Present Status of Plasma-Wall
Interactions Research and Materials
Development Activities in the U.S.

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I. Introduction

It is well known in the fusion engineering community that the plasma confinement performance in magnetic fusion devices is strongly affected by edge-plasma interactions with surface components. These plasma-material interactions (PMI) include fuel particle recycling and impurity generation both during normal and off-normal operation. To understand and then to control PMI effects, considerable effort has been made, particularly over the last decade in US, supported by Department of Energy, Division of Development and Technology. Also, because plasma-facing components are generally expected to receive significant amount of heat due to plasma bombardment and run-away electrons, materials must tolerate high-heat fluxes (HHF). The HHF-component research has been conducted in parallel with PMI research. One strong motivation for these research activities is that DT-buring experiments are currently planned in the Tokamak Test Fusion Reactor (TFTR) in early 1990s [1].

Several different but mutually complementary approaches have been taken in the PMI+HHF research. The first approach is to conduct PMI experiments using toroidal fusion devices such as TFTR. The second one is to simulate elemental processes involved in PMI using ion beams and electron beams etc. The last one but not least is to use non-tokamak plasma facilities. Along with these laboratory activities, new materials have been developed and evaluated from the PMI+HHF point of view. In this paper, several major PMI+HHF research facilities in US and their activities are briefly reviewed.

II. PMI+HHF Research Activities

1. In-tokamak PMI experiments

In-tokamak experiments are probably the most direct approach to understand edge-plasma interactions with materials. However, it is generally difficult to obtain dedicated machine time for PMI experiments in major tokamaks because obviously the highest priority goes to plasma confinement experiments. Also, deposition probe experiments, for example, may disturb the plasma confinement depending on probe positioning. The difficulty seems to arise from both technical and non-technical processes at large confinement facilities. Details of experimental plans should be implemented well in advance, which is not always possible for many cases.

Despite of these unavoidable difficulties, Princeton Plasma Physics Laboratory (PPPL), Sandia National Laboratories at Livermore and Albuquerque (SNLL and SNLA) jointly conducted a variety of in-tokamak experiments using TFTR in assessing tritium inventory for the DT-experiments [1]. These PMI experiments in TFTR drew attention from researchers at other major tokamaks such as the Joint European Torus (JET). These researchers included confinement physicists as well as surface physicists.

This PPPL-SNL collaboration has been recently extended to University of California, Los Angeles (UCLA) and University of Toronto for more thorough understanding of PMI effects in TFTR. Quarterly meetings of Materials Physic Group (MPG) consisting of researchers involved in this multi-institutional collaboration have been extremely valuable in exchanging unpublished data and in stimulating research interest.

Perhaps one of the most outstanding contributions of the MPG researchers is the understanding of graphite wall pumping effects, leading to an improved confinement refereed to as "supershots [2]" in TFTR in 1986. These wall pumping effects observed in TFTR are considered due to (1) hydrogen trapping in the surface layer [3]; (2) hydrogen co-deposition with carbon [4]; and (3) temporal storage of hydrogen in graphite pore channels [5,6]. More recently, first comprehensive characterization of TFTR-redeposited carbon materials has been done at SNL and UCLA. The characterization effort include various surface analysis [7] and re-sputtering yield measurements [8]. These characteristics of redeposited materials have long been subject to endless discussion in the fusion community because it is experimentally difficult to reproduce the exact same redeposition condition in non-tokamak facilities. The results of characterization of TFTR-redeposits are believed to provide answers to several frustrating arguments.

2

2. Ion, electron beams and outgassing experiments

In plasma-materials interactions, there are many elemental processes to be understood. Important among them are: (1) hydrogen recycling via implantation and reemission; and (2) erosion via sputtering or evaporation. The use of ion and electron beams is reasonable to simulate and to understand these individual PMI events. Also, it is probably true that these beam facilities are easier to define experimental conditons and more flexible in machine time than tokamaks. As a result, bulk of the existing PMI-related data base is contributed by experimental work done by ion and electron beam facilities [9].

Major ion beam facilities are located at SNLA and SNLL, and are currently used for two major objectives: (1) simulation of plasma bombardment; and (2) ion beam surface analysis. The ion bombarding flux for these ion beam facilities typically ranges from 10^{14} to 10^{16} ions cm^{-2} s^{-1}. Also, the ion bombarding energy tends to stay in the keV range in most cases. These conditions are similar to those seen at the first wall in contact with the scrape-off layer plasma. So, the ion beam facilities have been extensively used for the first category of applications. In the second category, one of the most outstanding ion beam applications is the in-air Proton Induced X-ray Emission spectrosocpy (PIXE, see Fig. 1) technique developed at SNLA [10]. Many plasma-facing graphite components from TFTR have been already analyzed non-distructively [1].

For HHF experiments, an electron beam facility: EBTS (see Fig. 2) located at SNLA has been exclusively used to evaluate various graphite materials under simulated disruption and run-away electron bombardment conditions. Significant amount of data has been produced by this electron beam facility as shown in Fig. 3 [11]. Also, many collaborative experiments have been actively conducted with Japanese institutions such as Institute of Plasma Physics, Nagoya (IPP, Nagoya). In some cases, however, the electron beam data is subject to discussion with respect to the depth of energy deposition because ions come to rest much sooner in solid than electrons at the same energy. To conduct better-defined HHF experiments, recently a high-power ion beam facility: IBTS has been built at SNLA. In this facility, actively cooled components tests can be done using a pressurized water circulating system. Major features of these facilities are listed in Table 1.

Outgassing experiments have been actively conducted at SNLL since graphite was used as the plasma-facing component in TFTR. The outgassing behavior of graphite is so complex that new research interest has been generated in the PMI community. The outgassing data base has been established, including various graphite materials by SNLL (see Fig.4)[12].

3

3. PMI experiments in non-tokamak plasma facilities

3.1. The TPX and PISCES-A facilities

In most existing tokamaks, the impurity production is dominated by edge-plasma interactions with limiters and divertor plates. In these cases, the ion bombarding flux generally ranges $10^{17} - 10^{18}$ ions s^{-1} cm^{-2} and also the ion bombarding energy varies from 100 to 400 eV. Obviously, these conditions are not easily attainable by ion beam facilities. Also, it is necessary to understand several plasma effects such as (1) plasma-driven permeation; and (2) redeposition associated with re-ionization followed by transport.

Under these circumstances, an RF plasma facility: Tritium Plasma Experiment (TPX, see Fig. 5) was built in 1982 at SNLL[13] and a reflex-arc discharge plasma facility: Plasma Interactive Surface Component Experimental Station-A (PISCES-A, see Fig. 6) was constructed in 1984 at UCLA [14]. Both of these plasma facilities are capable of generating steady-state plasmas. As to ion bombarding flux, TPX covers the orders: $10^{16} - 10^{17}$ ions s^{-1} cm^{-2} and PISCES-A covers the orders: $10^{17} - 10^{18}$ ions s^{-1} cm^{-2}, together of which are believed to fill out the gap between the ion beam and in-tokamak experiments. Major features of these two plasma facilities are shown in Table 2.

The TPX facility can use tritium, meaning that tritium retention can be directly evaluated. Also, in-situ Auger electron spectroscopy (AES) can be performed. This facility has made a significant data base in terms of tritium retention in various graphites as shown in Fig. 7[15]. Using PISCES-A, due to the high plasma density and electron temperature, one can conduct materials erosion experiments in which the degree of redeposition is controllable between less than a few % and higher than 80 % [16]. To date, PISCES-A still is the only non-tokamak facility that has experimentally demonstrated materials redeposition effects. Also, collaborative experiments have been actively conducted using PISCES-A [17].

In some cases, however, the experimental difficulty was pointed out for PISCES-A as opposed to TPX. For example, it is unavoidable to expose the material sample to the air before surface analysis. This can raise uncertainty of the surface analysis data because in general plasma-bombarded surfaces are extremely air-sensitive. Also, the PISCES-A vacuum system is not bakable so that the base pressure is of the order of 10^{-6} Torr for most cases. For better-defined materials experiments, one might need lower vacuum pressures. To improve on these experimental difficulties, a new plasma-surface interactions research facility: PISCES-B has been recently built at UCLA.

4

3.2. The PISCES-B facility [18]

A new plasma-surface interactions research facility: PISCES-B has recently been constructed at UCLA. A schematic diagram of the PISCES-B facility is shown in Fig. 8, and major features are summarized and compared with those of PISCES-A in Table 2. The facility consists of the following components: (1) steady-state plasma generator; (2) multi-port plasma experimental chamber; (3) differentially pumped RGA; (4) swing & linear sample manipulator; and (5) *in situ* AES-SIMS surface analysis station.

The vacuum chamber sections are all bakable and the base pressure of the order of 10^{-8} Torr is attainable by means of two turbo molecular pumps with a total pumping speed of 6000 l/s. Also, the main experimental chamber has 10 line-of-site ports, all the axes of which point the sample position. These line-of-site vacuum ports are installed with optical equipment such as CID camera and infra-red pyrometers for surface temperature measurements. Two large (8 cm x 25 cm) windows are specially designed for plasma spectroscopy measurements with a 1.0 m monochromator and an optical multi-channel analyzer (OMA).

The sample can be transported in-between the main experimental chamber and the *in situ* surface analysis station using the swing-linear sample manipulator. The regular sample is a circular disk with a diameter of 5 cm and a thickness of 5 mm. However, it is possible to load the main chamber with a sample as large as 30 cm x 30 cm.

The plasma generator in PISCES-B can sustain steady-state plasmas of hydrogen isotopes, helium, argon and nitrogen. Also, it has been found that PISCES-B can generating a wider range of plasma density and electron temperature than PISCES-A. Similarly to PISCES-A, the intrinsic energy of ions generated in the PISCES-B plasma generator is around 1 eV or less. Therefore, the ion bombarding energy is controlled by applying a negative dc bias to the sample, which is at the floating potential. The dc bias voltage can be as high as 500 V. From the PMI-parameters listed in Table 2, PISCES-B is considered to be an excellent simulator of the divertor conditions in toroidal facilities such as ITER.

Using PISCES-B, first erosion experiments have recently been conducted for boronized graphite as a candidate plasma-facing component material for ITER. The data is shown in Fig. 9. Notice that boronized graphite exhibits 30% reduced erosion, relative to iso-graphites, from room temperature to 1300 °C. To evaluated carbon-alternative materials, other international collaborations are also in pregress with KFA-Jülich, NET-team and IPP-Nagoya. A schematic collaboration diagram is shown in Fig. 10.

III. Materials Development Activities

One of the most crucial but expensive components of the PMI+HHF research is to develop materials that can meet the requirements for plasma-facing components. Ideally, the materials development should proceed in such a way that the production and test facilities iterate with feedback until the requirements are achieved. However, this process is not always possible, particularly if only industries can play a production role. Also, collaborations with industries can be sensitive when it comes to proprietary issues. In most cases, therefore, fusion materials development in US starts with testing materials listed in production catalogues. As a result, researchers in the fusion community must make a risky compromise in selecting the "best" material. Unfortunately, this seems to be the case in the C-C composites development for the CIT and ITER divertor applications [19].

Several exceptional cases are briefly described here for readers' information. Argonne National Laboratory (ANL) should be considered as an exceptional institution in this regard since metallic materials production facilities are well equipped at least for the quantities needed for the PMI-related research. From 1980 to 1987, copper-lithium alloy development was conducted at ANL. These alloys are intended to be used as an actively cooled plasma-facing component that spontaneously bears a low-Z lithium layer on the surface via Gibbsian segregation. These alloys were also tested in the PISCES-A facility in 1986. It was found that the erosion yield of copper-lithium alloys was about a factor of 2-3 lower than pure copper [20]. Unfortunately, this finding was not sensational enough to draw attention from the fusion materials community because pure copper is known as an extremely easy material to be sputtered, compared with other materials. Also, recent efforts on brazing materials development and analysis at SNLA deserve some compliments here. These brazing materials are intended to be used for contacting copper as the base metal and several plasma-facing materials such as graphite and tungsten [21]. In general, the development of special materials is such a time-consuming process that not all the industries would even try unless a sizable market is guaranteed.

Another exceptional materials development activity has been in progress at UCLA in collaboration with a Japanese graphite materials manufacture (Toyo Tanso Co.). In this collaboration, boronized graphite is tested at the PISCES-B facility. The erosion and postbombardment outgassing data from UCLA will be implemented as the feedback information in the next production process. Also, this boronized graphite collaboration has been recently extended to SNLL for tritium inventory measurements, SNLA for thermal shock tests and ORNL for neutron irradiation.

IV. Summary

Major PMI+HHF facilities and their activities may be summarized as follows:

(1) UCLA   PISCES-A: Edge-plasma physics experiments.

               PISCES-B: Materials erosion experiments and in-situ AES+SIMS.

(2) SNLA   EBTS: Electron beam facility high-heat flux experiments.

               IBTS: Ion beam facility high-heat flux experiments.

               Ion beam facilities for PIXE, NRA and RBS analysis.

(3) SNLL   TPX: Tritium retention experiments.

               LAMPE: Carbon+hydrogen co-deposition experiments.

(4) ORNL   Outgassing facility for vacuum properties measurements of graphites.

               RFTF: RF-plasma facility for wall conditioning experiments.

(5) HEDL   HEBF: Electron beam tests in a hot cell for neutron activated materials.

Collaborations among these facilities and also with industries have been extremely effective in enhancing research activities (see Fig. 10). From a budget point view, these collaborations are strongly encouraged because normally the same facility for the same purpose is unlikely to be funded elsewhere. Also, it is believed to be important for researchers in the PMI+HHF community to interact with those from confinement facilities such as TFTR and DIII-D. In short, the research activities are coordinated in such a way that institutional and individual expertise is appreciated and unnecessary competitions are avoided.

Acknowledgements

7

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Table 1   High-heat flux test facilities at SNLA.

HHF parameters	EBTS	IBTS
Beam species	e-beam	H^+ beam
Beam voltage (keV)	30	40
Beam current (A)	1	20
Total heat flux (kW)	30	800
Sample size (cm^2)	up to 1800	up to 100
Pulse duration (s)	0.05 to continuous	up to 12
Target cooling	Closed loop water (50GPM at 300PSI)	Closed loop water (500GPM at 1000PSI)
Diagnostics	IR pyrometer Optical pyrometer IR camera RGA Video camera	IR pyrometer Optical pyrometer IR camera RGA Video camera

Table 2   Non-tokamak plasma facilities for PMI experiments at SNLL and UCLA.

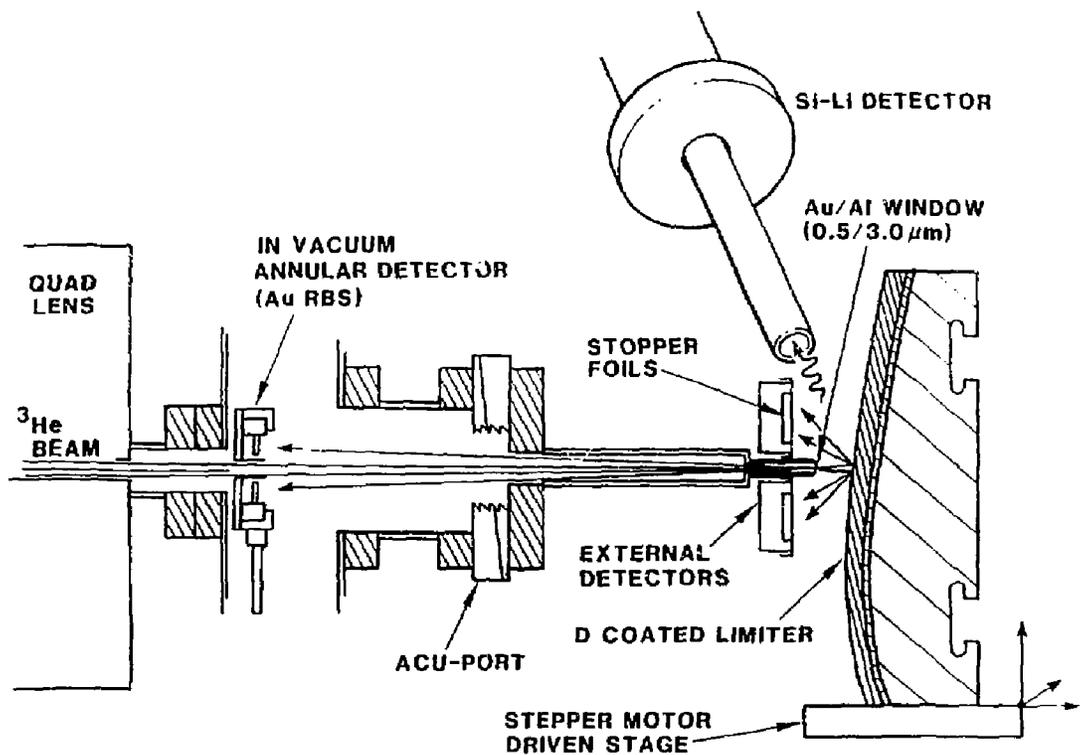| PMI parameters	TPX (SNLL)	PISCES A (UCLA)	PISCES-B (UCLA)
Plasma generation	RF & glow (200W)	Reflex arc (40 kW)	Reflex arc (50 kW)
Plasma species	H, D, T, He Ar, N, O	H, D, He Ar, N	H, D, He Ar, N
Mode of operation	Continuous	Continuous	Continuous
Plasma density (cm^{-3})	$10^{10} - 10^{11}$	$10^{11} - 10^{13}$	$10^{11} - 10^{13}$
Electron temperature (eV)	3-7	3-30	3-50
Ion bombarding flux (ions s^{-1} cm^{-2})	$10^{15} - 10^{17}$	$10^{17} - 10^{18}$	$10^{17} - 10^{19}$
Target area (cm^2)	10-20	50-300	50-700
Ionization mean free path for carbon redeposition(cm)	down to 100	down to 1	down to 0.5
Ion bombarding energy (eV)	15 - 300 (dc bias)	10 - 500 (dc bias)	10-500 (dc bias)
Base pressure (Torr)	10^{-8}	10^{-6}	10^{-8}
Operation pressure (Torr)	$10^{-3} - 10^{-2}$	$10^{-4} - 10^{-5}$	$10^{-5} - 10^{-3}$
Plasma & surface diagnostics	RGA Langmuir probe In-situ AES	RGA Langmuir probe OMA Monochromator	RGA Langmuir probe In-situ AES+SIMS OMA Monochromator IR pyrometer CID camera 10 line-of-site ports

Fig. 1 A schematic illustration of in-air PIXE technique at SNLA.

ELECTRON GUN
(30 kw)

IR CAMERA

IR PYROMETER

ELECTRON BEAM

SAMPLE STAGE
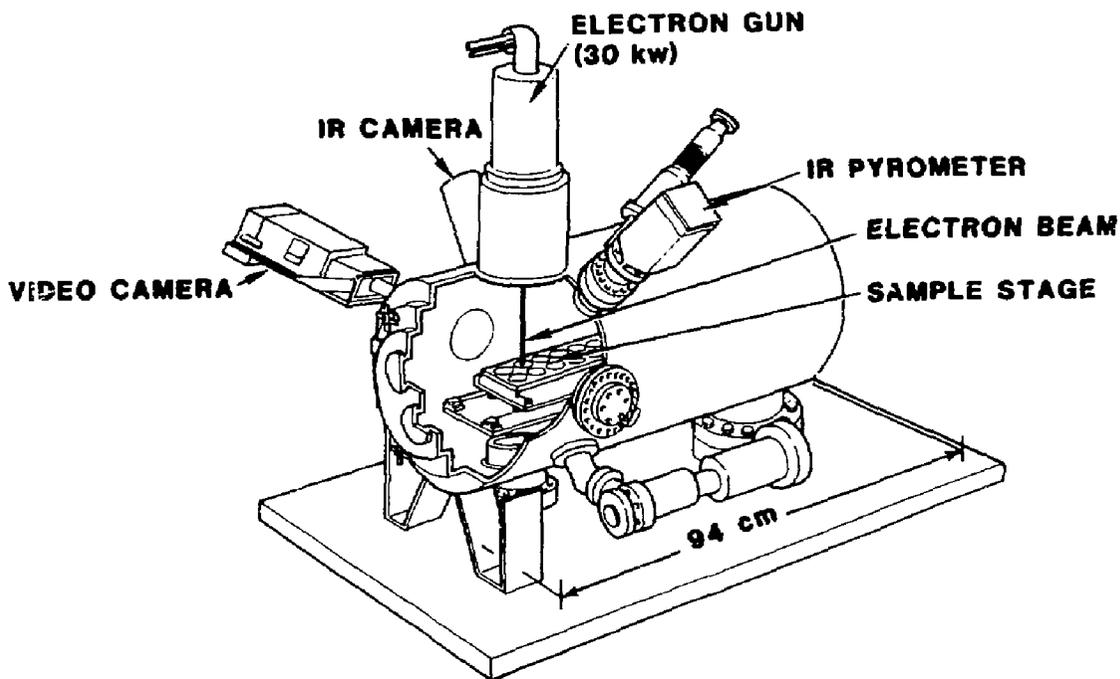
VIDEO CAMERA

94 cm

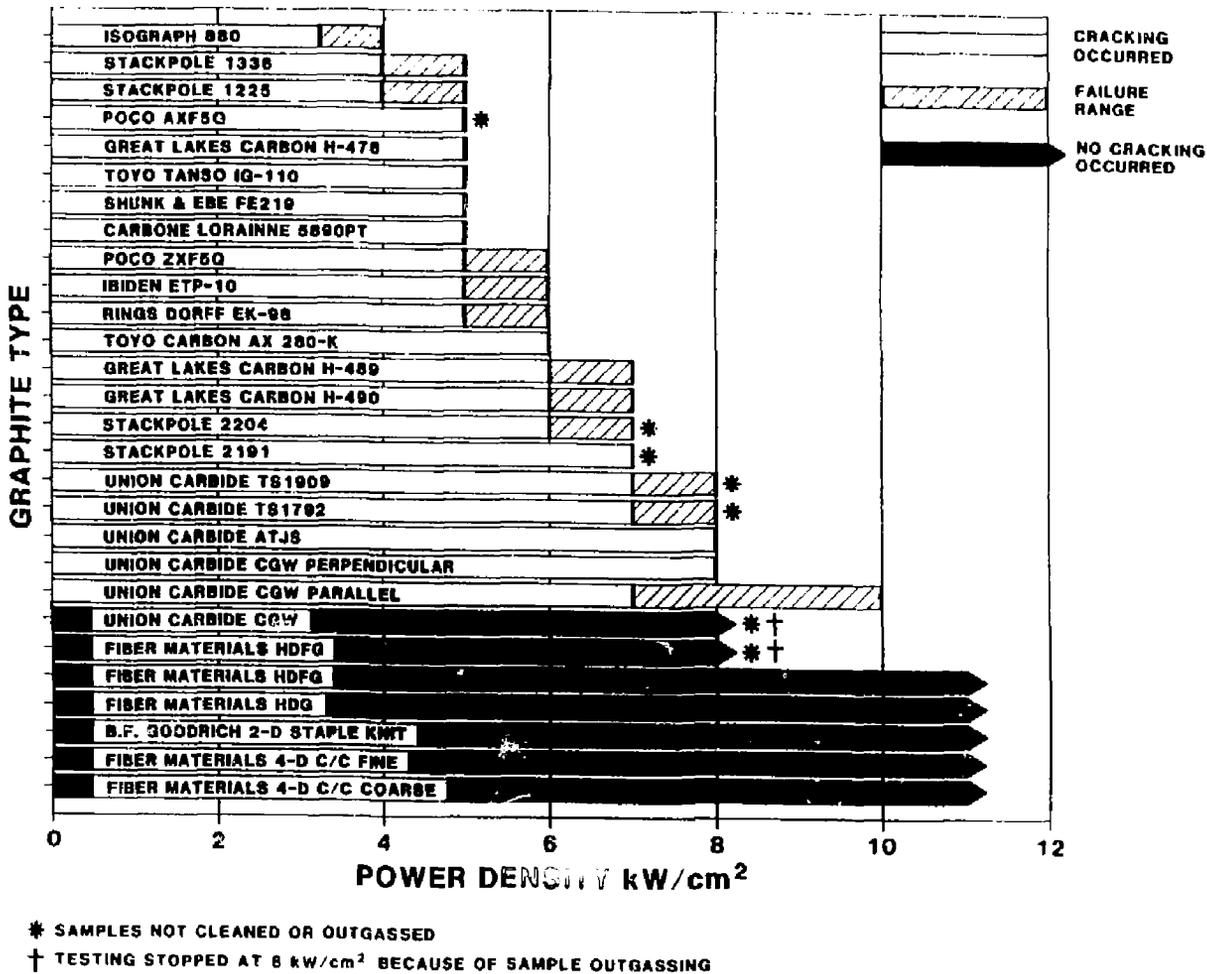Fig. 2 A schematic diagram of Electron Beam Test Stand:EBTS at SNLA.

Fig. 3 High heat flux test data base for various graphites (after Crossman et.al. [11]).
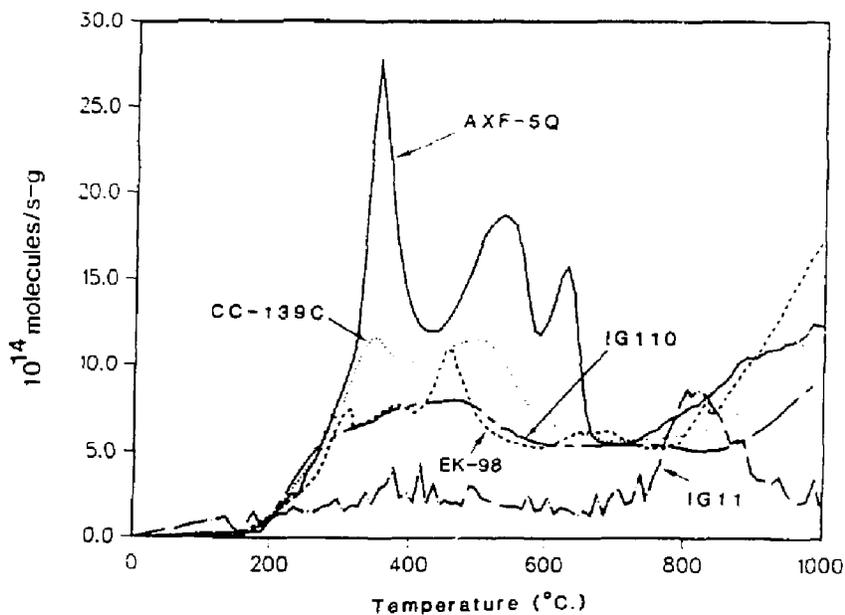
Fig. 4 Outgassing spectra for various graphites (after Pontau and Morse [12]).
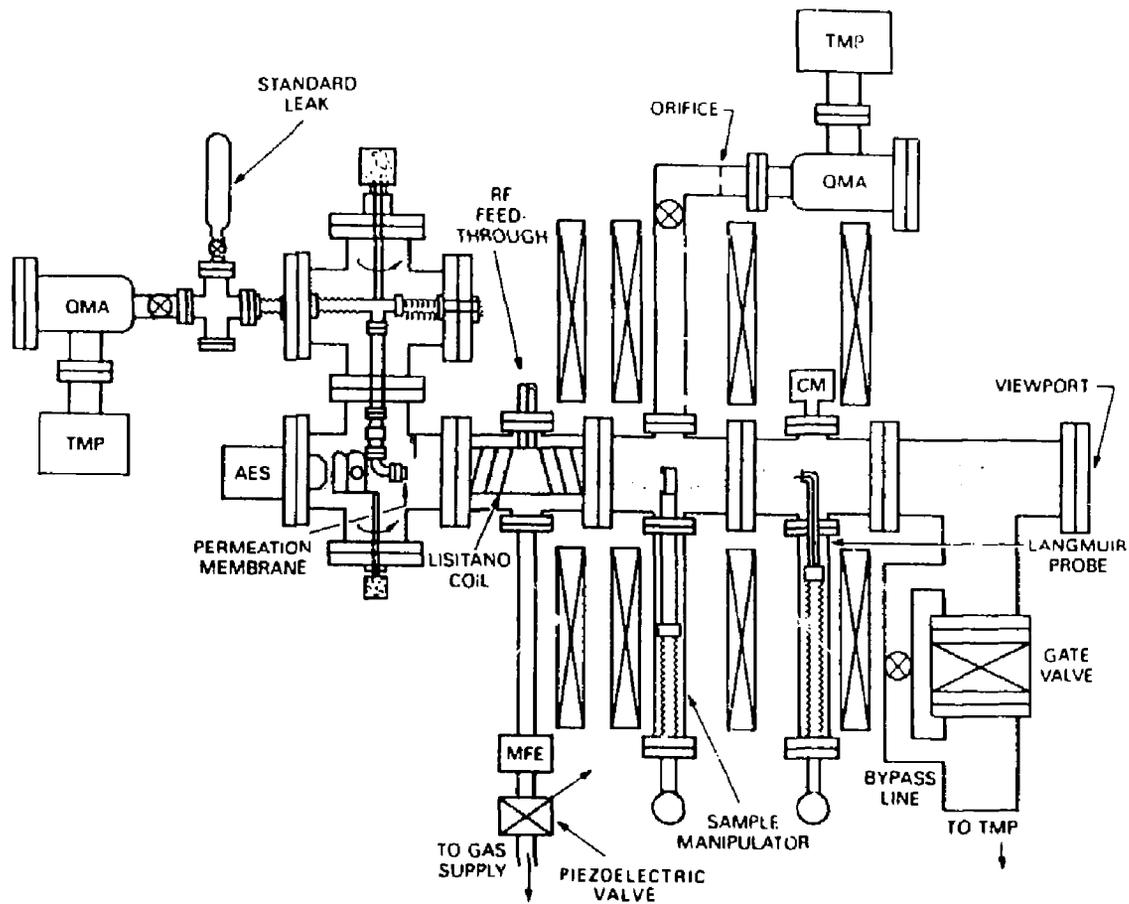
Fig. 5 A schematic diagram of the TPX facility at SNLL.

Spectroscopic
Diagnostic Port
OMA & Photomultiplier

Turbomolecular Pumps
and Gate Valves

Main Magnets

Source Magnets

Trim Magnets

Cathode

Gate Valve

Sample Manipulator

Sample Interlock
Chamber

Fast Probe X-Y Spatial Extent
and Sample Exposure Region

Langmuir Probe

Anode

Gas Inlet

Ion Gauges

Fig. 6 A schematic diagram of the PISCES-A facility at UCLA.

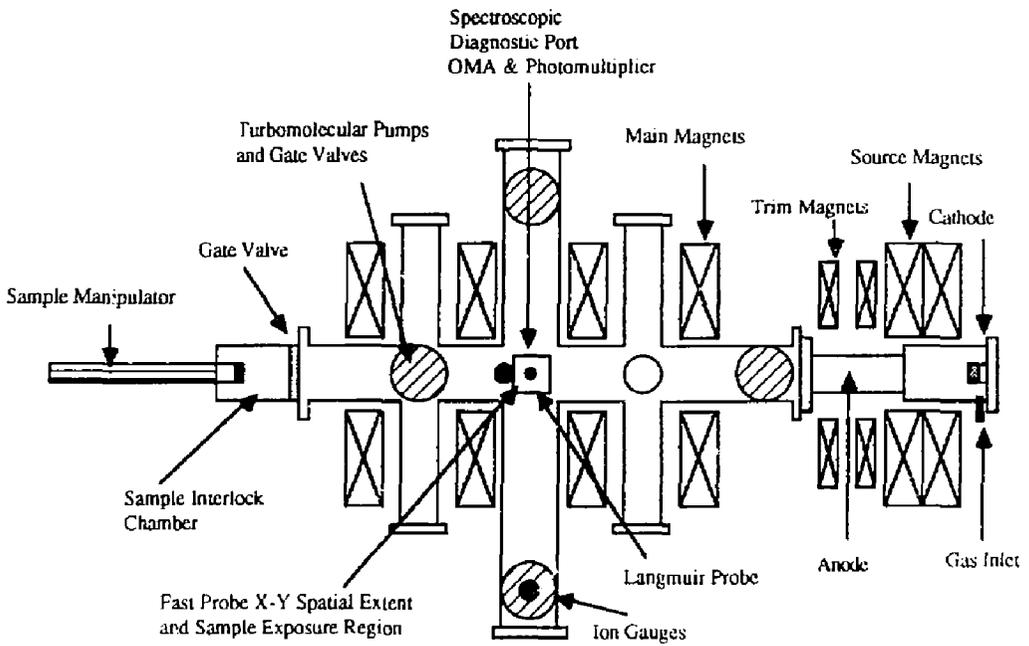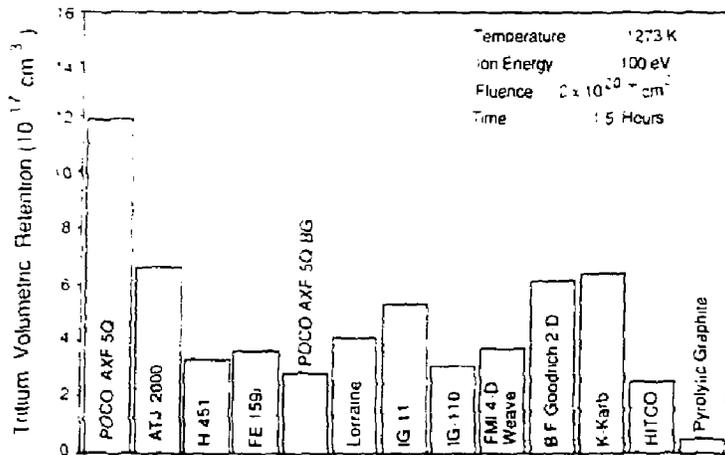Fig. 7 Tritium inventory data for various graphites (after Causey [15]).

SURFACE ANALYSIS STATION
(SAM+SIMS)

MAIN PLASMA CHAMBER

PLASMA SOURCE

SWING-LINEAR SAMPLE MANIPULATOR
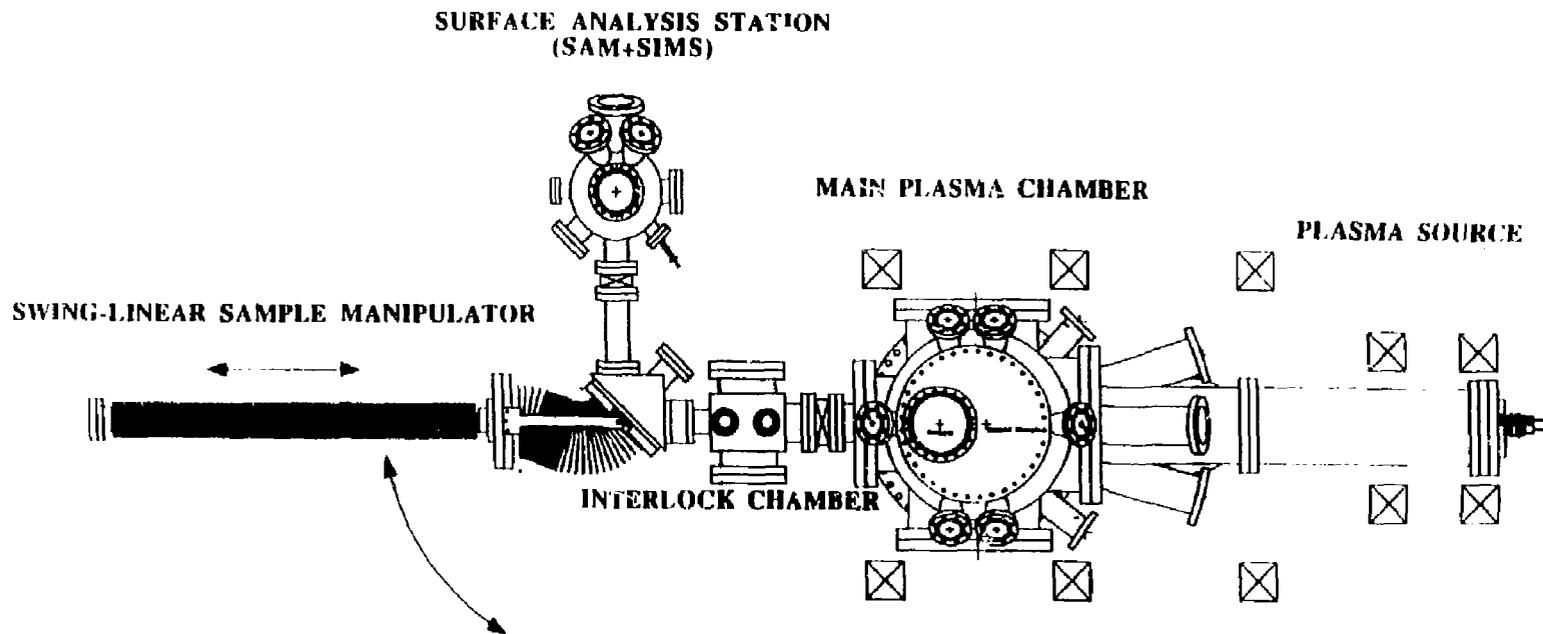
INTERLOCK CHAMBER

Fig. 8 A schematic diagram of the PISCES-B facility at UCLA.
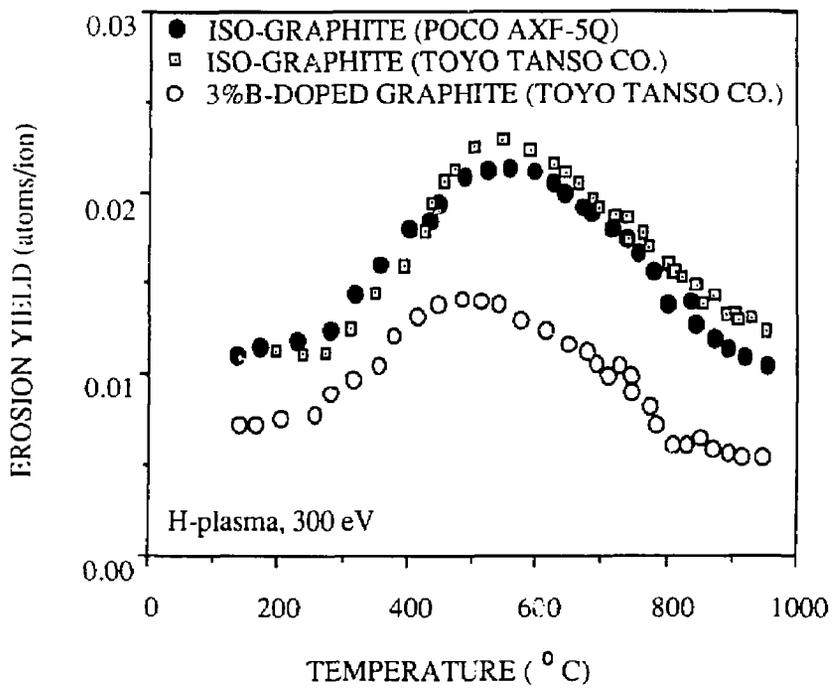
Fig. 9 Chemical sputtering of boronized graphite and iso-graphites (after Hirooka et.al. [18]).

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┌─────────┐ (1)  ┌──────────────────────────┐        (1) ┌─────────────┐
│  TFTR   ├──┐   │          PISCES          │         ┌──┤     PMI     │
├─────────┤ (2)  ├─────────────┬────────────┤        (2)│   theory    │
│  SNLL   ├──┤   │             │            │         ├──┼─────────────┤
├─────────┤ (3)  │  Materials  │  Physics   │        (3)│     CCT     │
│  SNLA   ├──┤   │             │            │         ├──┼─────────────┤
├─────────┤ (4)  │  PISCES-B   │  PISCES-A  │         │  │    DIII-D   │
│  ORNL   ├──┤   └─────────────┴────────────┘        (4)├─────────────┤
├─────────┤ (5)                                       ├──┤     PBX     │
│  ANL    ├──┤                                          │  └─────────────┘
├─────────┤ (6)                                        (5)
│  DIII-D ├──┘        ┌──────────────────────────┐    ┌──┤   Nagoya    │
└─────────┘           │        ITER-R&D          │    └──┴─────────────┘
                      ├─────────────┬────────────┤
┌─────────┐ (7)       │  Erosion &  │  Gaseous   │
│  KFA    ├──┐        │ redeposition│  divertor  │
├─────────┤ (8)       └─────────────┴────────────┘
│  NET    ├──┤
├─────────┤ (9)
│ Nagoya  ├──┤
├─────────┤ (10)
│  Toyo   ├──┘
│  Tanso  │
└─────────┘
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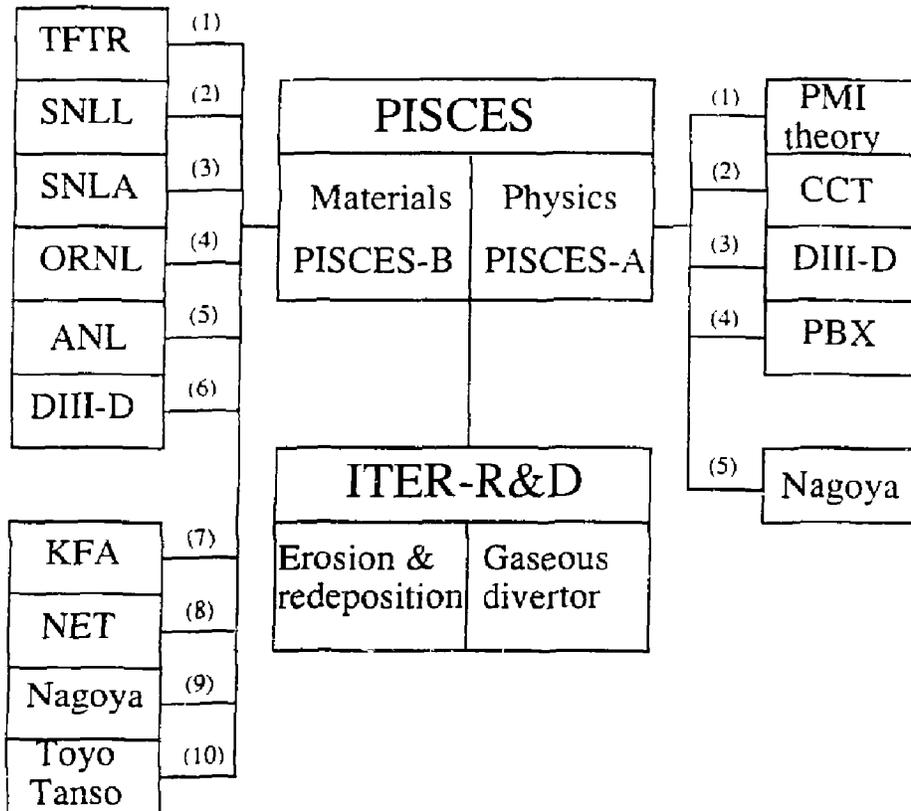
Materials collaborations

(1) DT-Materials Physics Meeting
(2) B-doped graphite: T-inventory
(3) B-doped graphite: thermal shock
(4) B-doped graphite: nuclear properties
(5) He self-pumping
(6) Ceramic insulators tests for ADP
(7) TEXTOR graphite tile analysis
(8) NET-candidate materials test
(9) Al-Li alloy test
(10) B-doped graphite: production

Physics collaborations

(1) RF, biased limiter analysis
(2) Biased divertor in CCT
(3) Biased divertor in DIII-D
(4) Biased divertor in PBX
(5) RF limiter

Fig. 10   A collaboration diagram of the PISCES-team for 1989-1990.