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ABSTRACT

The DIvertor Material Evaluation System (DIMES) at DIII–D is a collaborative program between General Atomics, Sandia National Laboratories (SNL), and Argonne National Laboratory (ANL). This program was initiated in response to the need for understanding the interaction between the plasma and divertor surface materials in tokamaks. Material erosion, tritium retention, disruption effects and material transport are very important topics for the design of ITER. The first phase of the DIMES study is integral material exposure measurements. The second phase of the study is the installation of the DIMES sample changer mechanism. The mechanical design goal for the second phase is to allow the insertion of instrumented samples into the bottom divertor plate region of DIII–D without venting the tokamak. Different material samples can then be exchanged overnight after as few as one plasma shot of exposure. This paper presents the results of the integral experiments, the design of the DIMES sample changer mechanism and the planning of material evaluation experiments at DIII–D using the DIMES mechanism.

1. INTRODUCTION

Selection of a suitable divertor target material is a central issue for high power, long-pulse divertor tokamaks such as ITER. The ability of divertor plates to survive over extended periods during the physics and technology phases of ITER operation stands out as the most critical issue. For the ITER design, experimental data are necessary on material erosion, tritium retention, and disruption effects for different candidate materials and material transport in a diverted plasma. The DIMES program has been initiated to address some of these issues. The first phase of this study has been devoted to integral material exposure measurements. The second phase of the study includes the installation of a DIMES sample changer mechanism and the performance of different divertor relevant material exposure experiments. With the sample changer mechanism in place, DIMES will become the first experiment that can expose large (4.5 cm diameter), extractable material samples to a divertor plasma for a single discharge or for a series of discharges using selected plasma conditions.

DIII–D is an excellent test bed for divertor materials studies for several reasons: 1) versatility in magnetic configuration, 2) capability to operate in ohmic, L–, H–, and VH–modes, 3) high auxiliary heating power, 4) ability to withstand high-energy disruptions, and 5) the availability of extensive plasma edge diagnostics. The versatility in magnetic configuration allows a variety of plasma configurations and thus a variety of edge plasmas can be made incident upon the DIMES sample surface. In the diverted configuration, the strike points can be positioned such that the DIMES sample surface is located outside the outer strike point, within the outer strike point, within the private zone, or near the inner strike point. Up to 5 MW/m^2 peak power has been observed at the outer strike point during high power neutral beam injection in DIII–D. The plasma can also be run in a limiter configuration with the last closed flux surface residing either well away from or directly on the DIMES sample surface. Disruption studies also appear possible. High stored energy disruptions can be induced to deposit significant energy on the floor of the vessel in the vicinity of the DIMES sample. DIII–D has demonstrated the capability to withstand such disruptions, without adversely affecting subsequent plasma operations. Most importantly, DIII–D has developed an extensive battery of edge diagnostics. Edge electron temperatures and densities in the scrape-off-layer (SOL) are obtained using the multipulse Thomson scattering system during the entire discharge with as little as 6 ms between data times. The Charge Exchange Recombination (CER) system can determine ion temperatures in the SOL. Divertor electron temperatures and densities are measured with an array of Langmuir probes, while a fast stroking probe is available for the SOL. Infrared TV is used to monitor the power flux to the divertors. H_α-filtered visible TV is used to view the divertor from above as well as tangentially. A multichord visible spectrometer with a seven-channel Fast Optical Multi-Channel Analyzer (FOMA) head is presently being installed to view the divertor and DIMES sample head. The SPRED spectrometer has recently been modified to allow its viewing chord to be scanned through the inner and outer SOL. An aggressive program for divertor materials study planned on DIII–D is described below.

2. INTEGRAL EXPERIMENTS

Two experiments were performed during the first phase of the DIMES program. They are the exposure of twelve well characterized DIII–D tiles for a period of eight months, and a DIMES sample that contained a layer of ^{13}C on the plasma facing surface for a period of five months.

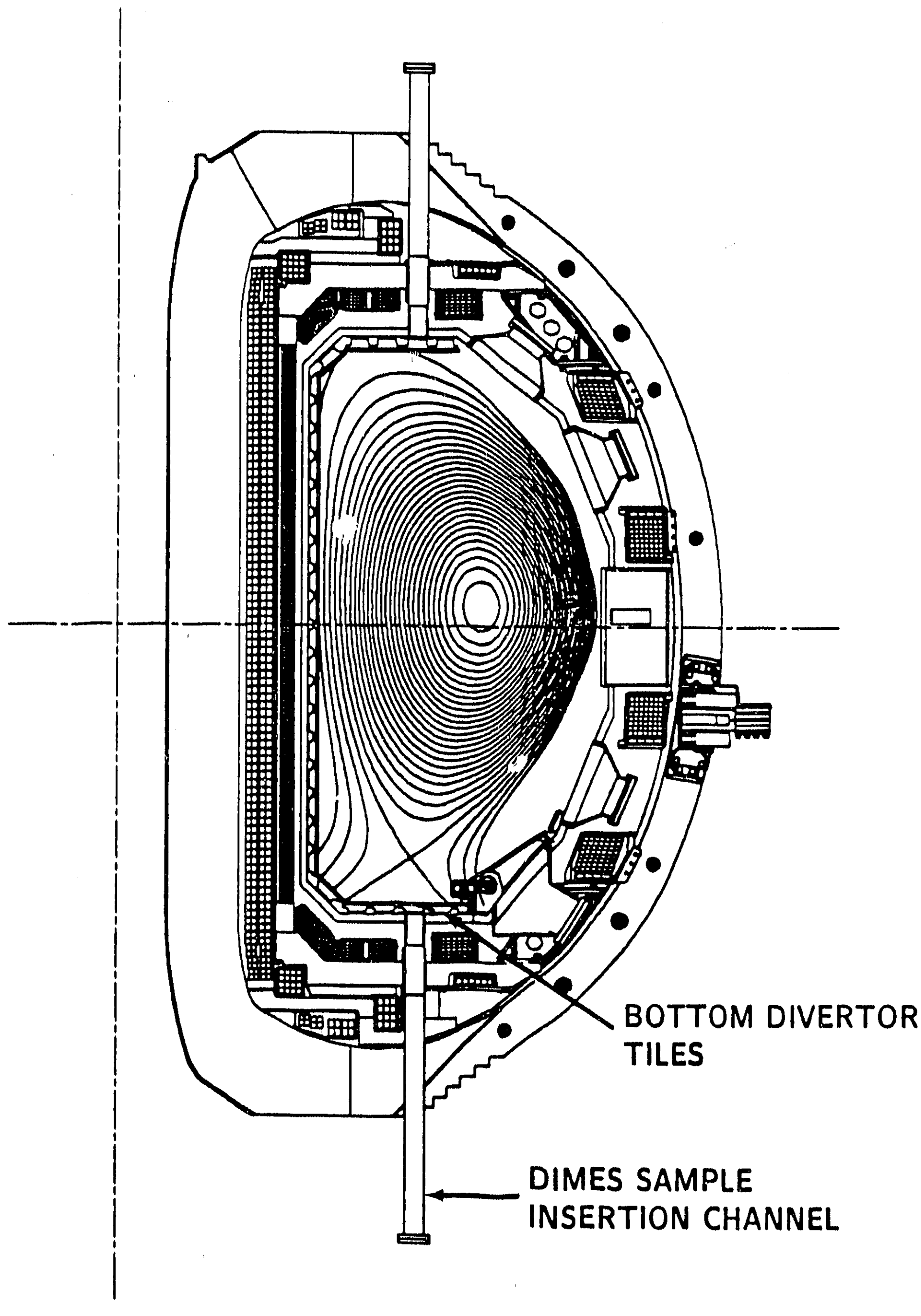
2.1. Exposure of DIII–D Bottom Divertor Tiles

A set of twelve well characterized divertor graphite tiles was fabricated and installed in DIII–D in March 1989. These tiles were exposed to the plasma discharges for a period of eight months, then removed from DIII–D in December 1989. The tile surfaces were well characterized before and after the exposure by microprofilometry to an accuracy of $\pm 1\ \mu$. The location of the bottom divertor tiles is illustrated in Fig. 1. During this period of DIII–D operation, these divertor tiles were exposed to different types of normal and off-normal events. Normal events include ohmically-heated discharges, auxiliary-heated L–mode and H–mode discharges, and disruptions. Off-normal events included limiter tile cleanup and carbonization of the DIII–D vessel. Preliminary analysis identified 1700 bottom divertor discharges. The measured net erosion distribution of the tiles was compared to results obtained by the REDEP modeling code [1] as shown in Fig. 2. For the modeling calculation, the plasma parameters were characterized by the most frequent plasma shots. (An H–mode shot producing high power deposition at the strike points with measured plasma conditions of $T_e = 45$ eV, $n_e = 5.6 \times 10^{19}\,\mathrm{m}^{-3}$, $\theta_{\mathrm{pol}} = 43°$ at the outer strike point and $T_e = 12$ eV, $n_e = 12.7 \times 10^{19}\,\mathrm{m}^{-3}$, $\theta_{\mathrm{pol}} = 30°$ at the inner strike point. The magnetic field lines strike the divertor at a glancing angle of $\sim 3°$.) On DIII–D the strike points can be swept over most of the divertor floor area. A preliminary analysis of the distribution of strike point positions over the total exposure period was estimated by calculating the magnetic configuration using EFIT [2] for selected discharges at selected discharge times. It was found that the magnitude of net erosion was comparable between measured and modeled results. In addition, because of the unequal plasma densities at the outer and inner strike points, the analysis predicted a net transfer of sputtered carbon material from the outboard to the inboard region. The calculations shown in Fig. 2 were based on a preliminary strike point distribution and the agreement is quite good.

A complete search of relevant bottom divertor discharges will be performed and each of these discharges will be analyzed at 100 ms time intervals from 0.5 s to 6 s. Each interval will be grouped under ohmic, L–mode, or H–mode, and then relevant plasma parameters and strike point positions will be determined. These data will be used as input for REDEP to obtain a more accurate estimation of the erosion profile. Results will be presented in a future publication.

2.2. Exposure of ^{13}C-coated DIMES Sample

For the second integral exposure experiment, a thin layer 49 μg/cm^2 of ^{13}C was deposited over a 1 cm diameter area on the polished end of the DIMES graphite sample facing the plasma. The design of the DIMES sample is illustrated in Fig. 3. The sample was inserted into the bottom divertor of DIII–D machine as shown in Fig. 1, and exposed to about 500 plasma discharges over a period of 5 months. During this period, the plasma strike point varied considerably and numerous plasma disruptions occurred. Interpretation of this measurement is clouded by the fact that the sample surface was recessed from the surrounding divertor tile surfaces by $\sim$1 mm. The exposure noticeably altered the surface of the probe and surrounding tile area, which showed regions of erosion as well as deposition. The extent of erosion and redeposition was measured by mapping the ^{13}C to ^{12}C ratio over the surface of the probe by



DIII–D
ELEVATION AT 150°

Fig. 1. Cross-section of DIII–D machine showing DIMES insertion port.

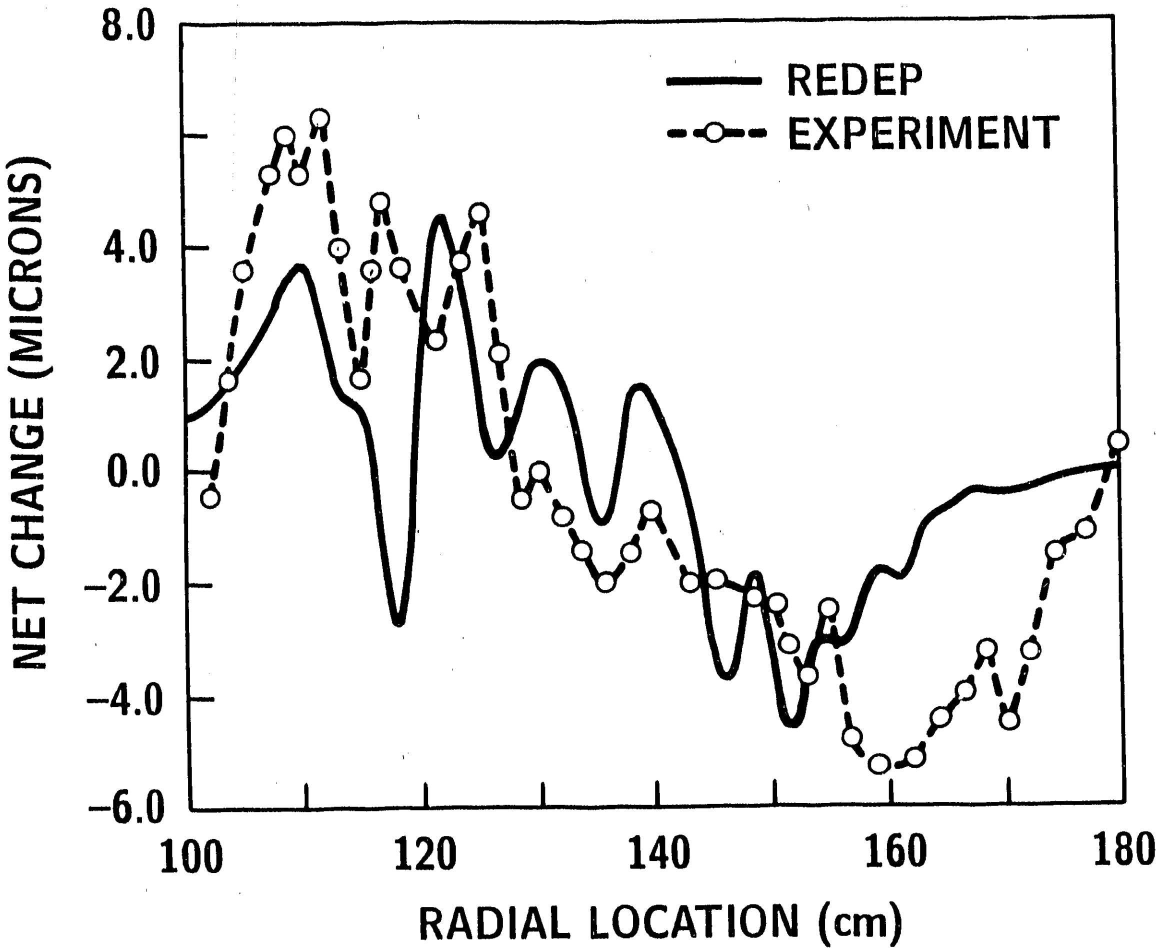


Fig. 2. Comparison of REDEP analysis with experiment. Erosion profiles after 1700 discharges.

secondary-ion mass spectrometry (SIMS) analysis. Measured results indicated that deposition of carbon from the surrounding tiles occurred over most of the exposed DIMES sample. Near surface ^{13}C material, sputtered from the original deposit, was detected only in areas of the sample that were shadowed from deposition of material eroded from the surrounding tiles. For future experiments, shorter sample exposure periods will be possible, thus enabling a more detailed correlation to be made between the DIII–D plasma properties and erosion rate. Effects due to adjacent tiles and sample alignment can also be determined.

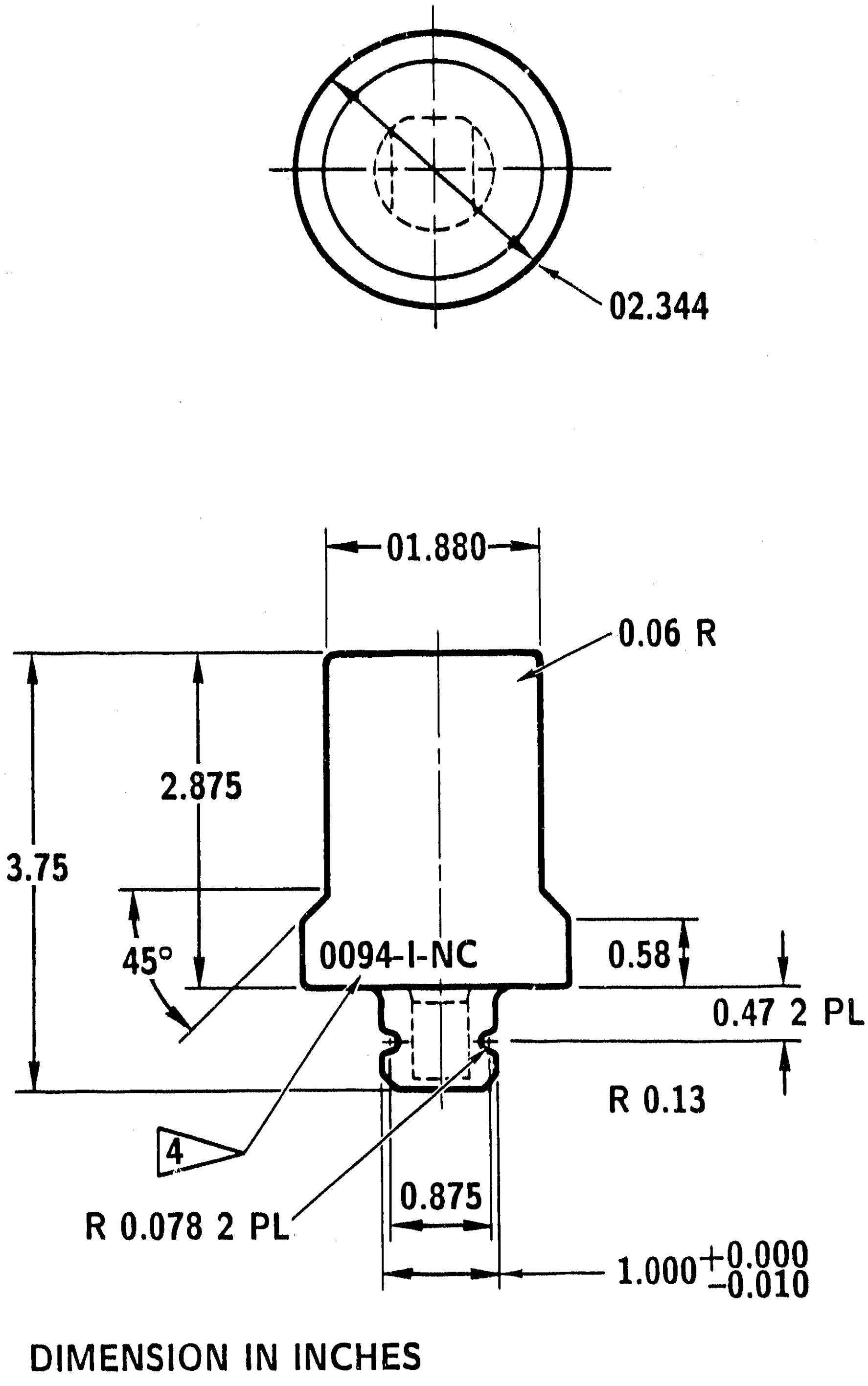


Fig. 3. DIMES sample design.

3. DIMES SAMPLE CHANGER MECHANISM

The second phase of the study is the installation of the DIMES sample changer mechanism, and the performance of short exposure experiments using samples of different materials.

3.1. Mechanical Design

The DIMES sample shown in Fig. 3 has a cylindrical geometry, a diameter of 4.25 cm and a height of about 7.3 cm. The mechanical design goal is to allow insertion of instrumented samples into the divertor plate region of DIII–D without venting the tokamak. In 1991, to obtain a reliable sample changer design, we evaluated five different design options. A bellows and hydraulic cylinder design was selected. The bellows will be able to separate the motorized moving parts from the high vacuum region of DIII–D. A schematic is shown in Fig. 4. Allowances are made for as many as 10 electrical leads to be connected from the sample to external instruments. The sample changer mechanism is expected to be installed in DIII–D in the second quarter of 1992. With the sample changer in place, different material samples can be exchanged overnight after as few as one plasma shot of exposure.

3.2. Experimental Plan

In preparation for the experimental program of exposing DIMES samples of different configurations and materials for different plasma discharges in DIII–D, a solicitation for ideas for DIMES experiments was distributed to the fusion plasma surface interaction community. More than 20 proposed experiments were received. Some of these are piggyback experiments that can be performed in conjunction with

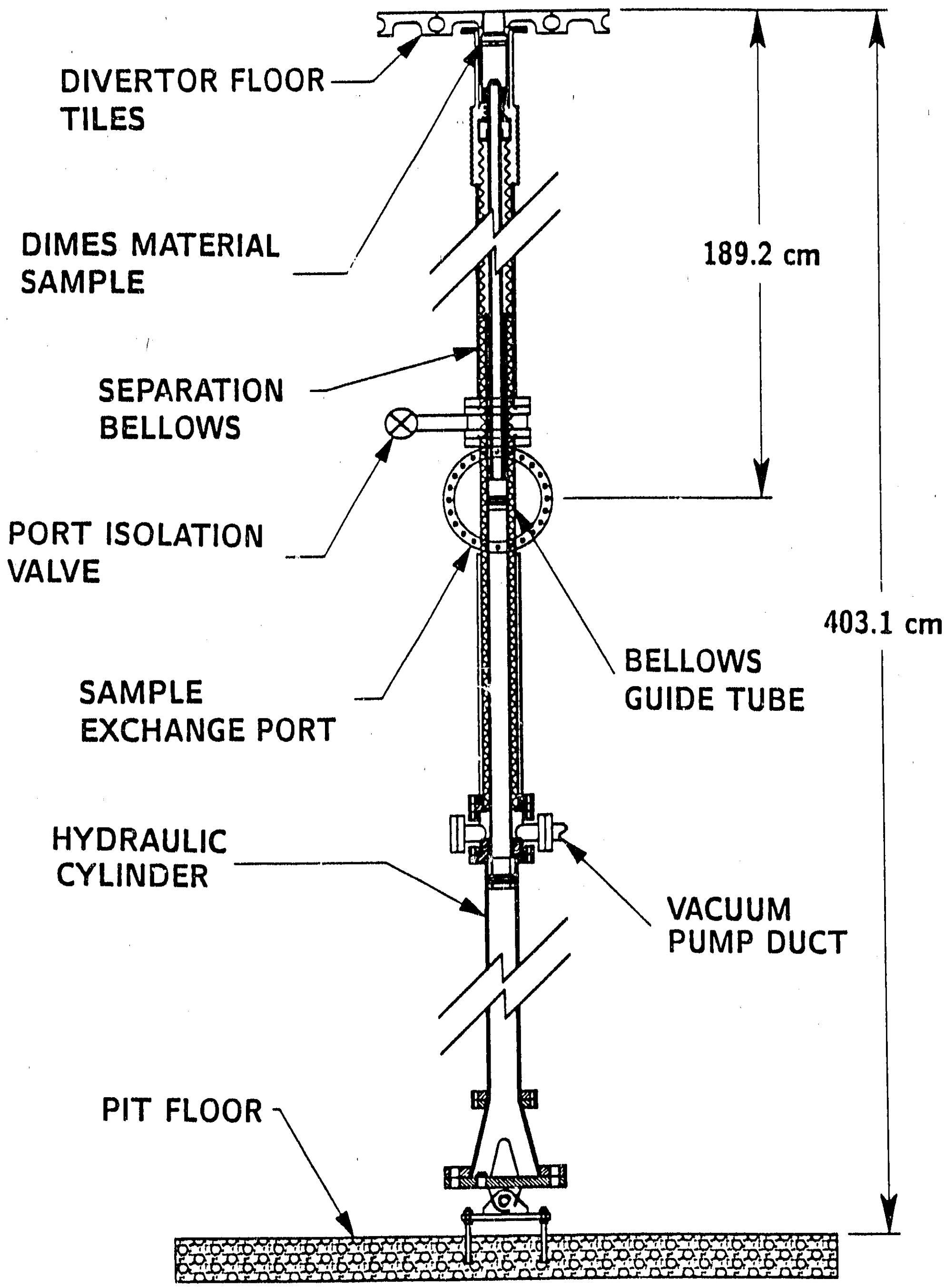


Fig. 4. Schematic of the DIMES sample changer mechanism design.

other DIII–D physics experiments. Some of these will require specific DIII–D runtime. The set of proposed experiments can be separated into five groups as follows.

1. Erosion/Redeposition Measurements with DIMES. Erosion/redeposition studies of divertor strike plate material are important for the ITER design and are the primary goal of the DIMES program. Several experimental techniques will be pursued. Profilometry of a graphite sample exposed to strike point plasmas and comparison to the REDEP and WBC [3] modeling codes at ANL will constitute the first phase of the effort.

   Similar to the integral experiment, a DIMES sample with a thin layer of ^{13}C deposited in a small spot near the center of the sample face (prepared at SNL-Livermore) will be exposed in the divertor floor. After exposure to multiple plasmas with the strike point positioned on DIMES, the sample will be removed and the distribution profile of ^{13}C will be measured using SIMS at SNL-Livermore. Spatial distribution of ^{13}C due to erosion and redeposition can be used as data for bench marking REDEP.

   Using a thin film monitoring technique being developed by SNL, erosion and redeposition data can also be obtained on a single shot basis without removing the sample. Long thin parallel strips of a conducting film are deposited onto an insulating sample surface. Increased resistance through a strip will indicate erosion, while increasing conductance between adjacent strips will indicate deposition. These measurements can be made between shots.

   As a part of the gaseous divertor studies to be carried out on DIII–D, the effects of deuterium gas injection on the erosion rate of the divertor material will also be studied. This is to study the potential reduction of surface erosion due to the reduction in electron temperature and redistribution of incident power.

In all cases, the power to the strike point will be measured using an Infrared (IR) camera located at the top of the vacuum vessel. Spectroscopic data from the sample surface will be obtained with the multichord divertor spectrometer which is being developed at General Atomics. Probe measurements of the divertor strike point plasma will be used to characterize the plasma.

2. Disruption Induced Erosion. The uncertainty of the effects of disruptions on the ITER divertor plate is very high. Primitive models indicate severe effects on graphite tiles, while more sophisticated models, including a vapor cloud shielding effect, indicate very tolerable levels of erosion. Recent ion and electron beam measurements also indicate severe effects, while ex-tokamak plasma impact experiments show good vapor shielding results. Several disruptions will be induced onto the DIMES sample and the sample will be removed for profilometry, directly yielding net erosion. Spectroscopic and IR camera measurements will be made. Probe measurements, if possible, will contribute to the analysis. The ^{13}C tracer technique discussed above will also be used.

3. Deuterium Retention in ITER-Relevant Divertor Materials. Retention of tritium in first wall materials of a burning reactor is a serious safety issue. Retention of deuterium in DIMES samples will be measured by exposing samples that have been purged of deuterium content by baking at high temperature under vacuum. After exposure to the plasma conditions of interest, deuterium content will be measured ex-situ by a variety of techniques at SNL.

4. New Materials Exposure. Many new materials, coatings and infiltrated materials are being proposed for application as a fusion first wall and/or divertor strike plate. DIMES is well suited to testing the durability and performance of these materials to the high-power divertor strike point plasma.

After successfully passing some preliminary ex-tokamak thermal cycling tests, these samples can be exposed to the DIII–D plasma. Cracking and crazing of the surface will be observable with a vertical viewing camera, and the sample can be removed from the plasma should delamination of the surface material appear possible. Candidate materials for testing include the B_4C-coated graphite samples from Kurchatov Institute, Troitsk, Moscow; ITER candidate materials; high Z coatings (such as tungsten) and boron infiltrated material proposed by University of California, Los Angeles . Net erosion rates can be measured using profilometry, and relative sputtering rates can be obtained with spectroscopy. Thermal effects can be determined with the IR camera. Transport of material from the DIMES sample to the vessel wall will also be investigated.

5. Boronization Coating Evaluation. The DIMES sample will be in position during a boronization run, and upon removal the coating will be characterized ex-situ by a variety of techniques at GA and SNL. The coated sample will then be reinserted for exposure to the plasma and removed again for erosion measurements.

4. CONCLUSIONS

The DIvertor Material Evaluation System (DIMES) at DIII–D is a collaborative program between General Atomics, Sandia National Laboratories, and Argonne National Laboratory. The first phase of this study is integral material exposure measurements. A group of twelve DIII–D divertor tiles was exposed to the plasma for a period of eight months. The tile surfaces were well characterized before and after the exposure by microprofilometry. The measured net erosion distribution was compared to results obtained by the REDEP modeling code. The second phase of the study is the installation of the DIMES sample changer mechanism. The mechanical design will allow insertion of instrumented samples into the divertor plate region of DIII–D without venting the tokamak. With the sample changer installed, different material samples can be exchanged overnight after as few as one plasma shot of exposure. Experiments are being planned to study the interaction between the plasma and the divertor surface material. The critical issues of material erosion, tritium retention, disruption effects and material transport can then be addressed.

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