UCLA/PPG--1247

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PISCES Program
Plasma-Surface Interactions Research
Summary of Research 1988-1989

PISCES-Team*

UCLA PPG #1247 May, 1989

*PISCES-Team includes:

Research Staff	Senior Support Staff
Prof. R.W. Conn	J. Elverum
Dr. Y. Hirooka	G. Gunner
Dr. W.K. Leung	T. Sketchley
Dr. R. Doerner	P. Luong
Dr. L. Schmitz	A. Sharafat

Graduate Students
R. Lehmer
G. Tynan
Y. Ra
P. Chia

Institute of Plasma and Fusion Research
University of California, Los Angeles
Los Angeles, CA 90024

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MAJOR OBJECTIVES OF THE PISCES-PROGRAM

(1) To understand materials behavior subject to high-flux, continuous plasma bombardment in fusion devices.

(2) To evaluate and develop new materials for use as plasma-facing components in fusion devices.

(3) To understand the atomic physics associated with the transport of impurities in the edge-plasma.

(4) To understand the behavior of the edge-plasma which interacts with surface components.

(5) To develop innovative techniques to modify and control the edge-plasma characteristics.

(6) To collaborate with national and international groups to conduct PSI-experiments in the areas where PISCES can play an unique role.

PISCES PROGRAM AT UCLA

Funding Agency: US Department of Energy, Office of Fusion Energy

Faculty Staff: Prof. R.W.Conn (Principal Investigator of PISCES)
Director of IPFR

Research Staff: (1) Surface and Materials Physics (in PISCES-B):

Dr. Y.Hirooka(Co-Principal Investigator of PISCES)
Principal Scientist, IPFR

Dr. R.Doerner
Staff Scientist, IPFR

(2) Plasma Physics (in PISCES-A):

Dr. L.Schmitz
Senior Scientist, IPFR

Dr. W.K.Leung
Staff Scientist, IPFR

Senior Support Staff:

(1) Computing:	A.Sharafat
(2) Mechanical:	T.Sketchley J.Elverum
(3) Electrical:	G.Gunner P.Loung

Graduate Students: R.Lehmer
C.Ping
Y.Ra
G.Tynan

HIGHLIGHTS IN THE PROGRAM HISTORY

FY84 - PISCES-program funded by DOE-OFE.
- First collaborative experiments with ANL on Cu-Li alloy erosion.
* PISCES-A facility in operation.
* Water-cooled scanning Langmuir probe.

FY85 - First experimental evidence of the redeposition effect on the net erosion.
- Simulated pump limiter in PISCES-A.
* AES-SIMS surface analysis station constructed.

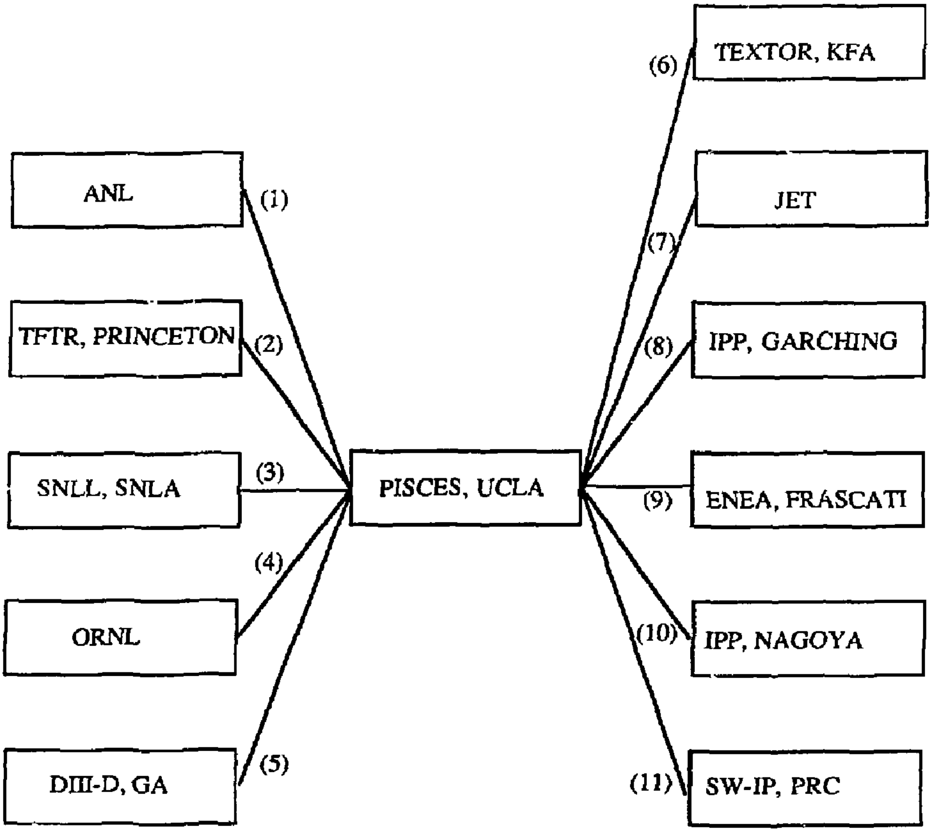
FY86 - Graphite erosion-redeposition experiments
- International collaboration started with IPP, Garching, on graphite erosion.
* Optical diagnostics established (OMA etc.).

FY87 - First off-line hydrogen plasma pumping experiments in PISCES-A.
- First **E** x **B** experiments in PISCES-A.
- Collaboration with ENEA, Frascati on the NET-candidates materials.
* First fast reciprocating Langmuir probe.
* PISCES-B design started.

FY88 - Graphite radiation enhanced sublimation experiments in PISCES-A.
- Biased limiter experiments in PISCES-A.
- CCT experiments started in collaboration with Tokamak Lab.-UCLA.
- Collaboration with China, SWIP on edge-plasma physics.
- Collaboration with KFA on plasma spectroscopy.
* SEM-EDX installed (TRW).
* PISCES-B plasma source in operation.

FY89 - Boron-doped graphite erosion experiments in PISCES-B.
- First biased divertor experiments in PISCES-A.
- Gaseous divertor experiments in PISCES-A.
- Collaboration with Japan, IPP Nagoya on the RF-limiter
- Collaboration with the NET-team, Garching the materials erosion.
* PISCES-B with in-situ AES-SIMS completed.

COLLABORATIONS WITH OTHER INSTITUTIONS



(1) Cu-Li alloy erosion exps.-85'
(Dr. A.Krauss)

(2) TFTR-exposed tile erosion exps.-88'
Deposition probe exps.-88'
(Dr. S.Kilpatrick)

(3) Gaphite pumping exps.-87'
Tungsten erosion exps.-88'
Co-deposition: ITER R&D-89'
(Dr. K.Wilson)

(4) Carbon impurity transport-88'
(Dr. J.Hogan)

(5) He-conditioning exps.-88'
Graphite tile analysis-88'
Groovy tile exps.-89'
(Dr. G.Jackson)

(6-1) Plasma spectroscopy exps.-88'
(Dr. A.Pospieszczyk)
(6-2) Ceramics materials erosion-89'
(Dr.J.Winter)
(6-3) TEXTOR graphite tile analysis-89'
(Prof. A.Miyahara and Dr.H.Dipple)

(7) JET-exposed graphite tile erosion exps.-89'
(Dr.P.Coad)

(8) Radiation enhanced sublimation exps.-88'
(Drs. C.Wu-NET, J.Bohdansky)

(9) NET-candidate materials erosion exps.-87'
(Dr. E.Franconi)

(10-1) RF-limiter exps.-89'
(Dr. T.Shoji)
(10-2) Graphite erosion exps.-89'
(Dr.A.Sagara)

(11) Omegatron exps.-88'
(Dr.E.Wang)

MAJOR FACILITIES

IN

THE PISCES PROGRAM

The PISCES-A facility[1] (Fig. 1) has been extensively used for Plasma-Materials Interaction studies and is currently devoted to boundary layer physics experiments, biased limiter and divertor simulation experiments, and the testing of novel divertor and edge management concepts. The plasma source consists of a hot LaB_6 cathode with an annular, water-cooled copper anode and attached drifttube. The vacuum system includes four turbo-molecular pumps with a pumping speed of 1500 l/s each. The main diagnostics include: (1) motor-driven water-cooled Langmuir probes; (2) a fast scanning probe capable of measuring radial density, floating and plasma potential, as well as flow velocity and Mach number profiles; (3) a 1.3 m Czerny-Turner monochromator with OMA system; (4) a fast reciprocating probe for density and potential fluctuation measurements; (5) several baratron and ionization gauges for neutral pressure measurements; (6) a CID camera; (7) an IR surface temperature monitor. A CAMAC crate with slow and fast data loggers and a Micro Vax computer system is used for data acquisition and processing.

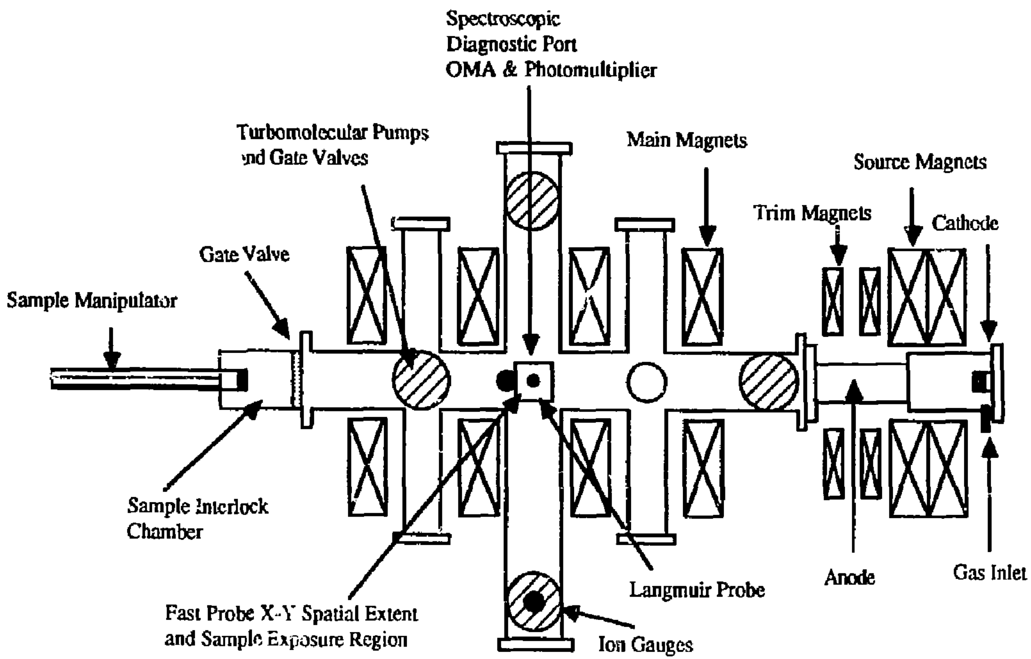
Differential pumping is employed to achieve a neutral gas pressure of $2x10^{-4}$ - 10^{-2} torr in the plasma source, while keeping the main chamber pressure between $6x10^{-5}$ and $2x 10^{-3}$ torr. Plasma is produced in H_2, D_2, He, and Ar gas. Plasma densities of 10^{11} - 10^{13} cm^{-3} and electron temperatures of 3 - 30 eV are presently achieved.

The plasma diameter can be adjusted beweeen 3 and 10 cm by three independent magnet coils located in the source region. The main chamber magnetic field (variable between 100 and 1700 gauss) is produced by four water-cooled coils.

The PISCES-A chamber provides good diagnostic access. The fast scanning probe system has been extensively used for 2-D and 3-D mapping of plasma density and potential profiles during biased limiter and divertor simulation experiments and tests of magnetized probe theory and presheath measurements.

[1]D. M. Goebel, G. Campbell, R. W. Conn, J. Nucl. Mater. **121** (1984) 277

Fig. 1 PISCES-A: Plasma-surface interactions research facility at UCLA.



A new plasma-surface interactions experimental research facility: PISCES-B has been designed and constructed at UCLA. A schematic diagram of the facility is shown in Fig. 1. The PISCES-B facility is designed specifically for the surface physics and chemistry experiments. For this purpose, the following features are given: (1) the vacuum system is pumped by two turbo-molecular pumps with the effective pumping speeds of 5000 l/s and 1000 /s. (2) the vacuum chamber sections are fully bakable so that the base pressure is of the order of 10^{-9} torr; (3) the main vacuum chamber has 10 line-of-site ports focusing at the sample surface; (4) a differentially pumped residual gas analyzer (RGA) to monitor gaseous plasma-surface interactions products (the minimum detectable partial pressure of 10^{-14} torr) ; (5) a temperature-controlled (RT-2000°C) sample probe; (6) In-situ surface analysis diagnostics including: Auger Electron Spectroscopy (AES) and Secondary Ion Mass Spectroscopy (SIMS); (7) an in-situ outgassing furnace with a dedicated RGA; (8) a 1.3 m monochromator coupled with an optical multi channel analyzer (OMA) for the in-situ spectroscopic detection of plasma-surface interactions products (9) a scanning Langmuir probe, the data from which is processed by a MicroVax computer. A special swing-linear motion sample manipulator has been constructed to transport the sample between the main plasma chamber and the surface analysis chamber without air-exposure.

The PISCES-B facility has been successful in generating steady-state plasmas of hydrogen, deuterium, helium and argon. The plasma densities of 10^{11} - 10^{13} cm^{-3} and electron temperatures of 3 - 45 eV have been achieved as shown in Fig. 2. The plasma operation space is found to be wider than the PISCES-A-facility, which is presumably owing to the large pumping speed of the turbo molecular pump to control the neutral particle density. In fact, the neutral pressure of the plasma working gas in the main chamber can be as low as 10^{-3} torr and as high as 10^{-5} torr. The ion bombardment energy is controlled by applying a DC-bias to the sample probe in the range from the floating potential to about 500 V. The magnetic field is variable between 100 to 1000 gauss in the sample region and the corresponding ion gyro-radii are estimated to be between 1 and 5 mm. These plasma bombardment conditions easily allow us to simulate plasma-surface interactions in the limiter region as well as in the divertor region of tokamaks such as ITER and beyond. Important PSI-related parameters are listed in table 1.

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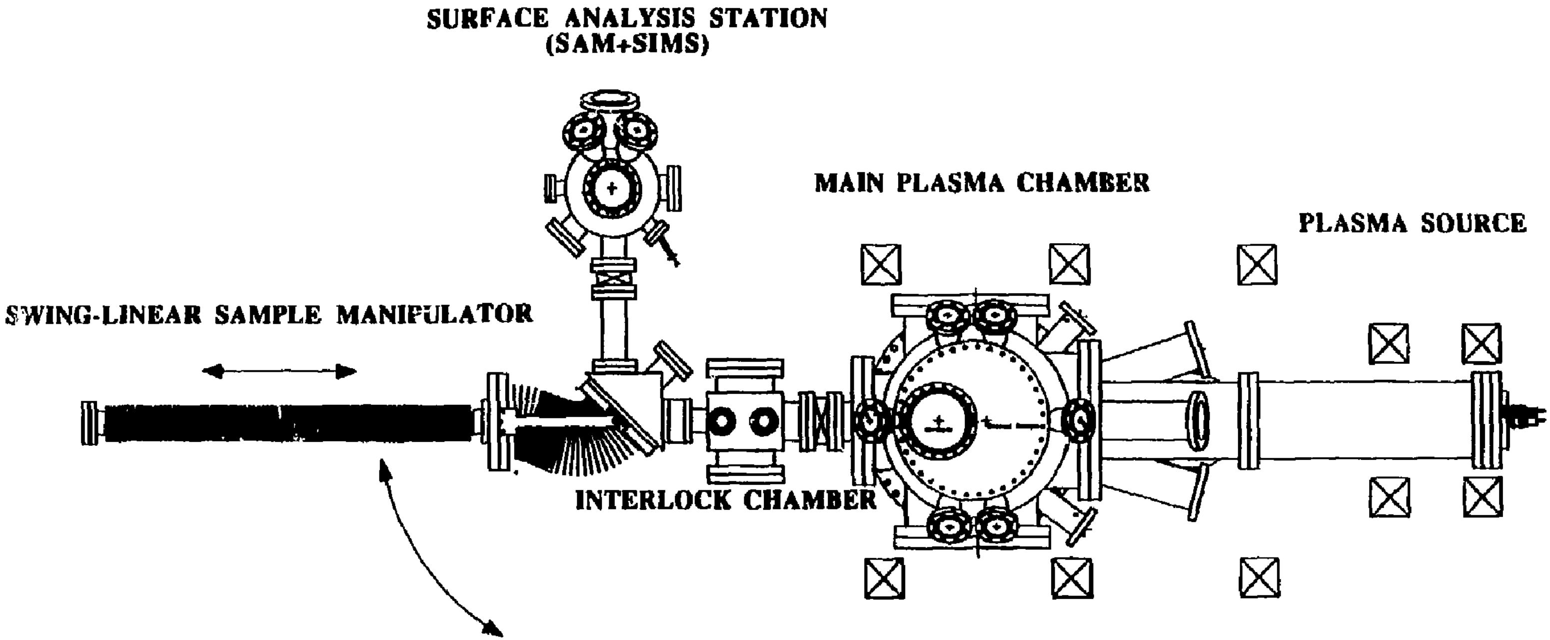
*Results to be presented at 36th AVS National Symposium at Boston, Oct. 1989.

Fig. 1 PISCES-B: Plasma-surface interactions research facility at UCLA.



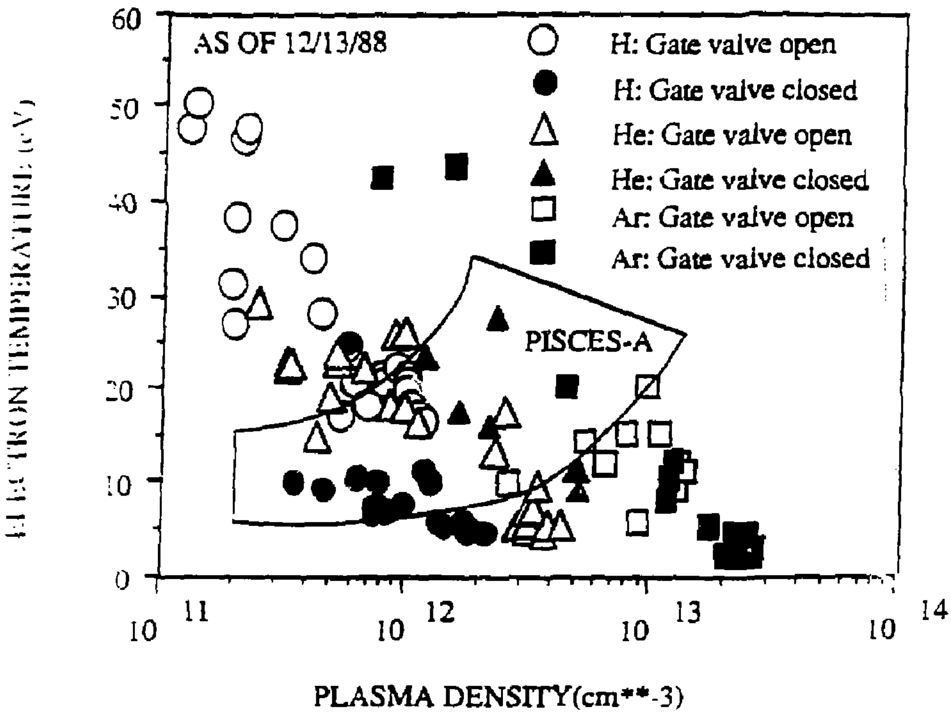


Fig. 2 Plasma operational spaces for the PISCES- A & B facilities.

Table I Comparison of PSI-related parameters in ITER and the PISCES-B facility.

Parameter	ITER (in Physics phase)		PISCES-B
	First wall	Divertor plates	
Surface components	C-C	PyG(⊥)	C-C, PyG (⊥, //), POCO, SiC, BN etc.
Average pulse duration (s)	> 100	> 100	continuous
Neutral pressure (torr)	10^{-5}-10^{-4}	10^{-4}-10^{-3}	10^{-5}-10^{-3}
Plasma density (10^{16}particles/m^3)	10-100	100-10000	10-5000
Plasma bombarding energy (eV)	10-200 (3kTe)	300-2400 (3kTe)	20-2000 (DC-bias*)
Particle flux(10^{20}particles/m^2s)	1	5-1000	10-1000
Heat flux(MW/m**2) Ave.	0.1-0.2	2-5	up to 10 (0.5 A x DC-2000V)
Peak	0.5-1.0	15	
Surface temperature (^{o}C)	< 2000	< 1500	RT-1800
Surface cooling scheme	radiative**	pres. water	radiative/air/water

*High voltage DC-power supply will be funded with ITER R&D program.
**Active water cooling is being considered.

The study of the physics of presheaths and tokamak-like scrape-off-layers in the PISCES plasma-surface interaction facility has lead to the development of a fast injection, spatially scanning combination emissive/mach probe diagnostic. The emissive probe is a unique diagnostic tool because it permits the simple, continuous monitoring of the space potential as long as the probe can emit more electrons than the incident electron flux from the plasma. In addition, a fast spatially scanning probe diagnostic is very important and unique tool in analyzing tokamak edge plasmas. Such a diagnostic can accumulate localized profiles of potential, density, temperature, parallel mach number, and heat flux, as well as the fluctuations of the first three quantities.

The fast scanning probe diagnostic in PISCES-A uses a pneumatic cylinder to drive a combination emissive and mach probe tip across the plasma column. This allows for single scan or shot profiles of the space or floating potential, density, and parallel mach number. Since the PISCES facility has a steady state plasma generator, profiles of the space and floating potentials under identical plasma conditions can be obtained by using successive shots of the fast probe. To record the floating potential profile, the emissive probe tip is left cold. To record the space potential profile, the probe is resistively heated so that it will thermionically emit electrons into the plasma. The probe will cancel the effect of sheath in front of the probe and electrically float at the space potential.

The fast probe actuator (figure 1) has a 15cm stroke and the total round trip time for the probe is 300msec. The probe is constructed of an alumina shaft with six holes for wires to pass through. The tip (figure 2) is made up of five electrical probes: a loop of thoriated tungsten wire for the emissive probe, and two pairs of unidirectional probes. Each pair of unidirectional probes has one tip that faces towards the source ("upstream") and the other faces away from the source ("downstream"). One pair has tips larger than the ion Larmor radius and is referred to as a magnetized mach probe, while the other pair is smaller than the ion Larmor radius and has been used to study ion flow in plasma wakes. The parallel mach number is computed from the ratio of the currents collected by the upstream and downstream magnetized probes. Density profiles are computed from the average of the current collected by the two probes.

The PISCES-A fast probe diagnostic has been used to study presheath profiles in front of material samples, the modification of the potential profiles and scrape-off layer lengths in biased scrape-off layer simulation experiments, ion flows in the wakes of probes in the plasma, modification of density profiles in RF limiter/divertor simulation experiments. In addition, the fast probe has been used to monitor plasma potential and density profiles in experiments on radiation enhanced sublimation, biased pumped divertor experiments, and divertor channel simulation experiments.

Based on the success of the PISCES-A fast probe diagnostic, another fast scanning probe diagnostic is under construction for the new PISCES-B facility. The quantities of interest in materials experiments are the electron temperature and density profiles. Mechanically, the PISCES-B fast probe diagnostic will be basically the same as the PISCES-A diagnostic except that the PISCES-B probe will have only a single probe tip. During the fast probe stroke, the probe tip voltage will be swept rapidly. This results in a number of Langmuir probe traces at different radii. These traces can be fitted automatically by the data acquisition system to produce a discrete spatial profile of electron temperature and density across the plasma column. The use of the fast probe in PISCES-B material experiments will minimize sample contamination resulting from sputtered probe materials.

R. Lehmer, et. al, A Fast Spatial Scanning Combination Emissive and Mach Probe for Edge Plasma Diagnosis, UCLA-PPG-1228 (1989)

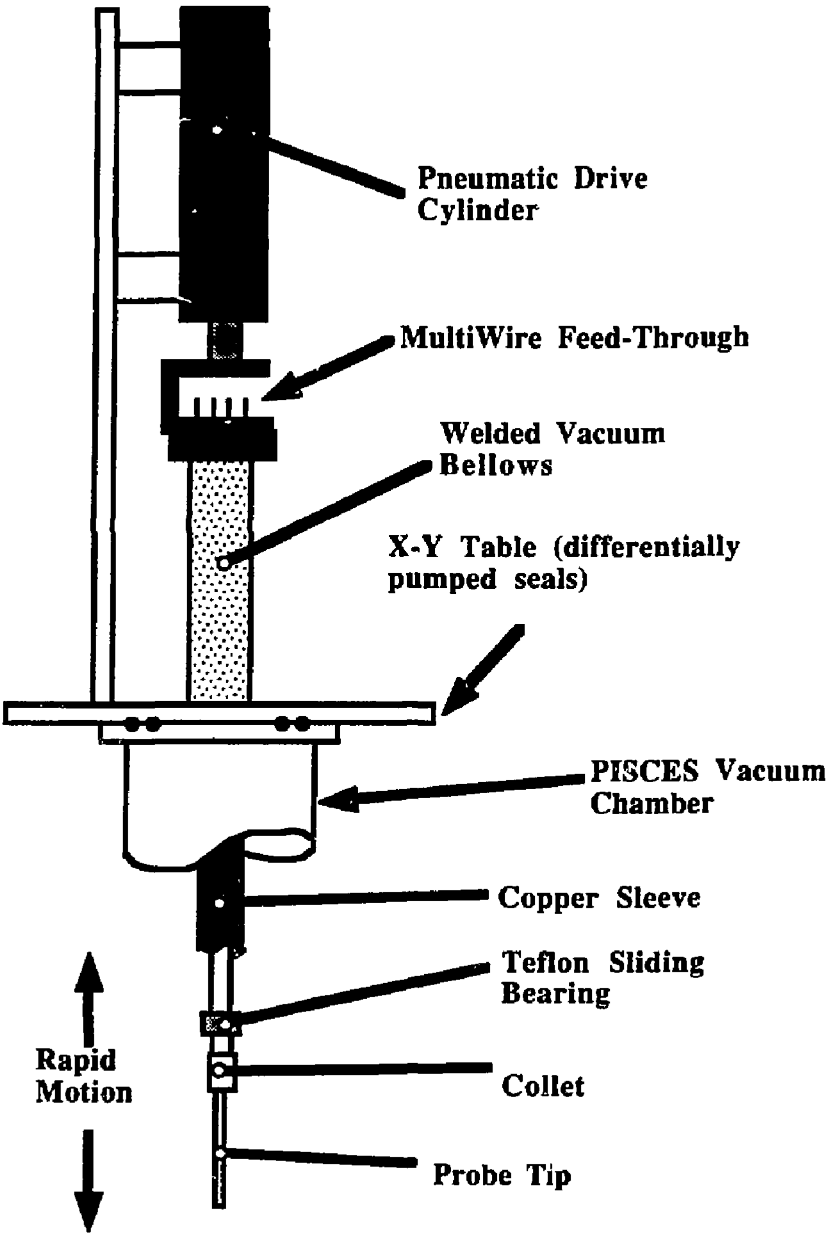


Figure 1: Schematic of the UCLA/PISCES-A Fast Scanning Probe Actuator

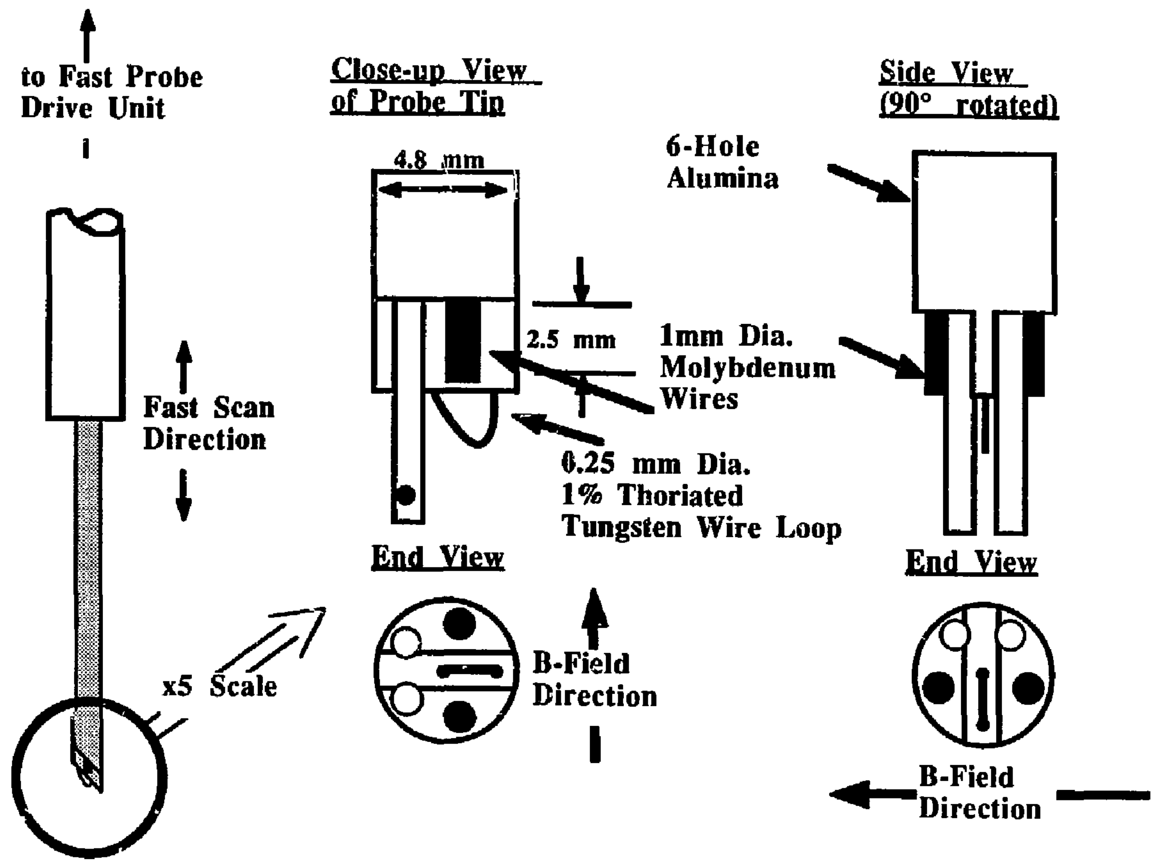


Figure 2: Geometry of the UCLA/PISCES-A Combination Emissive and Mach Probe Tip

An Omegatron Mass-Spectrometer For Plasma Ion Species Analysis

The measurement of the ion species and charge state distribution in the Tokamak boundary layer plasma is of importance for erosion/redeposition studies, impurity transport studies, and the evaluation of next generation materials for divertor and first wall applications. In contrast to impurity line spectroscopy (requiring density and electron temperature profile data for quantitative interpretation) and collector probes (sampling impurities over a large number of shots), the Omegatron Mass Spectrometer provides real time, locally resolved data on the ion species and charge state distribution in a strongly magnetized plasma.

A prototype Plasma Omegatron spectrometer has been tested in PISCES. In the conventional omegatron, ions are formed as the result of ionization of gas in a fine electron beam passing through the center of the analyzer along the magnetic field. In the plasma omegatron we allow the plasma to flow along the magnetic field into the analyzer through a small floating aperture. We employ a biasing technique to reduce the ion velocity along the magnetic field and, thus, achieve improved ion collection and sensitivity. Experiments have been performed to demonstrate the instrument's operation in the linear PISCES plasma device, at a magnetic field B = 1.3 kG. In a helium plasma, He ions as well as residual hydrogen ions (outgassing from previous experiments in H_2) have been detected (Fig. 1). The instrument's resolution has been found to be close to the theoretical value at a neutral pressure $p < 5 \times 10^{-4}$ torr.

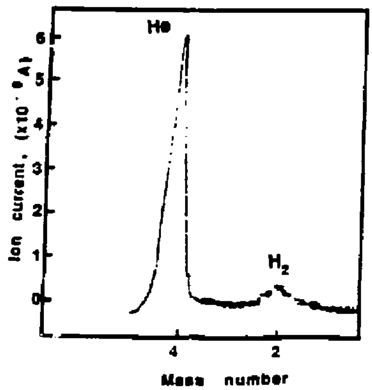


Fig.1: Mass spectrum of a helium plasma with residual hydrogen outgassing ($N_e = 5 \times 10^{12}$ cm^{-3}, $kT_e = 7$ eV).

In collaboration with Prof. E. Y. Wang (South Western Inst. of Phys., Leshan, PRC)

Spectroscopic diagnostics facility for PISCES A and B

Spectroscopic techniques have been applied in PISCES A and B in diagnosis of erosion yields [1], ion temperaure [2], impurities[2], density profile measurement [3] and RF plasma modifications [4]. Apart from its uniqueness in in-situ erosion yield measurement in material experiments, it emerges as an integral part of many edge physics experiments in both PISCES A and B.

The spectroscopic diagnostic instruments in PISCES Laboratory consist of a 1.3M Czerney-Turner spectrograph/monochromator, a .27M Czerney-Turner spectrograh /monochromator, an OMA system, a CID camera and computer image analysis system.

The OMA can be integrated with the spectrograph to obtained both spectral and spatial infromation of the plasma. A plot of the profiles of the line emission of ArII before and during RF field modification [3] of the plasma is shown in Fig. 1.

The CID camera can be used to obtain spatial emission profiles or, when integrated with the spectrograhs, can produce spectral and spatial profiles simultaneously. This is made possible with in-house development of interfacing the separate instruments and computer software.

In addition, an optical fiber array is being developed to upgrade the system so that the instruments can be interchanged for experiments in PISCES A and B without loss of considerable time for realignment and physical relocation of instruments.

Investigation of impurity transport and Hydrogen species mix measurements are planned. Routine support is provided for on going material experiments (e.g. C-B and high tempera[illegible] graphite experiments), and for physics experiments (e.g. RF experiment and gaseous divertor experiment).

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1. W. K. Leung et. al., JVST A, 7 (1989) 21.
2. W. K. Leung et. al., Bull. Am. Phy. Soc., Baltimore , vol. 31 , October (1986).
3. W. K. Leung et. al., Bull. Am. Phy. Soc., San Diego , vol. 32 , October (1987).
4. T. Shoji and PISCES group, to be published.

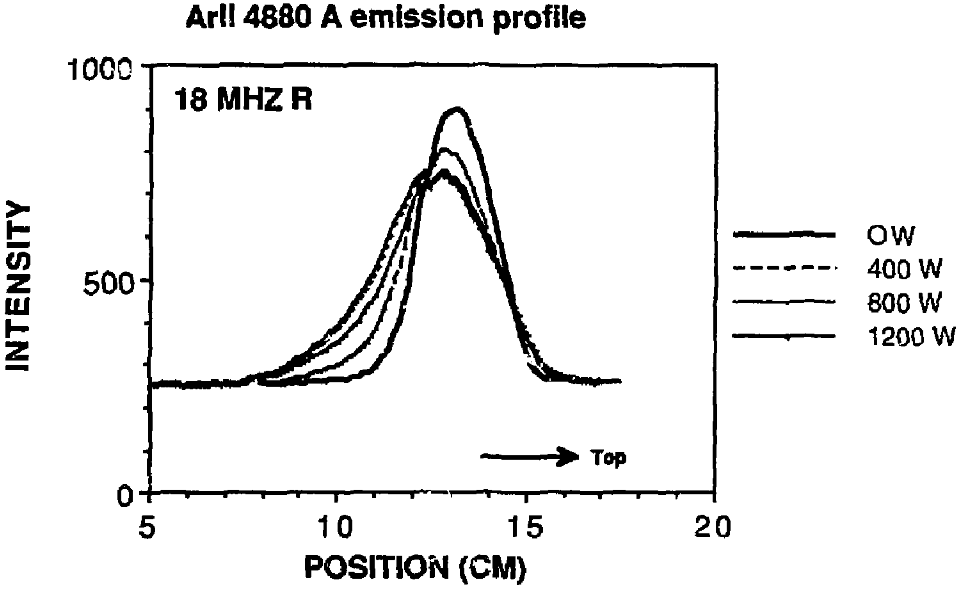


Fig. 1 Vertical emission profiles of the Ar plasma during RF experiment

The PISCES Data Acquisition System provides for the storage and manipulation of raw data from the PISCES-A, PISCES-B, and the CCT Tokamak. The main components of this data acquisition system are the CAMAC (Computer Automated Measurement And Control) crates containing fast and slow data loggers and a Vax Cluster consisting of a MicroVax-II and three Vax2000 workstations (figure 1). A serial Highway Driver interfaces the Vax Cluster with the CAMAC crates through fiber optic conections that provide for high voltage isolation.

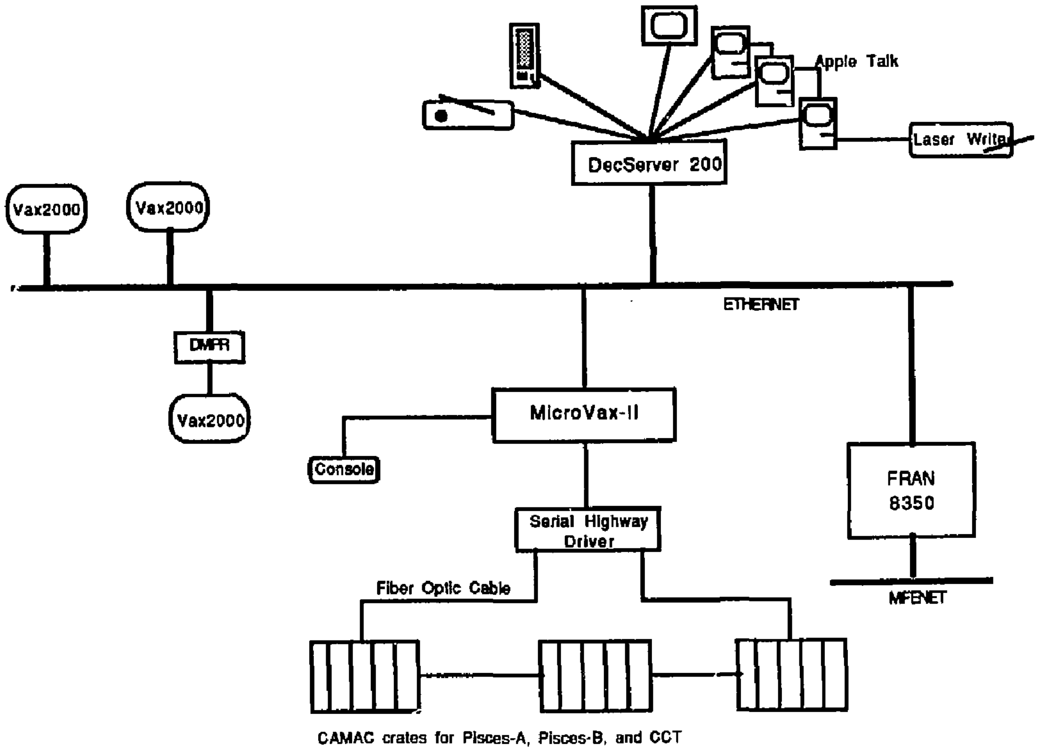
The CAMAC crate connected to the PISCES-A machine contains two 32-channel slow loggers and is capable of sampling data at a rate of up to 100 KHz. The number of active inputs is programmable and as fewer inputs are used available memory storage per channel and maximum achievable sampling rate are increased. Individual channels have descriptive logical names assigned to them, which facilitates user access to raw data. ORNL CAMAC crate drivers are used for setting up the data loggers and retrieving raw data from them. The MIT MDS software manages the storage of raw data and user access to the databases. The CAMAC crate connected to the PISCES-B machine contains one slow logger similar to the ones in PISCES-A.

PISCES-developed DACPs (Data Acquisition Control Programs) control continuous as well as post-triggered data sampling on the PISCES-A and PISCES-B machines. The DACPs provide user control of data acquisition functions as well as compute processed data from recently retrieved raw data. The CAMAC crate used by the CCT Tokamak contains two fast loggers with each 4 channels capable of sampling data at 1 MHz and one slow logger with 32 channels.

The MIT MDS software as well as the DACPs run on the MicroVax Cluster. Other customized softwares using IDL and MCCOOL graphics packages provide capabilities for realtime data analysis and manipulation. In addition, fluctuation analysis software has been developed by the PISCES group for use in analyzing fluctuation induced transport in CCT.

The Vax Cluster is connected through an Ethernet cable to a DecServer 200 terminal server serving three Macintoshes with a Dec Laser printer for hard copies, a modem , and a PC. Terminal emulation programs running on the Macintoshes facilitate transfer of data to and from the Vax cluster.

Figure 1: The Pisces Lab Data Aquisition System



HIGHLIGHT DATA

FROM

MATERIALS PHYSICS EXPERIMENTS

Using the PISCES-A facility, the redeposition of sputtered particles has already been demonstrated to reduce the net erosion significantly for several materials such as metals, graphite and ceramics*. The effect of redeposition is currently regarded as one of the most crucial issues in designing the plasma-facing components in the next-generation reactors such as CIT and ITER. In the present work, the chemical erosion yield of POCO-graphite (grade: HPD-1) as the reference material has been measured as a function of mean free path for electron impact ionization of methane molecule.

The plasma bombardment conditions are: the ions flux around 2 x 10^{18} ions cm^{-2} s^{-1}; and the ion bombarding energy set at 100 eV. The erosion yield is evaluated by the weight loss method. To minimize the error in weight loss measurements, the plasma bombardment fluence was always of the order of 10^{21} ions cm^{-2}. The erosion yield data is shown in Fig. 1 as a function of surface temperature for three different ionization mean free paths of 15cm (erosion condition), 5 cm (partial redeposition condition) and 1 cm (strong redeposition condition). Notice that the erosion yield changes drastically as the mean free path decreases. In this particular case, the ionization mean free path is calculated only for methane. However, it is also true that other hydrocarbon molecules are formed due to chemical sputtering. This means that the redeposition effect due to these hydrocarbon molecules becomes more important when the mean free path is relatively short.

One might extend the present data to the divertor region of ITER where the ionization mean free path of hydrocarbon is expected to be as small as 1 mm. In such a case, the chemical erosion yield will probably be two orders of magnitude lower than that without the redeposition effect. This might relieve one's concern with the life time issue of the plasma-facing components. However, it has been theoretically pointed out that if the angle of incidence of the redepositing particle transported along with the magnetic field is as high as 70-80 degrees with respect to the surface normal, one might have to be concerned with the "run away erosion" crisis for the divertor plate. Nevertheless, further investigation in this area is needed.

*See Y.Hirooka et.al., Nucl. Instr. & Methods-B 23(1987)458.
D.M.Goebel et.al., Nuclear Fusion 28(1988)1041.
E.Franconi et.al. J.Nucl.Mater 163-165(1989).

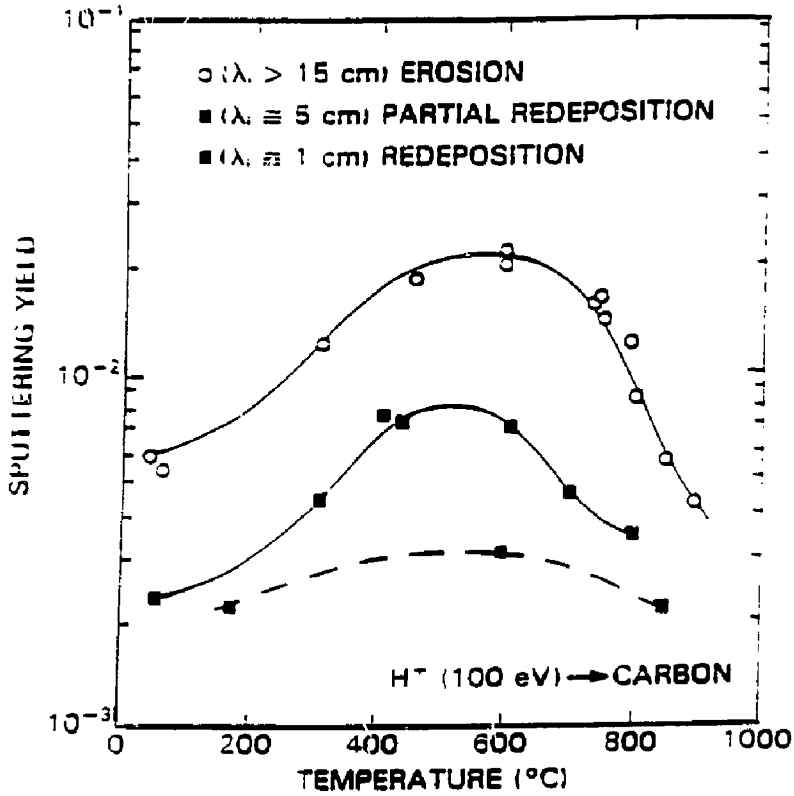


Fig. 1 Chemical sputtering of POCO-graphite as a function of surface temperature due to hydrogen plasma bombardment at an ion energy of 100 eV. Plasma parameters are set such that the ionization mean free path is 15 cm, 5 cm and 1 cm.

Erosion of Carbon-Deuterium Co-deposited Materials from TFTR

It is well known that materials once eroded from the plasma-facing components in a fusion device are likely to be redeposited elsewhere due to the poloidal and toroidal transport effects. Along with the change in plasma discharge conditions, the redeposited surfaces may then be subject to the high flux plasma bombardment to cause the erosion dominated condition. So, it is of significant importance to understand the erosion behavior of redeposited materials in tokamaks (often referred to as "tokamakium"). The need for the data on the erosion yield of tokamakium was first pointed out in the INTOR design study about a decade ago. Since then, however, only limited amount of experimental data has been obtained in this area.

In the present experiment, graphite tiles exposed to plasma discharges in the redeposition-dominated area of the bumper limiter of TFTR is subjected to deuterium plasma bombardment in the PISCES-A facility for erosion yield measurements. It is well known that graphite is used for the plasma-facing components in major fusion facilities. In this regard, tokamakium used here measurement is very "contemporary". The deuterium concentration in the carbon tokamakium is known to be about 2×10^{18} D/cm^2, from separate NRA measurements, which is about one order of magnitude higher than the typical surfaces in the erosion-dominated region in TFTR. So, one might understand that the redeposited material used here is a co-deposited material of deuterium and carbon. On the other hand, the concentration of the metallic impurities is as low as less than 1 %, which is extremely clean for a tokamak-exposed surface in general. The deuterium plasma bombardment conditions are: the ions flux around 2×10^{18} ions cm^{-2} s^{-1}; and the ion bombarding energy set at 300 eV. In this study, the in-situ erosion yield measurement technique* is used to evaluate the erosion yield. The surface temperature is raised at an average rate of 5 degs/s from room temperature to 950 C.

Shown in Fig. 1 are the erosion yield data for the carbon tokamakium, the graphite from the erosion-dominated area of TFTR and virgin POCO-graphite (grade: AFX-5Q) as the reference material. The erosion yields for the TFTR-eroded surface and POCO-graphite are essentially the same. The erosion yield of the carbon tokamakium is about 10-15% higher than those of other graphite materials. Also, one may notice that the temperature at which the erosion rate maximize for the tokamakium is somewhat lower. The details are still unclear, yet all these observations are consistent with the earlier measurements using amorphous hydrogenated carbon with relatively high hydrogen concentration.

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* See W.K.Leung et.al. J.Vac.Sci.& Technol.-A 7(1989)21.

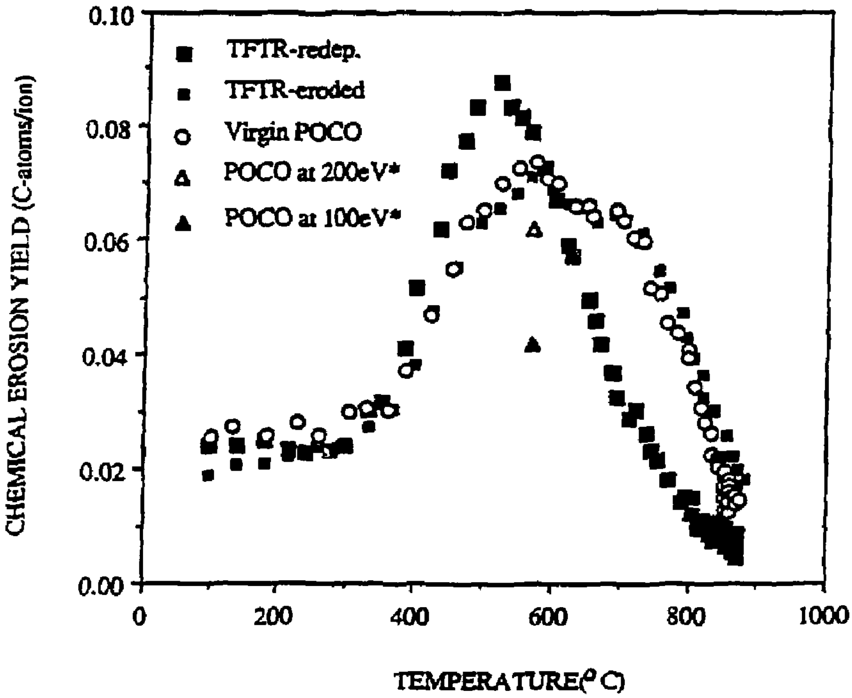

Fig. 1 Chemical sputtering of POCO-graphite as a function of surface temperature due to hydrogen plasma bombardment at an ion energy of 100 eV. Plasma parameters are set such that the ionization mean free path is 15 cm, 5 cm and 1 cm.

Reduced Chemical Sputtering of Boron-Doped Graphite Materials

Up to date, graphite materials have been extensively used as the plasma-facing material in the existing fusion devices. However, it is also true that graphite suffers from plasma-induced erosion such as chemical sputtering and radiation enhanced sublimation. Several observations have been reported concerning the effects of surface impurity on these erosion processes. The latest understanding of the surface impurity effect is that the impurity may act as an enhanced hydrogen recombination. As a consequence, the chemical erosion to cause the hydrocarbon formation is reduced. From the basic ion beam research, boron is also known to be one such impurity. However, there has been virtually no data on the erosion yield of boron-doped graphite due to hydrogen plasma bombardment under conditions expected in tokamaks like ITER or beyond.

Using the PISCES-B facility, the chemical erosion yield measurements have been conducted for 150 ppm boron-doped graphite (POCO-graphite Co.), 3% boron-doped graphite (Toyo Tanso Co.) and also POCO-graphite (grade: AFX-5Q) as the reference material. The erosion yield is evaluated by means of the in-situ spectroscopic technique** (data first spectroscopically measured and then calibrated by the weight loss method). The plasma bombardment flux is about 3×10^{18} ions cm^{-2} s^{-1} and the ion bombarding energy is set at 300 eV. The temperature of the sample is raised from room temperature to 950^{o}C. These conditions are believed to be relevant to the divertor area of ITER. No difference in the erosion yield for 150 ppm B-doped graphite and POCO-graphite. On the other hand, as shown in Fig. 1, the chemical erosion yield due to hydrogen plasma bombardment at 300 eV for 3%B-doped graphite has been found to be significantly smaller (about 30%) than that for POCO-graphite.

It follows from this result that further reduction is expected if one increases the boron concentration. However, from a practical engineering viewpoint, one might keep the material from being brittle due to the carbide phase (B_4C) formation. It is known that the critical boron concentration to form carbide is around 8-10%. In order to meet these requirements, the next experiments are being considered to be carried out using graphite doped with boron up to the critical concentration. This special material will be also supplied from Toyo Tanso Co., who has expressed strong interest in collaboration with the PISCES-group. As a part of collaboration, we have also suggested the possibility of manufacturing C-C composites with B-doped carbon in order to increase the thermal shock resistance.

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* Results to be presented at 36th AVS National Symposium at Boston, Oct., 1989.

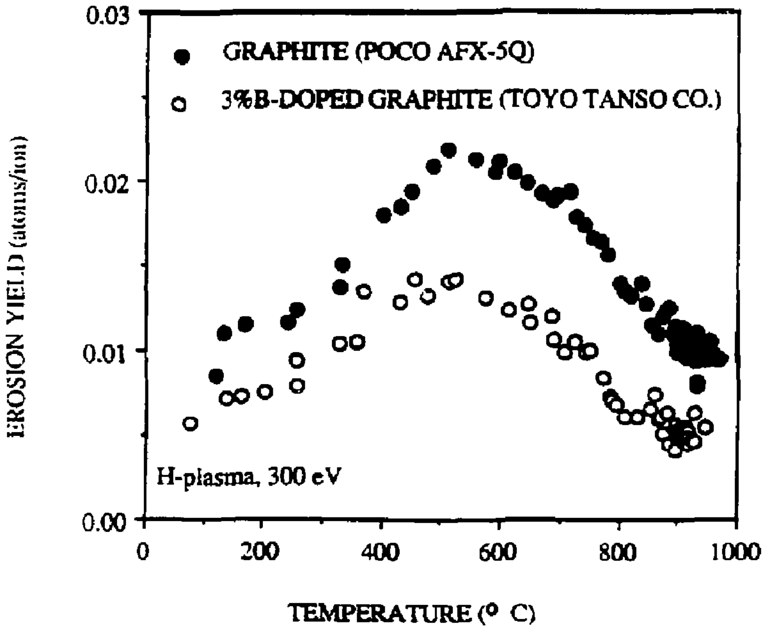

Fig. 1 Chemical sputtering of boron doped graphite and POCO-graphite as a function of surface temperature due to hydrogen plasma bombardment at an ion energy of 300 eV.

High Temperature Erosion of Graphite

The erosion behavior of graphite at elevated temperatures when subjected to energetic ion bombardment is becoming increasingly important, not only in future design efforts (i.e. CIT and ITER), but also in presently operating tokamaks. Radiation Enhanced Sublimation (RES) dominates the erosion yield of graphite at temperatures above 1000 °C. The mechanism responsible for RES is theorized to be the creation and migration of interstitial carbon atoms and vacancy sites through the graphite lattice. There has been some hope that the high erosion rates observed in ion beam measurements at low fluxes might abate significantly at higher fluxes. The question of the flux dependence of this erosion mechanism is now being investigated in PISCES.

A resistively-heated high-temperature (<2300 °C) graphite sample holder is used in the PISCES laboratory to study the flux dependence of the RES erosion yield. Erosion rates are monitored spectroscopically using the CI line at 9095 A. Weight loss measurements of the sample are then used to absolutely calibrate the spectroscopic data. High-temperature graphite erosion yields approximately a factor of two lower than the predictions of models have been obtained in PISCES under erosion dominated conditions (long mean-free-paths). Preliminary results indicate substantially lower erosion yields in redeposition dominated regimes (short mean-free-paths).

The phenomenon of carbon blooms is also attributed to high-temperature graphite erosion. Carbon blooms are predicted to be the result of a runaway erosion condition (i.e. a self-sputtering yield above unity) and have been observed in TFTR and JET. These runaway erosion conditions have been achieved in PISCES concurrent with large bursts of carbon radiation spectroscopically observed at the sample surface. Accompanying runaway erosion is a runaway current collected by the sample, which unfortunately quenches the PISCES plasma. Modifications are underway to increase the sampling frequency of the collected data to enable gathering of information during the relatively short bursts of carbon blooming observed in PISCES.

Results to be presented at 36th AVS National Symposium at Boston, Oct. 1989.

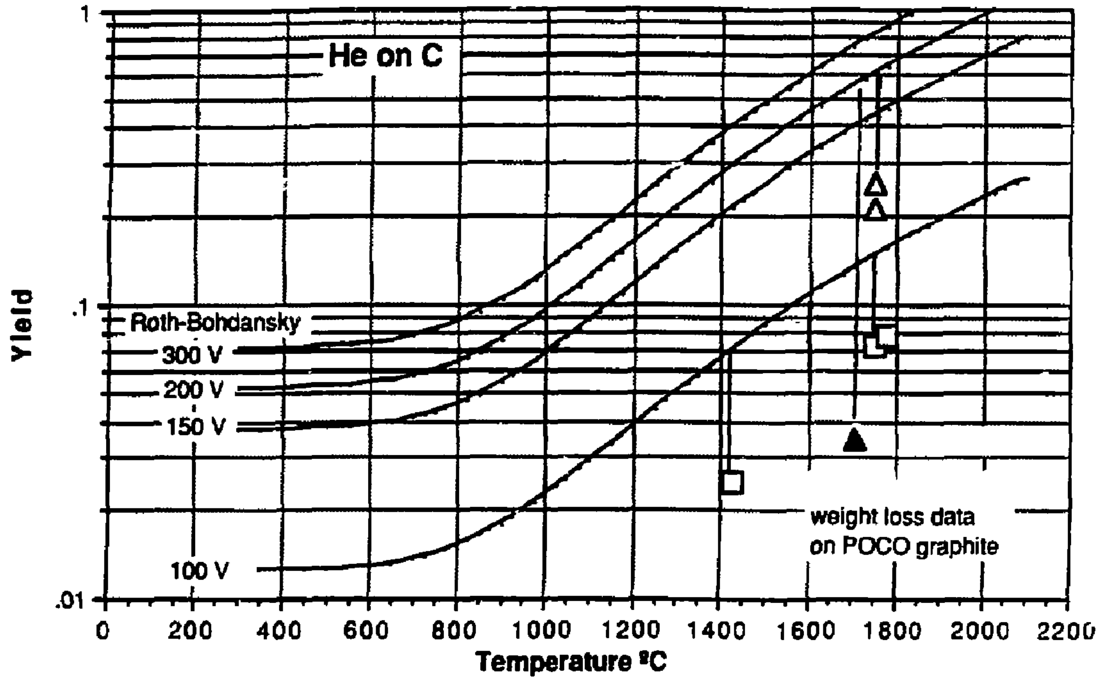

Figure 1- Comparison between theoretical erosion yield of graphite calculated by Roth and Bohdansky (solid lines) to experimental measurements in PISCES (symbols). The open symbols represent erosion dominated regimes, the solid symbol represents a redeposition dominated regime.

TEXTOR Tile Analysis

The PISCES program has been involved in evaluating the effects of surface conditions on the performance of plasma facing tokamak components*. Comparisons between tiles from different machines is often complicated by differing wall-conditioning techniques and different plasma exposure histories. A comparison of limiter tiles obtained from the TEXTOR tokamak at KFA-Julich is now underway.

Two types of limiters are employed in TEXTOR; an inner-bumper limiter (IBL) and a toroidal-belt limiter (ALT-II) located at 45 degrees below the outer midplane. Each limiter exhibits different interactions with the plasma. Under certain conditions, the IBL is observed to act as a sink for neutral hydrogen in the edge plasma region. ALT-II acts as a neutral gas source when in contact with the edge plasma.The plasma exposure histories of both of these limiters is well documented. Measurements during plasma operation in TEXTOR indicate a highly non-uniform heating of the IBL, whereas the power loading on ALT-II is much more uniform. Limiter tiles from both the IBL and ALT-II will be compared under identical plasma conditions in PISCES to determine the hydrogen retention ability and erosion characteristics of both type of tiles.

Surface morphology and impurity concentration measurements have been made of each tile before PISCES plasma exposure by Prof. Dr. Koizlik at KFA-Julich. Figure 1 shows representative data obtained from an ALT-II tile. The tile shows very little effect of having been exposed to the TEXTOR plasma. Only trace amounts of impurities are measured in the graphite and no physical damage of the tile is observed. Identical measurements will be done at UCLA following plasma exposure in PISCES. This investigation will be further supplemented by deuterium retention measurements using microprobe analysis by Dr. Doyle at SNLA.

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* See Y. Hirooka, et al. to be published in J. Vac. Sci. & Technol. May/June issue (1989).

Figure 1- SEM data of an ALT-II tile showing little surface morphology change from the original porous graphite surface.

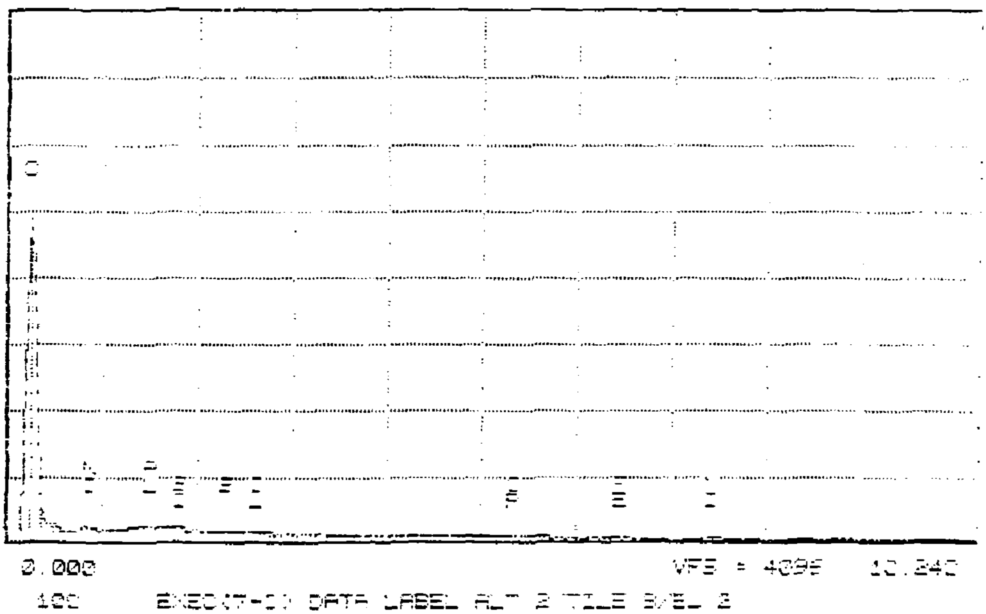

Figure 2- Analysis of an ALT-II tile reveals little impurity concentration in the graphite after plasma exposure.

A New Spectroscopic Method for the Measurement of Carbon Impurity Flux

Graphite used for the limiter in fusion reactor produces molecular carbon impurities, such as hydrocarbons and carbonoxides, as a result of interaction with the edge plasma. A new spectroscopic method is developed to measure the absolute quantity of the molecular impurity flux into the plasma.

The molecules chemically eroded from the graphite interact with the plasma and emit photons. If the plasma is hot and dense enough, most of the molecules eroded into the plasma will be ionized or dissociated. Since the number of photons which will be emitted from the ionized or dissociated molecules as certain molecular bands and atomic lines, called photon efficiency, was found from the previous gas injection experiment in PISCES-A [1], the absolute flux of eroded molecules can be known by measuring the intensity of bands and lines. The effect of escaping molecules due to the finite size of plasma can be minimized by measuring the emissivity at the center of graphite sample. Abel inversion is needed for this.

The new method is applied to the measurement of POCO graphite erosion yield by hydrogen plasma bombardment. The absolutely calibrated optical multichannel analyser (OMA) attacehed to the optical spectrometer is used to measure the spectral intensity. The brightness profile is measured either by the CID camera with interference filters or by a scanning mirror when the interference filter is not available. Most of the molecules chemically eroded from the graphite is assumed to be methane. The brightness profile is abel-inverted to give emissivity at the center. The photon efficiency of CH band from methane (Fig. 1) is used to convert the measured photon numbers into the actual number of methane molecules. The results are compared with the conventional weight loss measurement (Fig. 2). The good agreement of two results indicates the new spectroscopic method is valid.

Using the photon efficiencies for other bands and lines, a trial to separate chemical and physical sputtering yield is being made. Also, applying this method to the formation of high order hydrocarbons, such as ethylene and acetylene, and oxygen chemical sputtering is planned.

1. A. Pospieszczyk, Y. Ra, Y.Hirooka, R.W. Conn, D. M. Goebel, B.Labombard, R.E. Nygren, Poster presented at American Physical Society, Ft. Lauderdale, 1988

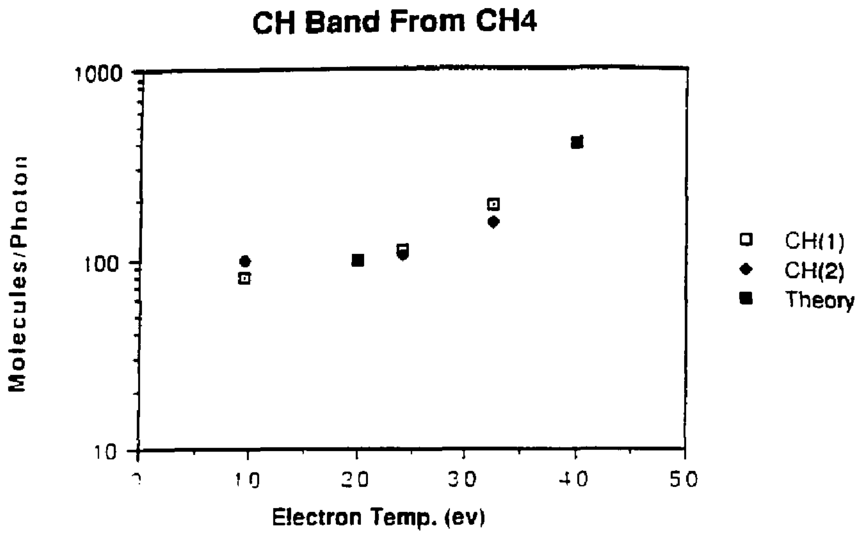

Fig. 1. The photon efficiency of CH band from methane.

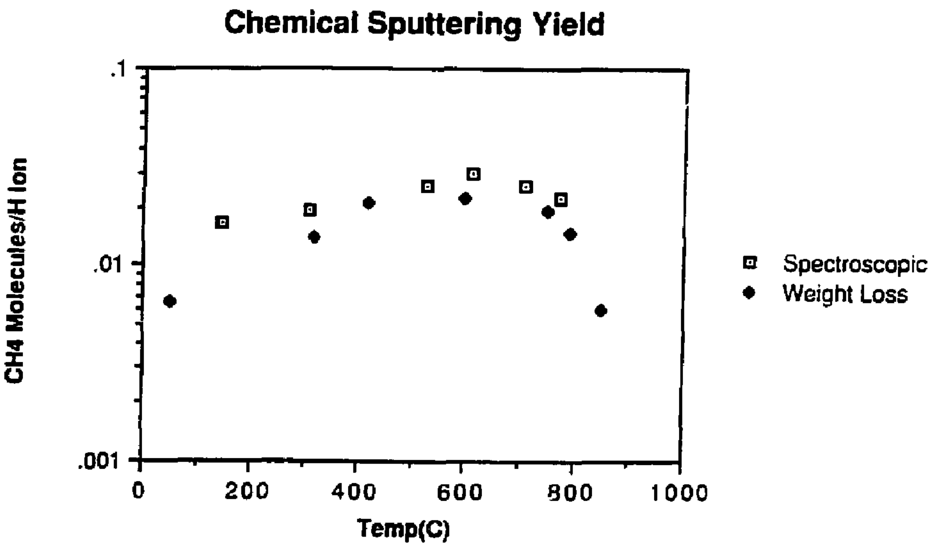

Fig. 2. Chemical sputtering yield of POCO graphite.

HIGHLIGHT DATA
FROM
EDGE-PLASMA PHYSICS EXPERIMENTS

UCLA has a program of experiments, theory and modeling, with the global objective of developing novel techniques for controlling plasma boundary layer flow. Divertor biasing is potentially a powerful tool to control particle transport and divertor heat load in tokamak confinement experiments. Our objective in the PISCES experiments is to model a variety of biasing schemes[1]. In particular, the work described here we try to infer diffusion and mobility coefficients from density and potential profiles measurements when electrically biased structures are inserted into plasmas simulating tokamak edge conditions. Figure 1 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. PISCES experiments simulate the upper configurations (Fig. 1a-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 :

$$\Gamma_{\perp} = -D\nabla n + \mu n E + n\frac{\mathbf{E}\times\mathbf{B}}{B^2} + \frac{\mathbf{B}\times\nabla p}{qB^2}$$

In addition, the fluctuation spectrum and, thus, the fluctuation induced transport in the boundary layer can be modified by electrical biasing. In PISCES, we investigate mobility induced flow, radial and poloidal ExB flows, and fluctuation induced transport in a biased scrape-off layer. 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, thermionically 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[2] for discharge conditions with T_e = 10 to 20 eV, n_e = 1 to 5 x $10^{12}cm^{-3}$, and B = 400 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 2. Longer scrape-off-lengths are observed when the field direction is reversed. Figure 3 shows the dependence of scrape-off lengths on the magnetic field for zero, positive, and negative bias.

Mobility and diffusion coefficients computed for the regime of medium to high neutral pressure, p > 6E-04 torr, show, by profile matching, that diffusion coefficients are Bohm-like while the ion mobility has to be slightly larger than classical to achieve agreement between computed and measured profiles.

In the low pressure regime, p < 3.5E-4, there is evidence that a strong radial electric field can significantly reduce the fluctuation-induced transport. Figure 4 summarizes the fluctuation results at a radius slightly inside the biased electrode. The power spectrum changes from a broad spectrum to a peaked spectrum, indicating that large incoherent fluctuations are stabilized while large amplitude coherent modes are destabilized. Density fluctuation levels do not change significantly with biasing, but the potential fluctuation levels decrease in the scrape-off layer during positive biasing. The cross-field particle flux normalized by the central density decreases by nearly a factor of 2 during positive bias of the electrode.

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[1]B. LaBombard, R. W. Conn, UCLA-PPG-1186, submitted for publication to Plasma Physics and Controlled Nuclear Fusion (1989)

[2]B. LaBombard, et. al, Biased SOL Simulation Experiments in PISCES: An Investigation of the Use of Electrical Bias to Modify Tokamak SOL Transport, presented at APS, Ft. Lauderdale, Nov. 1988

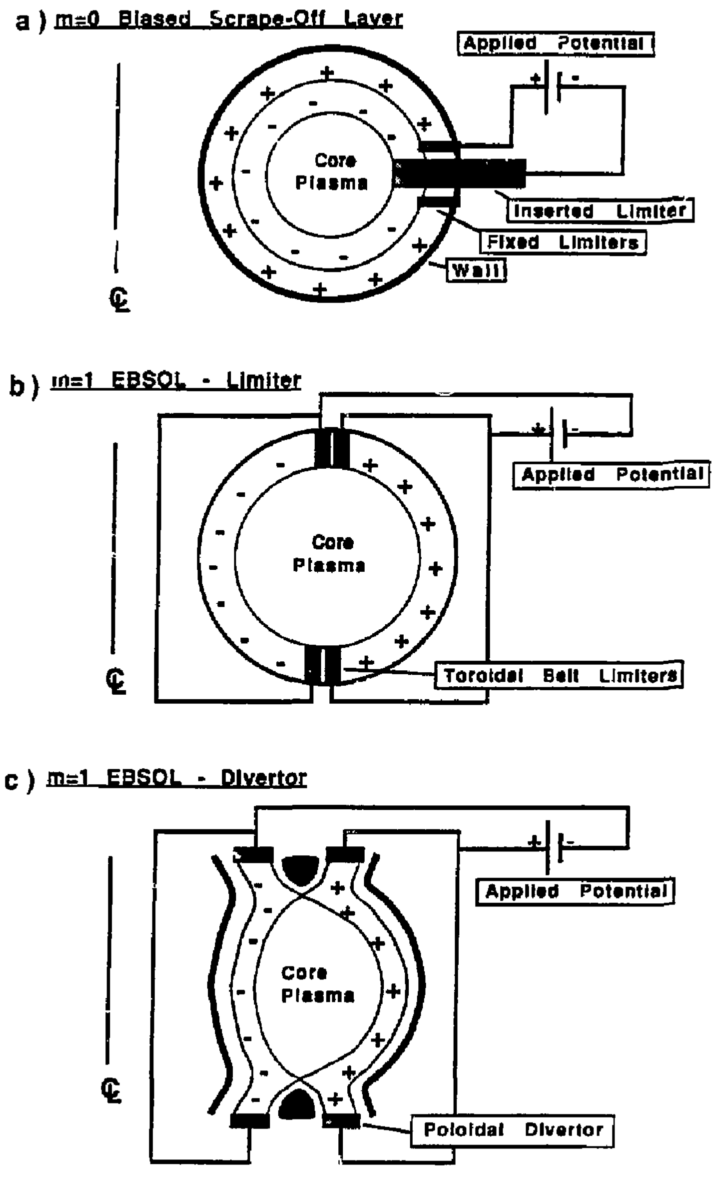


Fig. 1 Three examples of configurations with applied electrical biases.

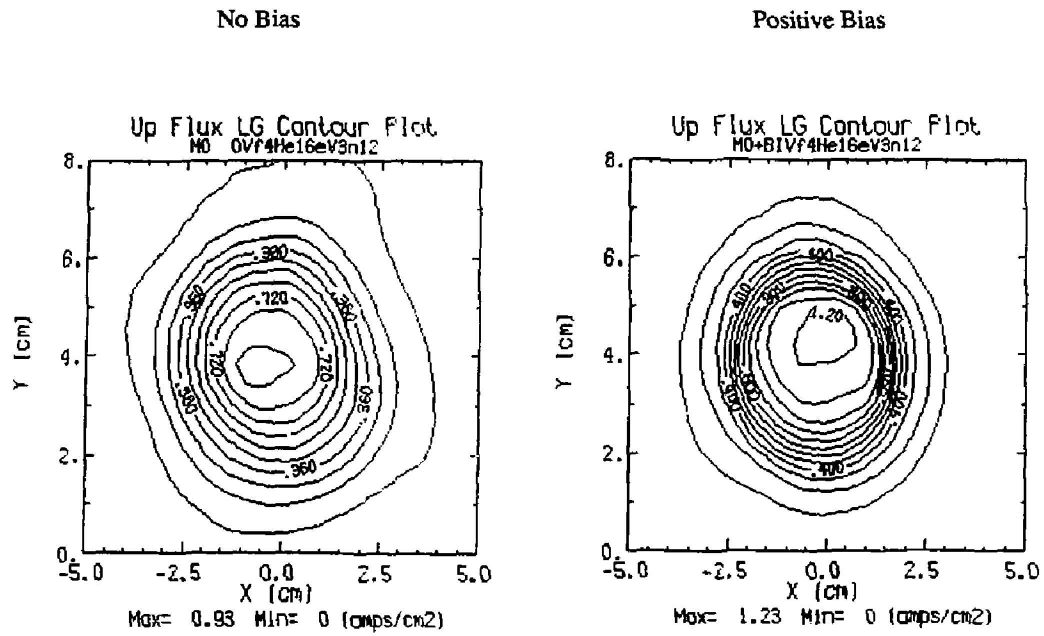


Fig 2. Flux contours perpendicular to magnetic axis, m=0 case

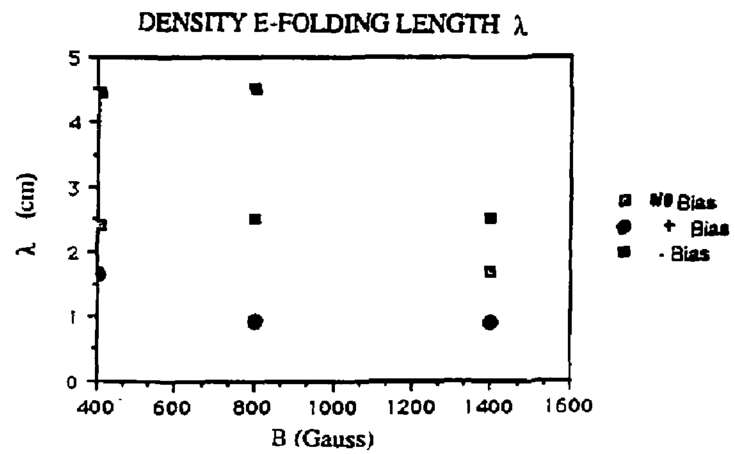
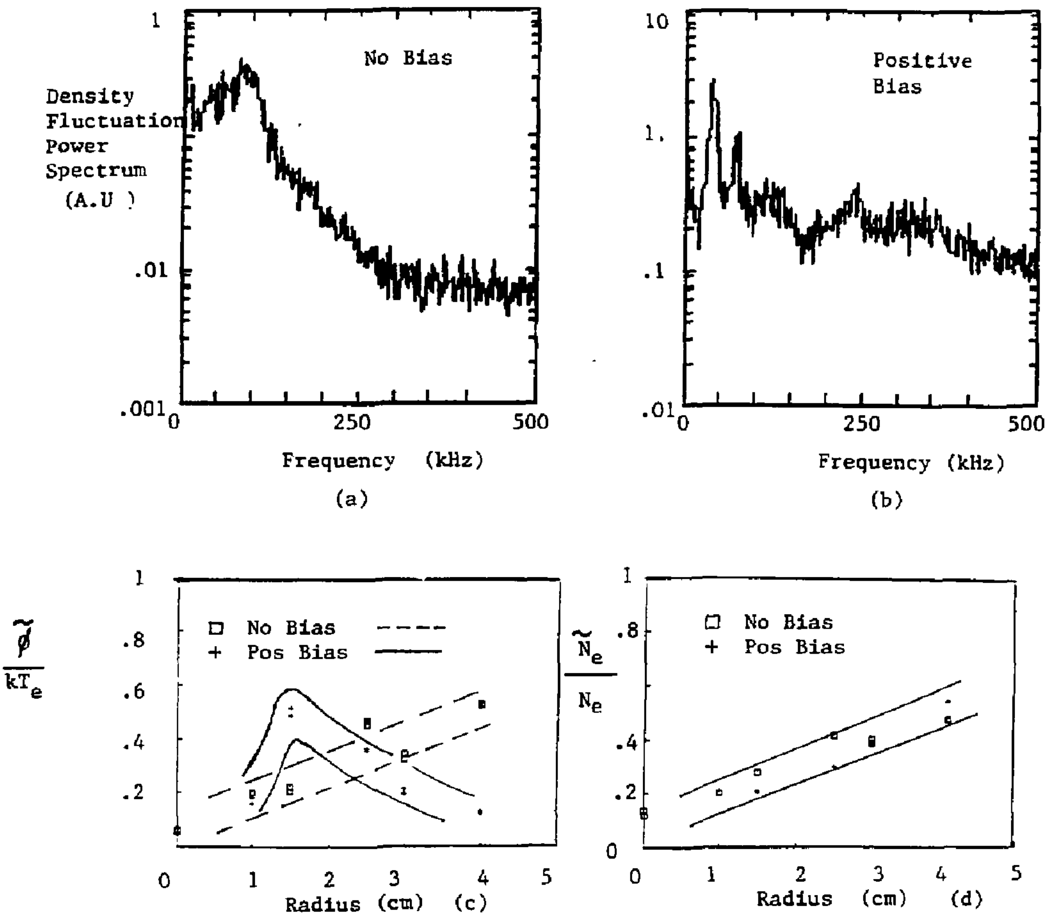


Fig. 3. Density e-folding lengths versus magnetic field in M=0 experiments.



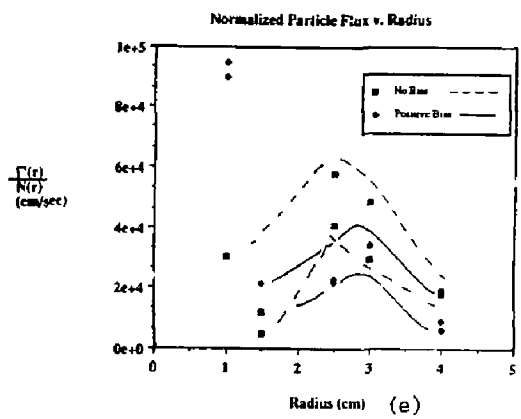


Figure 4: Fluctuations in PISCES Scrape-Off Layer Experiment
(a) Density Fluctuation Power Spectrum No Bias, R=1.5 cm
(b) Density Fluctuation Power Spectrum Pos. Bias, R=1.5 cm
(c) Potential Fluctuation Levels
(d) Density Fluctuation Levels
(e) Fluctuation Driven Particle Fluxes Normalized by Local Density; v. Radius

Experimental Studies of Biased Divertor Channels

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 pumped 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. 1), 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. 2 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.

D. M. Goebel and R. W. Conn, Observation of Enhanced Particle Removal Rates in Pump Limiter Simulation Experiments, J. Nucl. Mater **128 & 129** (1984) 249

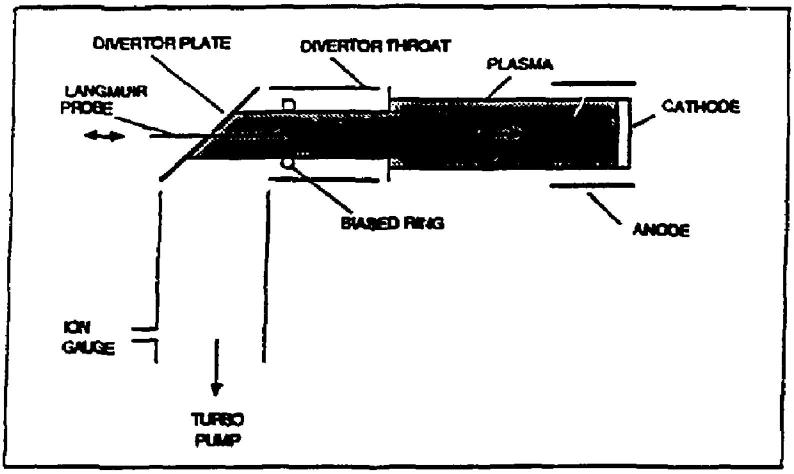


Fig. 1. Schematic drawing of a divertor simulation experiment in PISCES with the position of the biased ring electrode indicated.

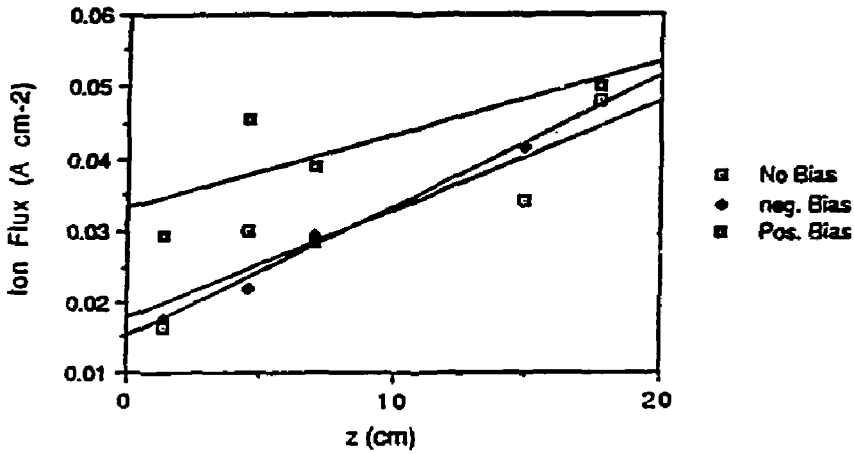


Fig. 2 Axial ion Flux in divertor throat versus distance z from neutralizer plate for ring biases of 0, -100 V and 60 V.

The concept of the gaseous divertor (or gaseous collector) as a possible alternative to the divertor heat flux problem in ITER is presently investigated in PISCES-A. The outboard scrape-off layer plasma in ITER enters the divertor region in the form of a thin sheet (7 cm width). Neutral gas confined in an annular slot of ~ 7 cm width can possibly distribute the divertor heat flux over a large surface area via charge exchange and radiation. By measuring the axial and radial density and electron temperature profile for different plasma parameters and neutral pressure, we attempt to identify the atomic and molecular processes involved indistributing the incident particle and heat flux (electron and ion-neutral collisions, excitation, charge exchange, and recombination).

In the PISCES simulation experiment (Fig. 1), a circular tube (7 cm diameter) is employed to test this concept. Neutral gas (H, D,He, Ar) at a pressure of up to 10 mtorr can be fed at the end of the tube. An axial, water-cooled Langmuir probe as well as a fast scanning radial probe are used to measure the plasma density, the electron temperature and the plasma potential. The neutral pressure can be monitored at three different positions along the length of the divertor tube by ionization and baratron gauges. Fig. 2 shows an axial density profile obtained in Deuterium for the plasma parameters $n_e = 10^{12}$ cm^{-3}, $kT_e =$ 4 eV. The plasma density decreases by a factor of 2.5 along the length of the tube without external gas feed. This is due to radial diffusion and elastic collisions with the neutrals trapped inside the tube as a result of the limited conductance and the effect of plasma pumping. The neutral D_2 pressure at the end of the divertor tube is p =1.3 mtorr. With external gas feed (p= 4 mtorr) and identical source plasma parameters, the density decays by a factor of ten due to the increased collision rate. After modification of the source magnetic geometry we expect to achieve densities $n > 3\times10^{13}$ cm^{-3} at $kT_e \sim 20$ eV. In this regime (plasma parameters relevant to the ITER annular slot divertor) the energy transfer to the neutral gas is primarily via charge exchange and excitation. We also plan to feed neutral gas at high pressure (p< 0.1 torr) to test the concept of balancing plasma and neutral pressure (gaseous collector). In a third phase of the experiment, we plan to measure to measure the parallel electron heat flux in PISCES as a function of electron-electron mean free path ($0.1\text{m} < \lambda_{ee} < 1$ m) and compare the results to theoretical predictions for the conduction as well as the convection dominated regime.

PISCES Gaseous Divertor Experiment

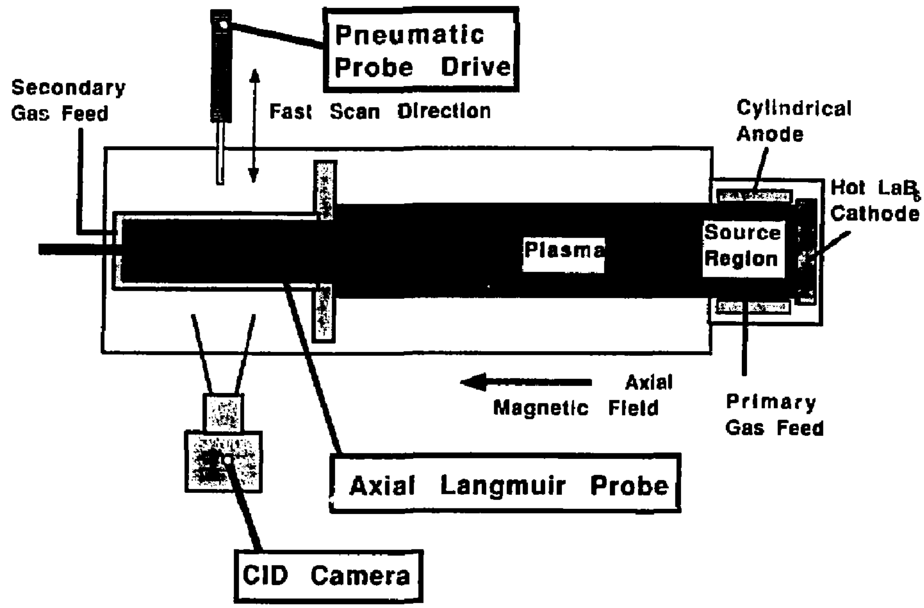


Fig.1. Schematic drawing of the gaseous divertor simulation experiment in PISCES-A with the gas feed and the probe diagnostics indicated.

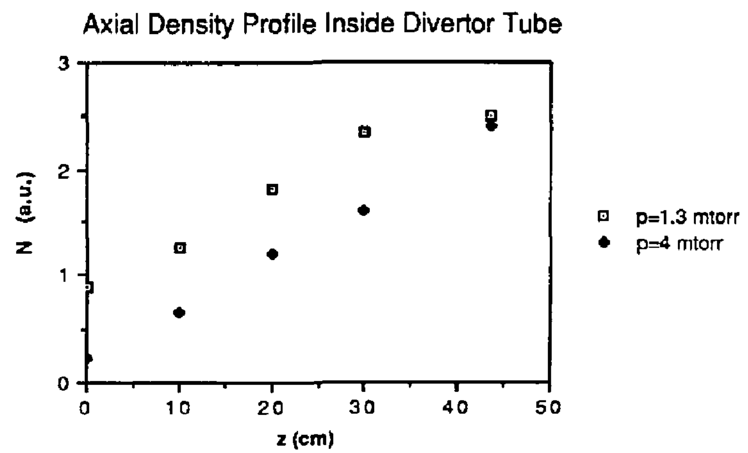


Fig.2. Axial density profile inside the divertor tube with (p=4 mtorr) and without (p=1.3 mtorr) external gas feed.

The presheath zone is loosely defined as the quasineutral plasma region separating the edge of a sheath in front of a wall surface and the bulk plasma. The potential drop along the presheath accelerates ions to the ion sound speed at the sheath edge. The detailed understanding of presheath physics is quite applicable to the work being done on plasma-wall interactions. Net erosion and redeposition rates will depend critically upon the effect of presheath electric fields and bulk flows of plasma on the motion of ionized impurities.

The first set of presheath experiments were threefold in nature: to characterize the presheath region profiles of density, potential, and parallel mach number; to assemble a database of experimental data to compare with theoretical models; and to test probe interpretation in a flowing plasma.

The characterization of the presheath region has been completed for wall surfaces perpendicular to the magnetic field. Potential, density, and parallel mach number profiles have been recorded for various plasma conditions. The data shows 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 (figure 1). The space potential profile measurement has been made possible by the development of a fast spatially scanning emissive probe. In addition, a CID camera diagnostic has been developed to infer H-alpha emissivity profiles.

Of the various theories have been examined for computing parallel mach numbers from probe flux measurements, the "Stangeby" model best fits the data. The "Stangeby" model computes the mach number from the ratio of the upstream and downstream fluxes collected by the mach probe. Other models stressing the importance of viscosity in plasmas are less reliable in predicting a mach number approaching unity near the sheath boundary (figure 2).

Future experiments will be conducted to measure the effect of finite ion Larmor radius on the presheaths of surfaces at oblique incidence to magnetic fields. The data from this experiment will be compared to theoretical calculations by Chodura. In addition, energy flows and parallel transport in plasma sheaths will be studied by measuring the sheath heat transmission factor. These experiments will be conducted at both normal and oblique incidence.

B. LaBombard, et. al, Presheath Profiles in Simulated Tokmak Edge Plasmas, 8th Int'l PSI Meeting, Jülich, FRG, May 1988 (UCLA-PPG-1171)
K. S. Chung, et. al, Plasma Flow Measurements Along the Presheath of a Magnetized Plasma, presented at APS/DPP, Ft. Lauderdale, FL, Nov. 1988

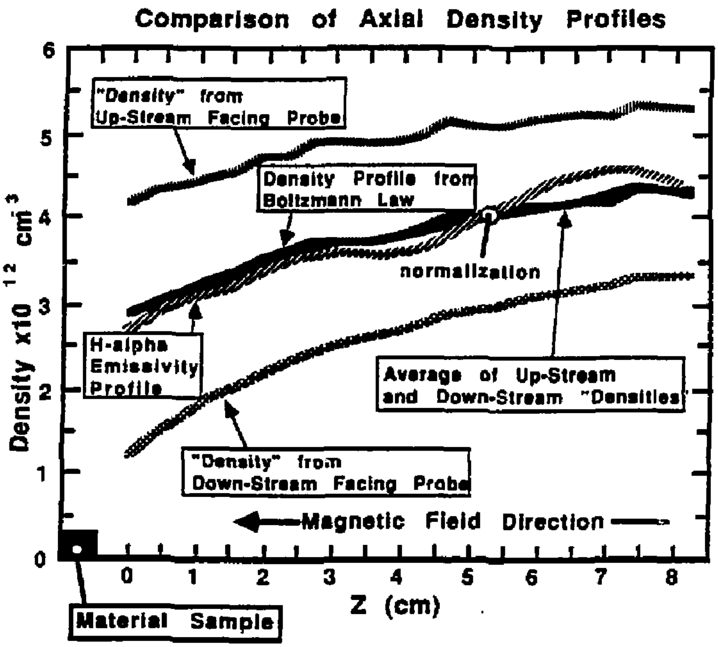


Fig 1: Density Versus Axial Position Along the Presheath in Front of the Wall Surface.

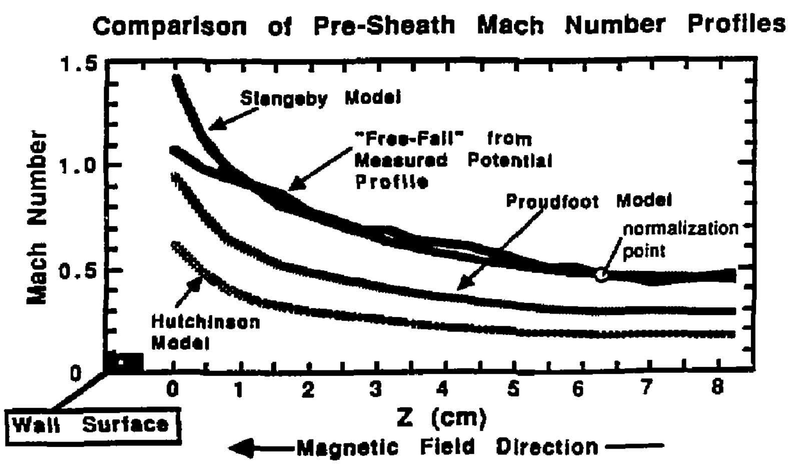


Fig 2: Mach Number Versus Distance Along the Presheath in Front of the Wall Surface.

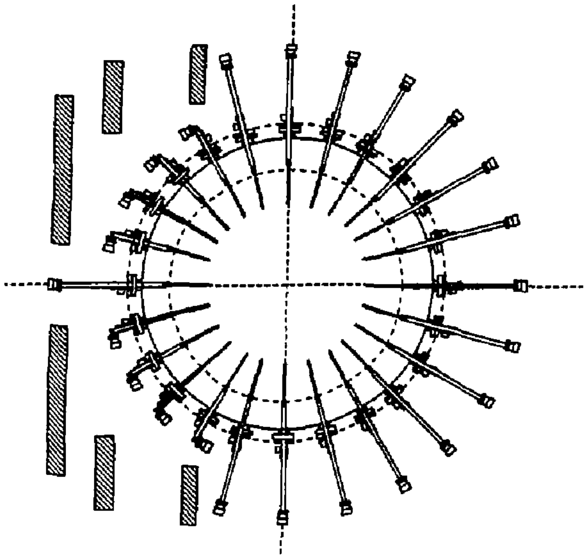
Observations from a number of other tokamak experiments suggest that the rate at which particles and heat diffuse across the magnetic field is higher on the outside midplane region than on the inboard midplane region. Such asymmetries can lead to a peaking of the heat fluxes on plasma facing components and also suggest that global confinement may scale with major radius or aspect ratio. Experiments are underway in cooperation with the Continuous Current Tokamak (CCT) at UCLA to search for poloidally asymmetric cross field particle transport. These experiments provide the first direct study of poloidally asymmetric transport in a tokamak. Experiments that may modify or eliminate such asymmetric transport and lead to an increase in global confinement by manipulation of the edge plasma are also planned to follow these experiments and are discussed elsewhere in this report.

Efforts for this reporting period have focussed on developing the hardware and analysis techniques necessary for the extensive measurements inherent in these experiments. A two dimensional (r,θ) array of probes has been constructed and installed on the CCT device (Fig. 1). Each probe tip is constructed to allow measurement of time-averaged plasma quantities and of fluctuation-driven transport processes. Using this probe array, a detailed 2-D picture of the edge plasma transport rates and resulting distribution of plasma can be obtained. High bandwidth amplifiers needed for the measurement of fluctuation-induced transport were developed and built during the reporting period, and the analysis techniques necessary for data interpretation were completed.

The hardware and analysis techniques used for the fluctuation-driven transport measurement were tested in a PISCES-A scrape off layer simulation experiment (see previous discussion in this report). Representative results from these experiments are shown in figure 2. Density fluctuation power spectra shown demonstrate that the fluctuations and associated transport may be modified by a DC radial electric field. These data are currently being analyzed and are expected to lead to demonstration experiments on the CCT device. The probe array has been constructed and installed on the CCT device, and the associated high bandwidth amplifiers have been developed and constructed. The analysis techniques have been developed and tested on a PISCES edge physics simulation experiment. First data from the CCT experiment is expected by the end of May 1989. Robert J. Taylor and Pat Pribyl of the UCLA Tokamak Lab were also principle contributors to this work.

[1] Tynan, G.R. et.al. Bull.APS 33(9)2051(1988)

[2] LaBombard, B. et.al. Bull. APS 33(9)2103(1988)

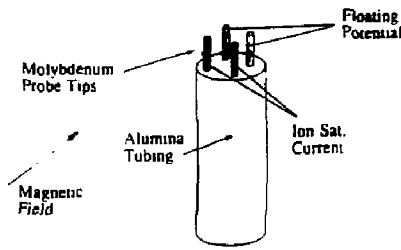


PLANNED EXPERIMENTS

Poloidal Asymmetric Transport

Fluctuation Induced Transport

Radial Electric Fields and Transport



Poloidal Array of Probes for Edge Physics and Transport Studies

Figure 1: The 'Mini-Densepack' Probe Array on the CCT Tokamak

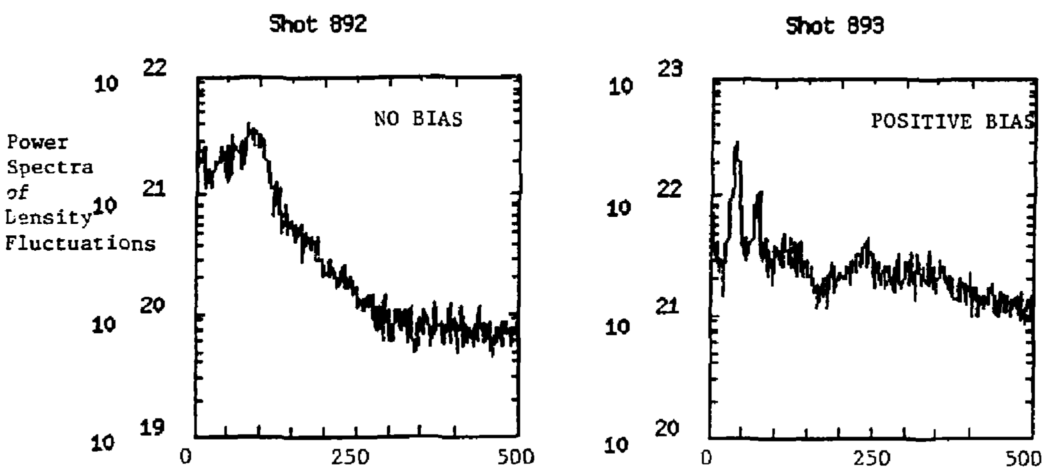


Figure 2: Density Fluctuation Power Spectra in the m=0 Biased Scrape Off Layer Simulation Experiments in the PISCES-A Facility

Edge Physics and Global Transport: The PISCES-CCT Biased Divertor Experiment

Interest in tokamak edge physics has increased with the observation of improved confinement regimes (e.g. the 'H-mode' and 'Supershot' regimes). There are indications that the edge plasma plays an important role in the transition to improved confinement, and that radial electric field in the edge influences global confinement. Tokamak transport may also be poloidally asymmetric with the highest transport rates occurring on the outside midplane region of the tokamak. With these observations in mind, an experimental concept aimed at reducing asymmetric transport and exploring the role of the radial electric field on confinement has been developed by the PISCES group and is being prepared for the first test in a tokamak.

The planned experiment is shown schematically in figure 1. A double null diverted discharge is used in order to isolate field lines on the outside midplane region from those on the inside midplane region. Field lines from these two respective regions are intercepted on conducting surfaces that are electrically isolated from the first wall and vacuum vessel. These conducting surfaces are then biased with an external power supply in such a way as to cause an increase in the magnitude of the radially inward electric field in the edge plasma region. Such an increase in the electric field causes a decrease in cross field particle fluxes in PISCES simulation experiments[1] (see previous section for details on these experiments). Possible physics mechanisms for this effect include cross field ion mobility effects and changes in fluctuation-driven transport due to the radial electric field [2].

During the past year, a 2-D (r,θ) probe array was constructed and installed on CCT, and a suitable experimental arrangement requiring a modest modification of CCT was identified. Simulation experiments have continued on PISCES-A to test the scaling of the technique and to investigate the effect of biasing on fluctuation-driven transport. During the coming report period, the first phase of the experiment will be implemented on CCT. A toroidally symmetric experiment is planned for CCT once the physics concept has been validated. A possible follow-on experiment in PBX is being considered pending results from the CCT experiments.

Robert J. Taylor and Pat Pribyl of the UCLA Tokamak Lab have also participated in the planning of these experiments and Brian LaBombard of the MIT Plasma Fusion Center was involved during the initial stages of the work.

[1] LaBombard, B. et.al. Bull. APS 33(9)2103(1988)

[2] LaBombard, B., Conn, R.W., Tynan, G.R., submitted to Pl.Phys. & Cont. Fus.

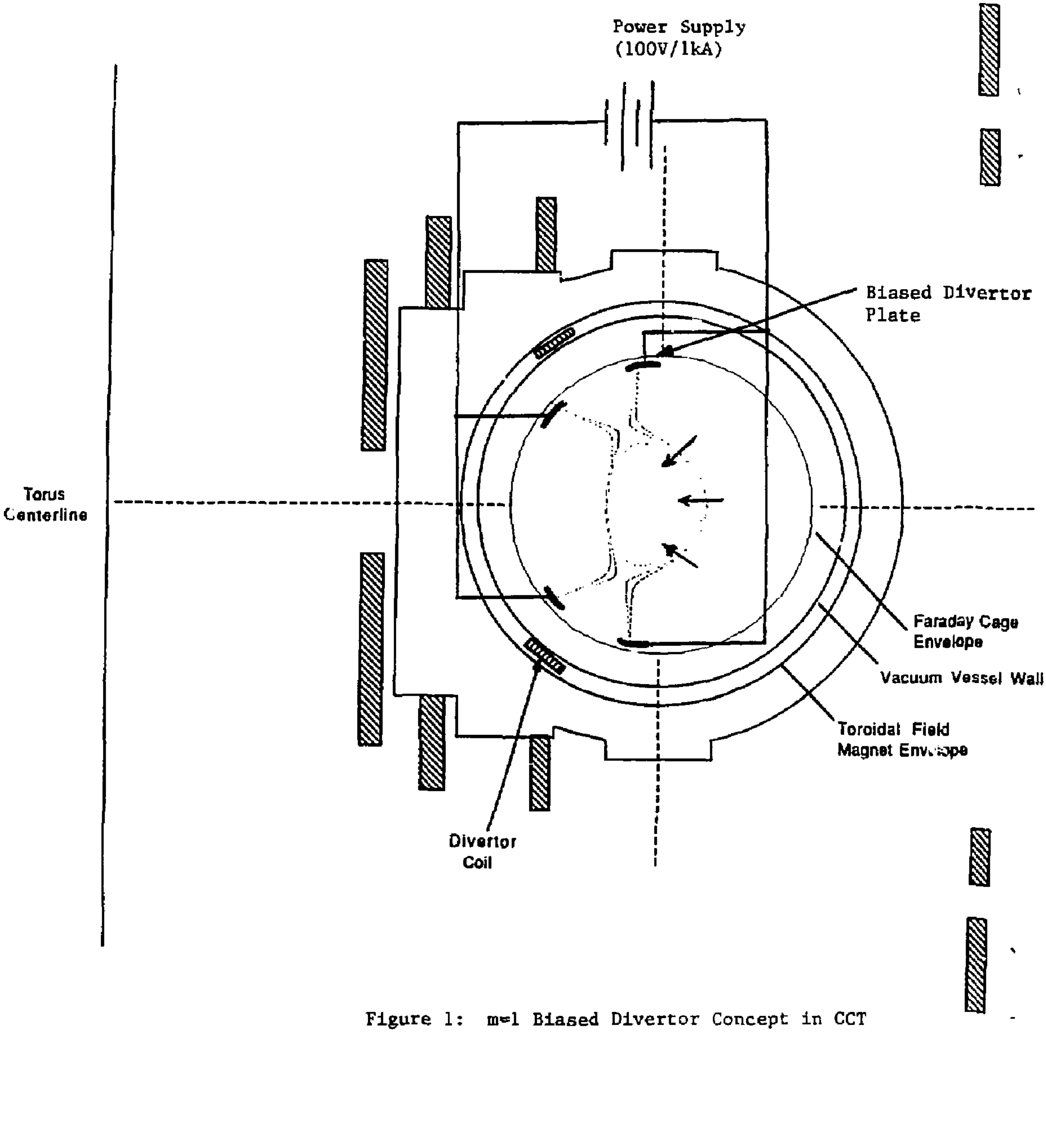


Figure 1: m=1 Biased Divertor Concept in CCT

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