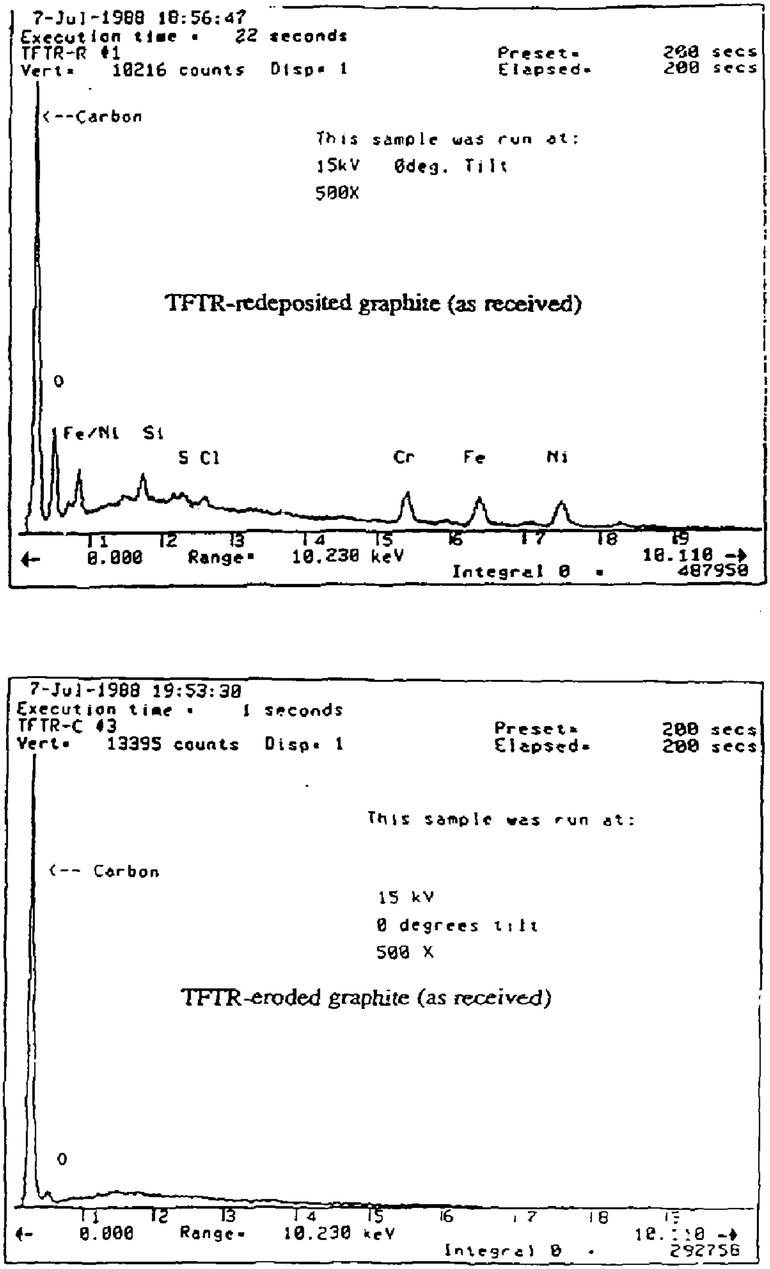


Fig. 7: EMPA analysis of the TFTR redeposited and eroded graphite tiles.

4. Erosion Behavior of Redeposition Layers from Tokamaks (Tokamakium)*

The sputtering behavior of the redeposited material found on tokamak components is of interest to present day experimenters, who may have to remove this material to condition their tokamak chambers, and to the designers of the next generation of machines, where redeposition may be crucial to the longevity of plasma-facing components and removal of some redeposited material may be necessary to control the tritium inventory. (Such measures may also be needed in TFTR.) The PISCES Program is providing data on the erosion behavior of redeposited materials.

The nature of the redeposited material found in tokamaks (tokamakium) depends strongly on factors such as the machine design and types of discharges. The limited studies of sputtering of redeposited materials, at UCLa and elsewhere, have shown values of erosion yield greater than and significantly below the typical values for virgin graphite.

The chemical and physical sputtering behavior of one example of tokamakium, from graphite exposed in TFTR as part of the bumper limiter, are described here. The deuterium plasma bombardment conditions are: ion bombarding energy of 300 eV; ion flux of 1.7×10^{18} ions s^{-1} cm^{-2}; plasma density of 1.4×10^{12} cm^{-3}; electron temperature of 11 eV; and neutral pressure of 3×10^{-4} Torr. The chemical erosion yield is measured with calibrated CD-band spectroscopy during the temperature ramp from 100 to 900 ºC at an average rate of about 5 deg/s. The spectroscopic data are further calibrated against weight loss measurements so that the absolute erosion rate can be evaluated.

The chemical erosion behavior of several graphites under deuterium plasma bombardment is shown in Figure 8. The chemical sputtering yield for the tokamakium sample is about 10-15% higher at its maximum, around 550 ºC, than the maximum for POCO. This greater maximum erosion yield is attributed to deuterium incorporated during redeposition. The significantly steeper temperature dependence (narrower peak) compared to other graphite samples has not been explained. In contrast, the chemical erosion yield of TFTR-eroded graphite is essentially the same as that of virgin graphite. No significant change in the impurity composition of TFTR-redeposited material is observed with EMPA after deuterium plasma bombardment (Fig. 9).

The erosion behavior in PISCES of the TFTR-redeposited material exposed to helium plasma is different than with deuterium plasma. Helium discharges are often used for wall conditioning in major tokamaks. This removal process in PISCES proceeds at the same rate as classical physical sputtering and leads to a surface with the same porosity and the same degree of cleanliness (i. e., no significant impurities - see Fig. 9) as a well-conditioned graphite surface.

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*See also Ref. 4

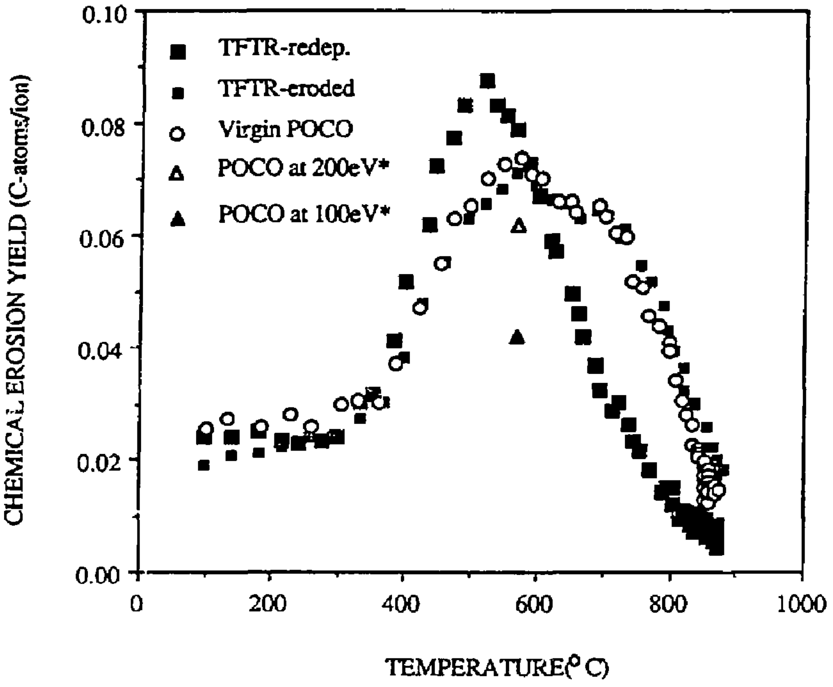
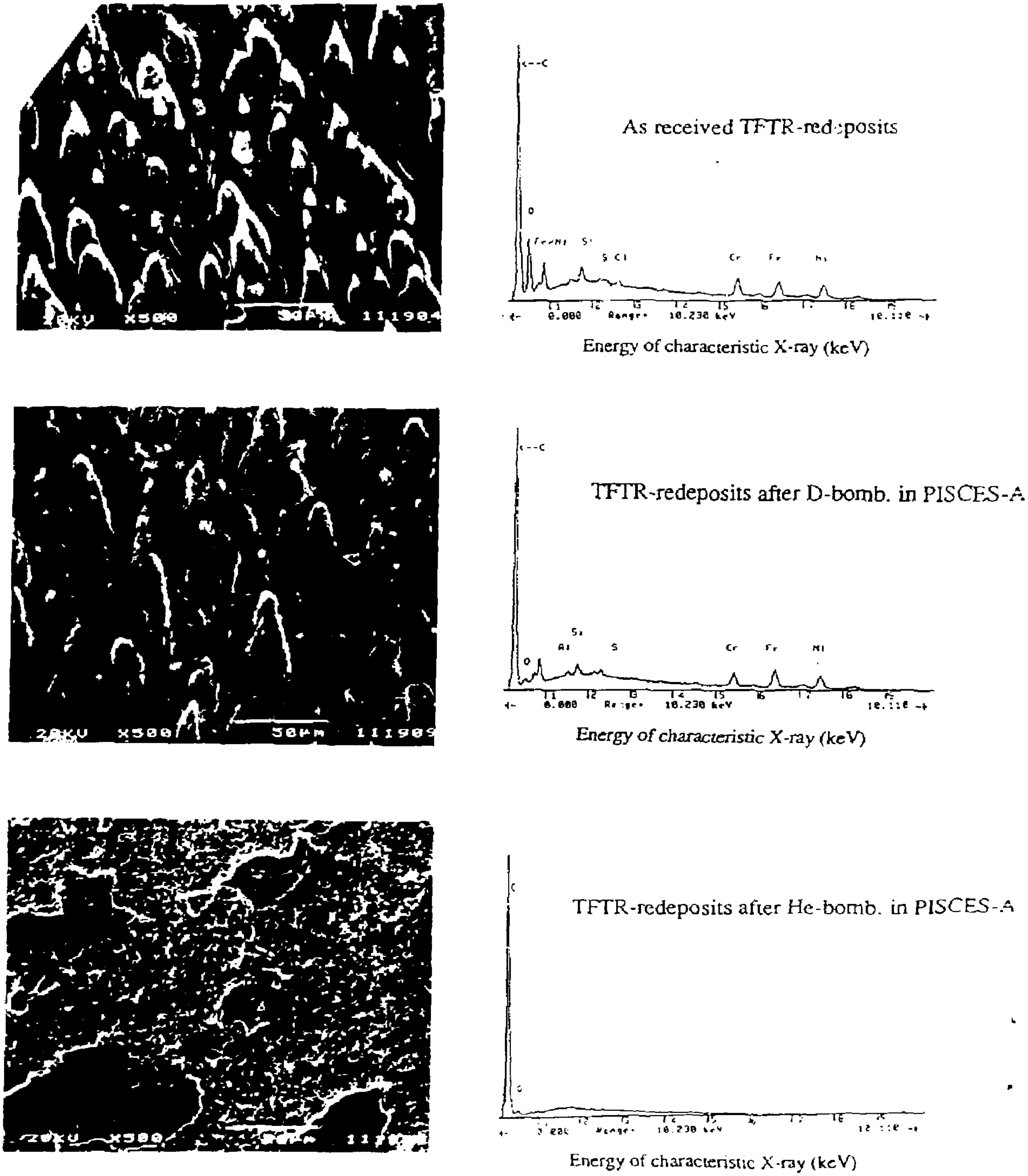


Fig. 8: The chemical erosion yields for samples of virgin POCO AFX-5Q, TFTR-redeposited material and TFTR-eroded graphite under high-flux deuterium plasma bombardment at 300 eV in PISCES. For comparison, the erosion yield data for virgin POCO graphite at 100 and 200 eV at 550 °C only are also shown.



As received TFTR-redeposits

TFTR-redeposits after D-bomb. in PISCES-A

TFTR-redeposits after He-bomb. in PISCES-A

Fig. 9: SEM-EMPA analysis of TFTR-graphite before/after plasma bombardment in PISCES.

5. High Temperature Erosion of Graphite*

In the next generation of fusion devices, such as CIT and ITER, designs for plasma-facing components have been proposed that will require graphite in service at temperatures well above 1000 °C. Above 1000 °C, the release of carbon from graphite bombarded by energetic ions climbs steadily with temperature and increases by more than an order of magnitude from the value for physical sputtering observed at lower temperatures. This phenomenon, radiation-enhanced sublimation (RES), results from a process somewhat different than physcial sputtering. Quite naturally, there is concern about the potential for very high erosion rates and interest in ways to mitigate any anticipated problems RES may cause in designing these machines.

RES was found in the early 1980's in experiments with ion beams. However, the flux dependence needed to scale up several orders of magnitude from ion beam conditions to plasma edge conditions for a fusion reactor has been controversial. There has been some hope that the high rates of erosion observed at these low fluxes might abate significantly at higher fluxes, but, until this past year, no high flux data were available for comparison. Erosion rates of POCO graphite have now been measured under reactor relevant conditions (about 10^{18} ions/cm^{2}s) in PISCES. The yields from the observed rates of erosion in PISCES experiments are roughly comparable to those seen in the ion beam experiments. Preliminary data for erosion in helium plasmas in PISCES are shown in Figures 10 and 11.

The high temperatures for these experiments in PISCES require additional heat supplied to the sample beyond that transmitted from the plasma, and the sample is heated resistively. Erosion rates are monitored spectroscopically using the CI line at 9095Å. The spectroscopic data are calibrated by weight loss measured at a lower temperatures using a sample similar to the resistively heated samples, but without high amperage electrical leads. Comparative data on spectral lines associated with emission of diatomic carbon have also been obtained. Also, a complete set of spectra for emissions at high temperatures in helium and in deuterium were obtained in conjuction with the spectroscopic studies in PISCES (Section 7).

Further data reduction to account for the dependence of the spectroscopic signal on electron temperature and further correlations with weight loss measurements are in progress. A slightly different sample geometry that will permit weight loss measurements on samples exposed at high temperatures is being developed at the suggestion of Dr. Joseph Bohdansky, who will collaborate on high temperature measurements of graphite erosion in the last quarter of 1988. Samples of various carbon-based materials supplied by the NET/ITER Group are anticipated in 1989.

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*See also Ref. 5

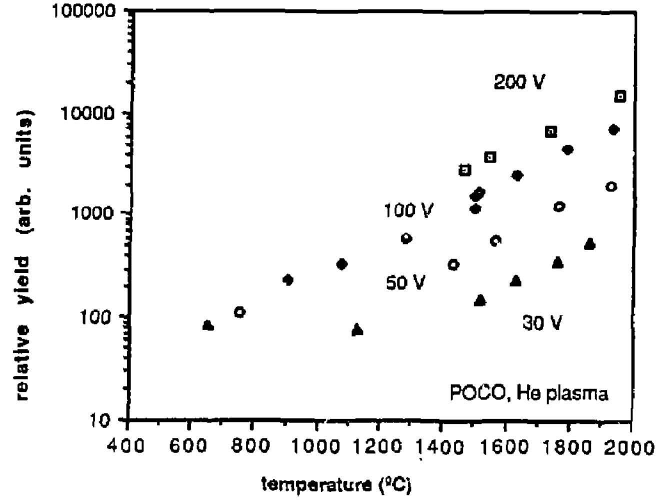

Fig. 10 Erosion of POCO graphite by helium versus sample surface temperature. Relative yield values are given for these preliminary data obtained from spectroscopic measurements. Correlation of these data with weight loss measurements to give absolute yields is in progress.

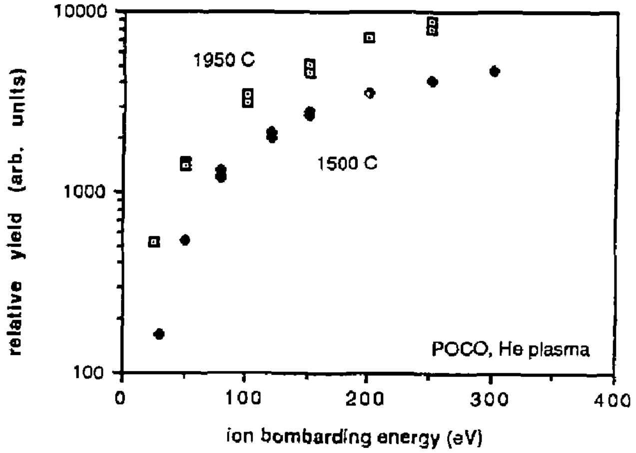

Fig. 11. Erosion of POCO graphite versus bombarding ion energy

6. Collaboration on TFTR Probe Measurements of Implanted D*

The need for accurate estimates of the tritium inventory that will accumulate in TFTR during D-T operation led to the formation of the TFTR D-T Physics Group, a working group chartered to develop the technical basis for such an estimate. The PISCES Program has contributed to this working group with information on erosion, redeposition, pumping and recycling -- all discussed in earlier sections of this report. The work reported here is an outgrowth of this collaboration with the D-T Physics Group.

The PISCES program supplied samples (types 2 and 3 below) for a TFTR probe experiment and collaborated with the TFTR team, SNL-A and SNL-L in the interpretation of results. The initial objective for the PISCES contribution was to expose graphite samples in TFTR that had received three types of surface conditioning treatments -- (1) virgin POCO, (2) samples from the TFTR bumper limiter in a region where erosion had occurred, and (3) samples conditioned by helium bombardment (He-PAP) in PISCES (see Section 1). The samples were mounted on Combined Electrical and Sample Exposure Probe (CESEP), which was inserted, withdrawn and rotated so that various portions of the samples were exposed to selected groups of the roughly 100 1.4MA discharges during the TFTR Isotope Exchange Experiment in April 1988. Various portions of the samples were exposed to some or all of the following discharges : 15 H discharges, 7 He discharges and 12 D discharges. The samples were removed and analyzed for retained deuterium and impurities by nuclear reaction analysis and by Rutherford backscattering at SNLA. Figures 12 and 13 show the deuterium profiles measured along and across several samples. The radial profiles (Fig. 12) indicate scrape-off lengths of 8-11 cm for the electron side during H, He and D discharges and about 5 cm on the ion side, after correction for the off-axis position of the probe. The larger value for the electron side is consistent with the much longer connection length than that for the ion side. The scrape-off length really pertains to the carbon (rather than light ions) which deposited from the plasma and saturated with D or H.

Large amounts of carbon deposition were found. Typical values gave an average of 1.5 - 3.0 x 10^{17} C/cm^2 per discharge. These data provide some insight into the amount of eroded and redeposited material that is transported during a single shot and is important because there is very little data available of this type. Oxygen and metal impurities were also measured. The hydrogen isotope to carbon ratio computed for the samples agreed reasonable well with spectroscopic data on the discharges. Steve Kilpatrick (PPPL) was the lead investigator, and Bill Wampler (SNLA) and Bob Bastasz (SNLL) were also principal contributors to this work.

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*See also Ref. 6

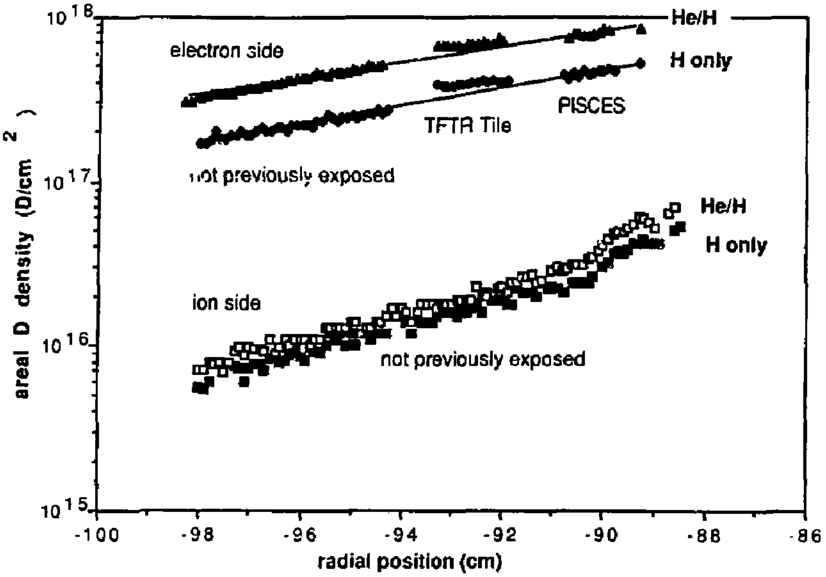

Fig. 12. Areal deuterium profiles for selected samples versus position in radial direction along the TFTR Probe. Minor radius of plasma is 80 cm.

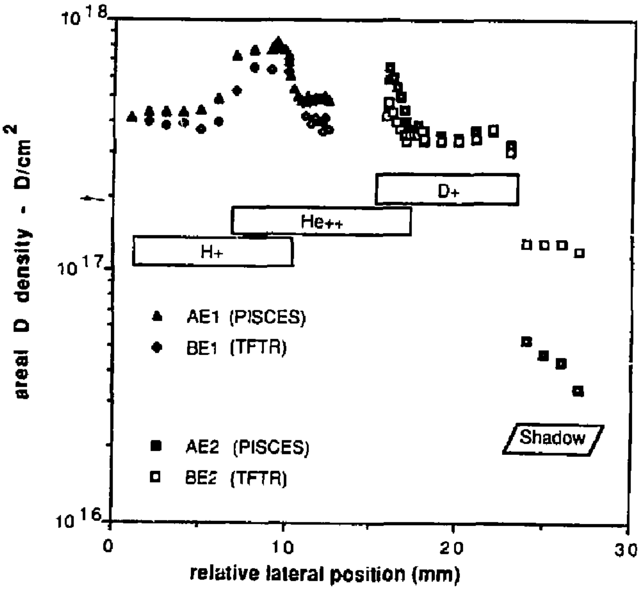

Fig. 13. Areal deuterium profiles across selected samples.

7. Spectroscopic Studies of Carbon Containing Molecules*

Existing tokamaks use carbon extensively for plasma-facing components, and carbon-containing molecules, such as CH and CO, play an important role in the transport of impurities Emission spectroscopy can reveal the strength and nature of the sources of molecular particles even at locations which are otherwise not easily accessible. However, the present data base is inadequate for this purpose. Information is needed on observable lines or bands with reasonable intensities that can be used for absolute measurements for the important molecules in a tokamak edge plasma.

The PISCES Program has produced spectrographic recordings of emissions produced when CH_4, C_2H_2, C_2H_4, CO, or CO_2 was blown into a steady state plasma through a slit aperture. From absolute measurements of the molecular fluxes and of the intensities of emission lines, the ratios between decay and excitation rates were calculated and absolute values of impurity fluxes were determined. For the spectrographic recordings, a camera attached to the optical spectrometer, with the gas plume (source) imaged onto the spectrometer slit, obtained simultaneous information about the spectral and spatial distributions of the emissions. PMT and OMA atttached to the spectrometer were used for the absolute measurements.

The spectrographs indicate that hydrocarbons and carbon-oxides play an important role in determining the distributions of oxygen and carbon within the plasma. This observation is consistent with previous findings on TEXTOR. The ratio between the decay and excitation rates of various emission lines were measured for several electron temperatures. The dramatic increase in the ratio for CH at electron temperatures above about 25 eV (Fig. 14) differs markedly from atomic lines for which the increase with temperature typically lessens at higher temperatures.

The break-up of carbon-containing molecules as they penetrated into the plasma was studied using the same setup described above for studying carbon and oxygen transport with the OMA attached to the spectrometer. The expanding gas cloud was imaged onto the entrance slit of the optical spectrometer so that profiles of the interesting emission lines were observed along the direction of their penetration into the plasma. (In a tokamak, this is the radial direction; in PISCES this direction is along the magnetic axis.) A profile of the CH molecular line measured during CH_4 gas injection is shown in Fig. 15. Computer calculations have been performed at ORNL which describe the penetration of carbon, oxygen, and hydrogen atoms into a discharge and account for all the individual steps in the break-up of these molecules on their way from the source (the gas injection slit). John Hogan of Oak Ridge National Laboratory models the process of molecules breaking-up in plasma and was a major contributor to this work.

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*See also Refs. 7, 8

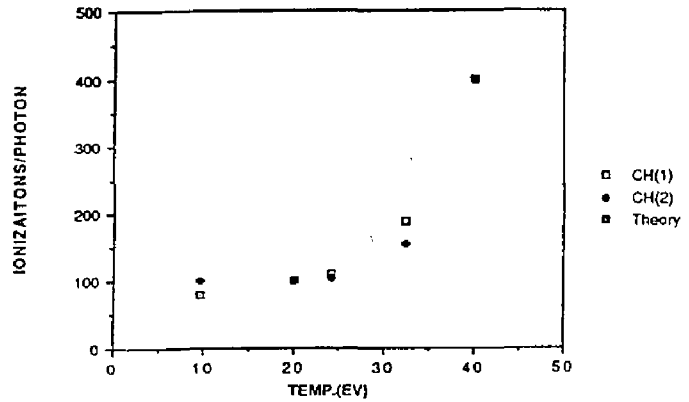

Fig. 14. Ionization per photon for the CH molecular line from CH_4 gas with two gas feed rates: CH(1), for 3.18×10^{18} CH_4 molecules/cm-s, and CH(2), for2.03×10^{18}.

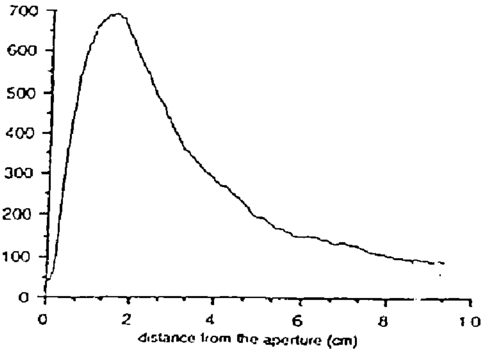

Fig. 15. Profile of CH band -- intensity versus distance from the aperture (source of the gas injection) along the direction of penetration.

8. Presheath Profile Measurements*

The presheath zone is loosely defined as the quasi-neutral region of plasma between the sheath in front of a wall surface and the bulk plasma. The potential drop along the presheath accelerates ions to the ion sound speed. For researchers in plasma-materials interactions, the significance of understanding the presheath physics lies in the dependence of erosion and redeposition upon the effects of presheath electric fields and the dependence of bulk flows of plasma on the motion of ionized impurities. The PISCES research on pre-sheath physics also is providing significant information for plasma physicists regarding the interpretation of data from probes.

The first set of presheath experiments in PISCES had three objectives: (1) the characterization of profiles of density, potential, and parallel mach number in the presheath; (2) experimental data for comparisons with theoretical models; and (3) direct tests, hitherto unavailable, of probe interpretation in a flowing plasma.

Characterization of the presheath region has been completed for wall surfaces perpendicular to the magnetic field. The data show good agreement between the measured density in the presheath and the density as computed by the Boltzmann relation from the variation of the space potential (Fig. 16). 3-D maps of plasma density and potential are made possible by the development of a fast spatially scanning emissive probe and the addition of a CID camera system.

Of the various theories examined for computing parallel mach numbers from probe flux measurements, the "Stangeby" model for mach probes best fits the data (Fig. 17). In this model, the net flow of the bulk plasma is related to the difference in the upstream and downstream probe flux data, and seems to be consistent with a simple particle "free fall" model. Other models stressing the importance of viscosity in plasmas are less reliable in predicting a mach number approaching unity near the sheath boundary. Brian LaBombard of the MIT Plasma Fusion Center was a principal contributor to this work.

Future experiments will measure the effect of finite ion larmor radius on the presheaths with the surfaces at an arbitrary angle to magnetic field. In addition to the effects of the presheath on particle flows, the effects on energy flows and transport in plasma sheaths will be studied by measuring the sheath heat transmission factor.

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*See also Refs. 9-12

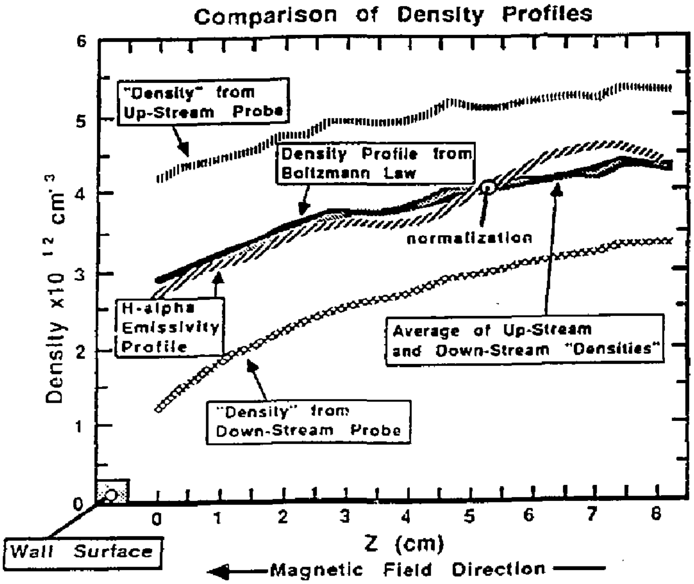

Fig. 16. Density versus axial distance along the direction from the wall through the pre-sheath along the magnetic axis.

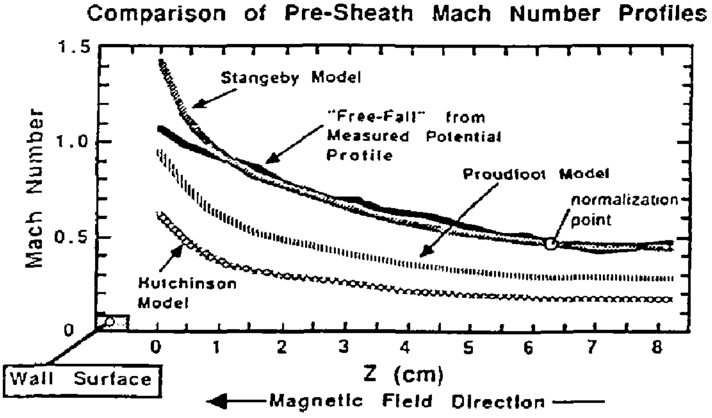

Fig. 17. Mach Number versus distance along the direction from the wall through the pre-sheath along the magnetic axis.

9. Biased Limiter/Divertor Experiments*

UCLA has a program of experiments, theory and modeling, with the global objective of developing novel techniques for controlling plasma boundary layer flow. Our objective in the PISCES experiments described here is to infer diffusion and mobility coefficients from density and potential profiles measure when electrically biased structures are inserted into plasmas simulating tokamak edge conditions. Figure 18 shows three examples. The m=0 ring simulates the ALT-I biased limiter experiment. The m=1 arrangement can be applied to divertors or limiters, and such applications are part of our ongoing collaboration in the Continuous Current Tokamak (See Section 10). PISCES experiments simulate the upper configurations (Fig. 18a-b).

The basic phenomenon involved in electrical biasing is as follows. When an electrically biased object in the plasma affects the radial potential profile, then the resulting radial electric fields drive cross-field particle fluxes. The governing equation for the cross-field flux based on a fluid model, for each species is : $\Gamma_\perp = -D\nabla n + \mu n E + n\frac{E\times B}{B^2} + \frac{B\times\nabla p}{qB^2}$

When the radial electric field is in the same direction as the density gradient, the biasing will impede the diffusion of plasma and perhaps affect the overall confinement of tokamaks.

A 2-D model of the PISCES discharge has been developed to infer diffusion and mobility coefficients from the density and potential profiles. The code includes the effects of source terms in the plasma and handles the hot, thermonically emitting cathode in the discharge. Mobility and diffusion coefficients are determined by matching profiles from experiments, measured using the PISCES fast spatially scanning emissive probe, to those which are solutions to the conservation of mass and energy equations as well as Maxwell's equations.

The m=0 and m=1 experiments have been done for discharge conditions with T_e = 10 to 20 eV, n_e = 1 to 5 x 10^{12}cm^{-3}, and B = 800 to 1400 G. In m=0 experiments, shorter scrape-off-lengths are observed when an inward electric field is applied, as is evident in Figure 19a. Longer scrape-off-lengths are observed when the field direction is reversed. The m=1 biasing also affects the profiles, but the effect is dominated by an ExB drift across the gap of the plates, and the resulting profiles (Fig. 19b) suggest some redirection of plasma flow.

Mobility and diffusion coefficients computed for a particular m=0 case show, by profile matching, that diffusion coefficients are Bohm-like while the ion mobility has to be slightly larger than classical to achieve the proper profiles. Dr. Brian LaBombard of the Plasma Fusion Center, MIT and an MIT graduate student Kyu-sun Chung were principal contributors to this work.

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*See also Refs. 9-12

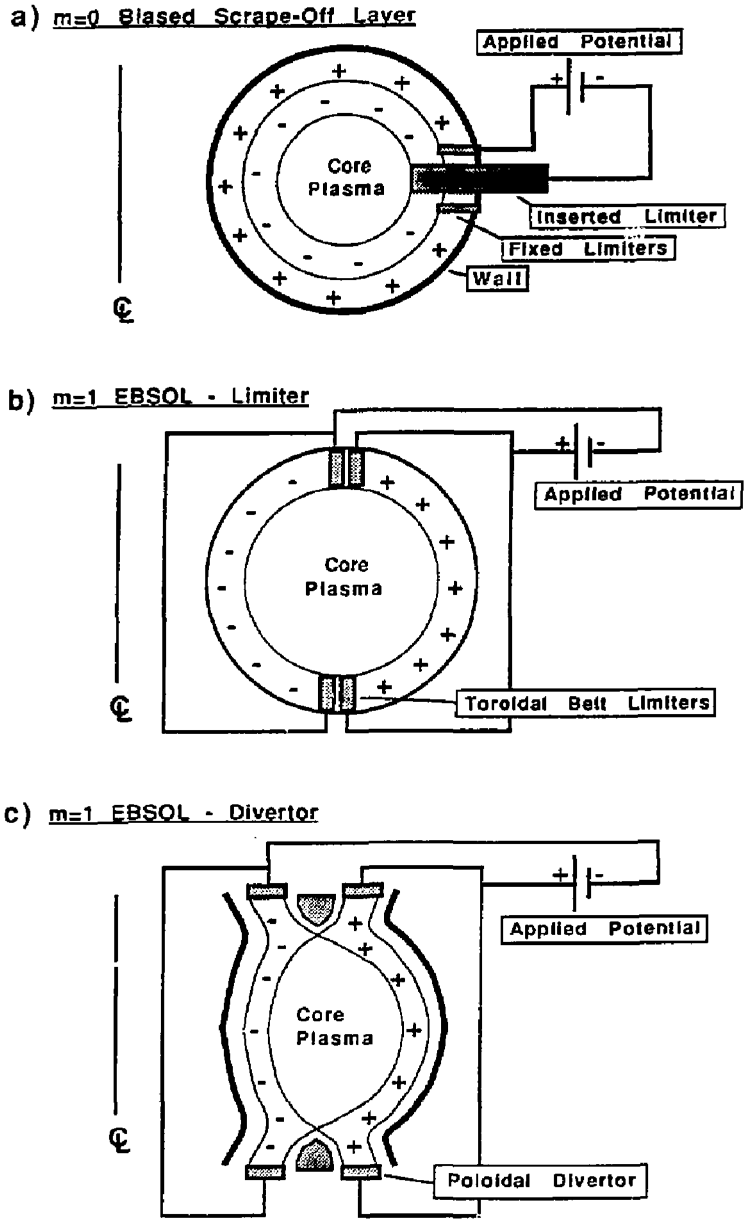

Fig. 18 Three examples of configurations with applied electrical biases.

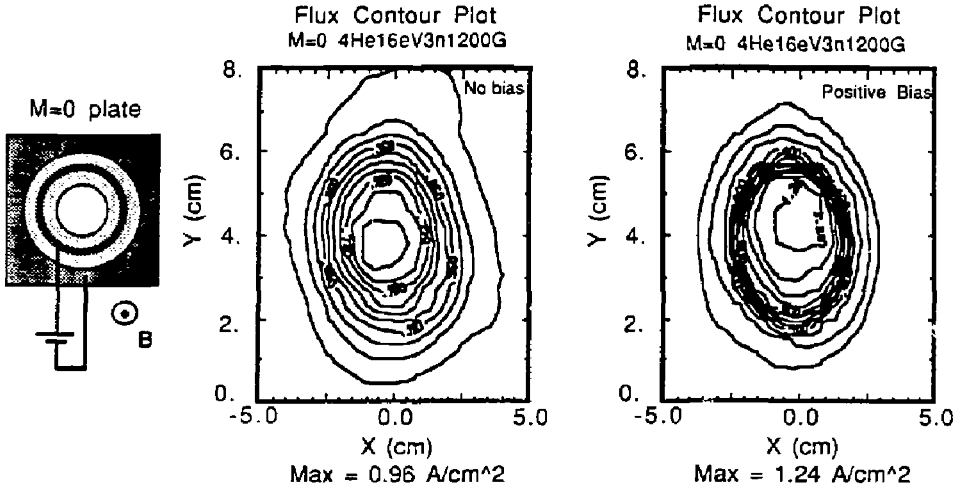

Fig 19a. Flux contours perpendicular to magnetic axis, m=0 case

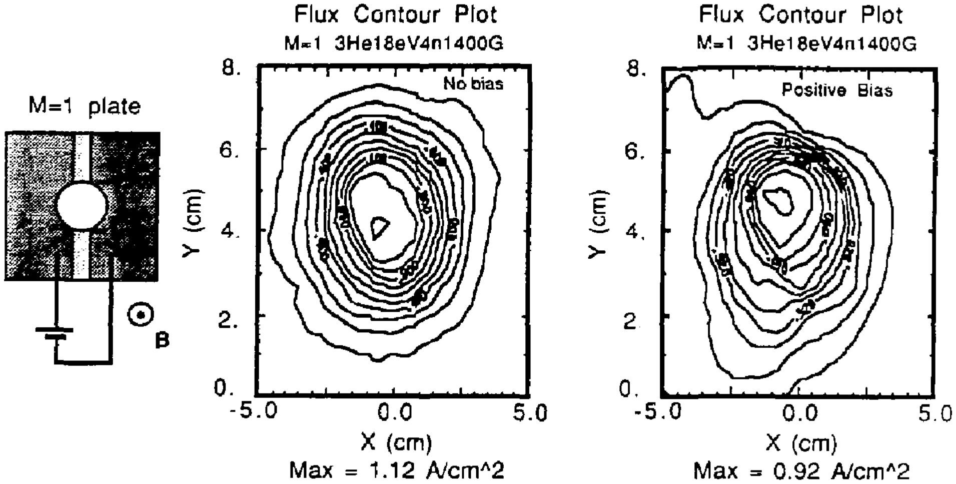

Fig. 19b. Flux contours perpendicular to magnetic axis, m=1 case.

10. Particle Transport in the CCT Tokamak Edge Plasma*

Observations in several tokamaks suggest that the rate at which particles diffuse across the confining magnetic field is higher on the outside midplane region than on the inboard midplane region. For example, measurements with a full poloidal array of probes in the ALCATOR-C scrape off layer plasma showed significant poloidal variations in the time-averaged density, potential and electron temperature (Fig. 20). Observations of asymmetric particle loads have also been made in the ALT-II pumped limiter experiment as well as in diverted discharges in ASDEX and in DIII-D. Such asymmetries can exascerbate the peaking of particle and heat fluxes on plasma-facing components. Conversely, methods for manipulating these asymmetries might be used beneficially to reduce peak heat and particle loads in future fusion devices such as ITER, where these loads present critical design problems.

The experiments reported here combine electrical biasing techniques with measurements of flow asymmetry. Two examples of biasing arrangements applicable to these experiments are shown in Fiqure 18b and 18c, Section 9. A brief description of electrical biasing is given there.

Early experiments in PISCES on electrical biasing showed a significant modification of the density profiles. In applying biasing techniques to CCT, the first step was to measure the existing flow asymmetries and related plasma parameters. Experiments have been initiated in CCT that measure the amplitude and phase of the electrostatic edge turbulence at several poloidal positions as well as the time-averaged density, potential, and temperature. (One possible explanation of the asymmetries is that the low frequency (10-100 kHz) plasma fluctuations that exist in tokamak edge plasmas have an amplitude and/or phasing dependence upon the local field curvature.) The CCT device is unique in that it provides full poloidal access to the edge plasma, permitting detailed studies of poloidally asymmetric transport.

Preliminary measurements indicate that the rms density fluctuation level is considerably higher on the outside midplane than on the inside midplane, as shown in Figure 21. Correlations of fluctuations in the density and potential indicate that the phase angle between these fluctuations is nearly equal at both poloidal positions. These two pieces of information together indicate that the cross field particle transport is significantly higher on the outside midplane than on the inside midplane.

Preparations are underway for detailed, fully 2-D experimental studies of the edge *turbulence and associated transport in CCT. Robert J. Taylor and Pat Pribyl of the UCLA* Tokamak Lab also were principal contributors to this work, as was Brian LaBombard of the MIT Plasma Fusion Center during the initial stages of the experiment.

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*See also Refs. 11-13

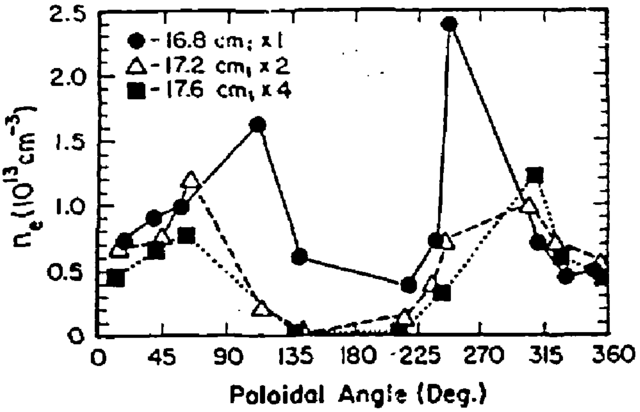

Fig. 20. Poloidally asymmetric plasma density in Alcator-C (B. LaBombard, B. Lipschutz, *Nuclear Fusion*, 27, 1, 1987, p81)

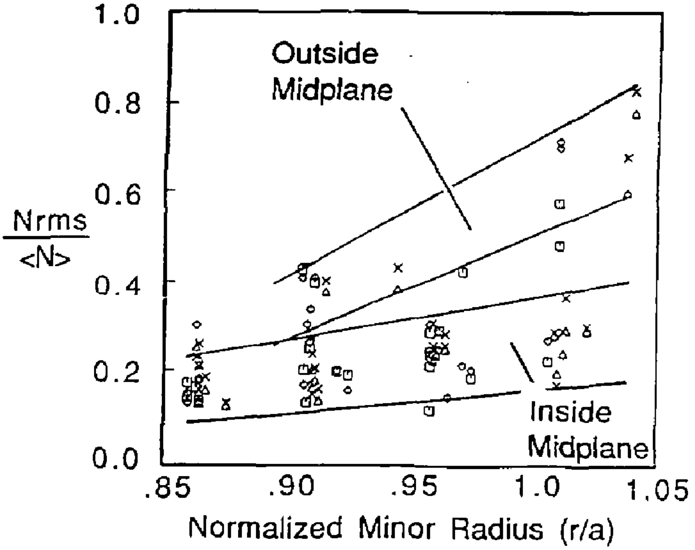

Fig. 21. Plasma density rms fluctuation levels observed on the inside and outside midplane in CCT.

11. Experimental Studies of Biased Divertors and Limiters*

Within the broad mission of the PISCES Physics Program to develop novel techniques for manipulating plasma edge flows, also described in previous sections, is a new bias technique now being tested in PISCES to improve the performance of tokamak divertors (or pump limiters). The specific objectives of this work are to optimize the biasing technique by modifying the bias conditions and throat geometry while retaining a low sputtering rate and impurity influx from the neutralizer plate.

Previous experimental simulations in PISCES indicate a substantial plasma flux loss, in the range of 50-70% of the incoming flux, between the divertor throat aperture and the neutralizer plate. Preliminary measurements show improvements of 20-30% of the pumping efficiency when a positive electrical bias is applied to the plasma at the divertor throat.

In the experimental arrangement (Fig. 21), the limiter throat is electrically insulated from the neutralizer plate and the plasma chamber. The bias is applied via a copper ring located inside the divertor throat. For moderate positive biases with respect to the divertor throat, e. g., a voltage U_b of 60 V and a current I_b of 1 - 10 A, the formation of a negative, ion-confining radial potential well inside the throat is observed. A 20-40% increase in the plasma flux reaching the neutralizer plate has been demonstrated for typical tokamak boundary layer plasma parameters ($n = 10^{12}$ cm^{-3}, $kT_e = 15$ eV). Fig. 22 shows a comparison of the axial density profile within the limiter throat for various ring biases. For positive bias, a corresponding 20-40% pressure increase is found at the divertor exhaust as a result of the improved pumping efficiency.

Dr. Brian LaBombard of the MIT Plasma Fusion Center was a principal contributor to this work.

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*See also Ref. 14

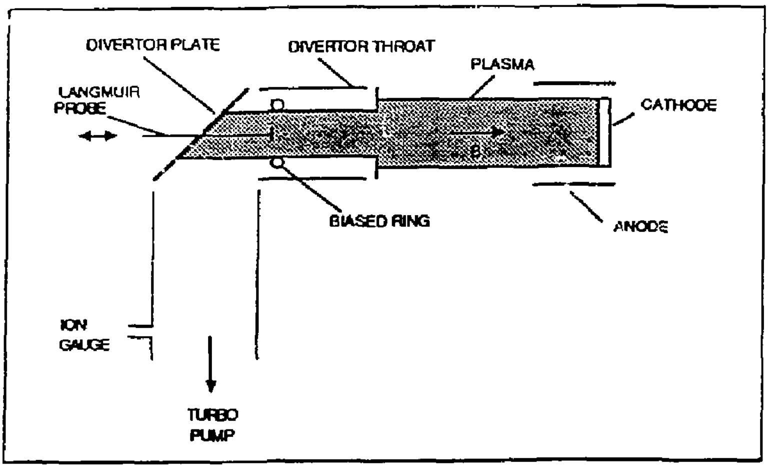

Fig. 22. Schematic drawing of a divertor simulation experiment in PISCES with the position of the biased ring electrode indicated.

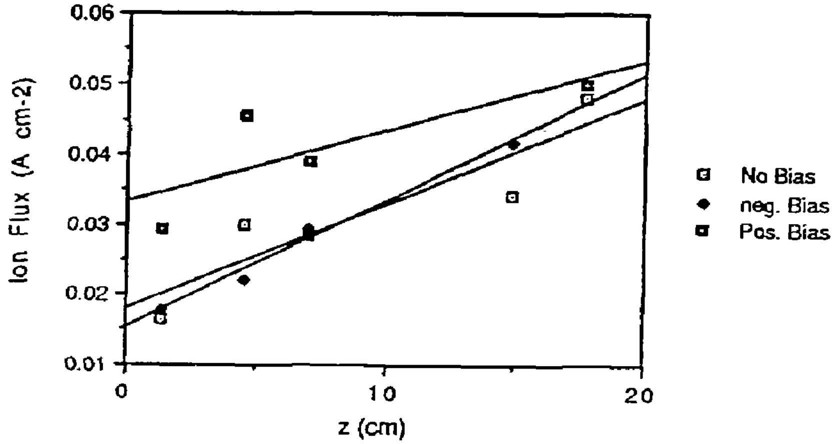

Fig. 23 Axial ion Flux in divertor throat versus distance z from neutralizer plate for ring biases of 0, -100 V and 60 V.

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