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Divertor and midplane materials evaluation system in DIII-D

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Abstract

The Divertor Materials Evaluation System (DiMES) at General Atomics has successfully advanced the understanding of plasma surface interaction phenomena involving ITER-relevant materials and has been utilized for advanced diagnostic designs in the lower divertor of DIII-D. This paper describes a series of recent successful experiments. These include the study of carbon deposition in gaps and metallic mirrors as a function of temperature, study of dust migration from the divertor, study of methane injection in order to benchmark chemical sputtering diagnostics, and the measurement of charge exchange neutrals with a hydrogen sensor. In concert with the modification of the lower divertor of DIII-D, the DiMES sample vertical location was modified to match the raised divertor floor. The new Mid-plane Material Exposure Sample (MiMES) design will also be presented. MiMES will allow the study and measurement of erosion and redeposition of material at the outboard mid-plane of DIII-D, including effects from convective transport. We will continue to expose relevant materials and advanced diagnostics to different plasma configurations under various operational regimes, including material erosion and redeposition experiments, and gaps and mirror exposures at elevated temperature.

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1. Introduction

For advanced tokamak experiments and power reactors, divertor surface and chamber wall

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material erosion and redeposition will have critical impacts on the performance of the plasma due to impurities transport, heat removal, tritium co-deposition and inventory, and the lifetime of the plasma facing components. The purpose of the Divertor Material Evaluation System (DiMES) [1] in DIII-D [2] is to provide measured data on suitable surface materials for advanced tokamak devices like ITER and fusion power reactors. Material samples can be inserted into the lower divertor of DIII-D and exposed to selected plasma discharges. Net material erosion and redeposition can be measured and results can be used to benchmark modeling codes [3].

The DiMES program has:

- Quantified the net erosion rate of carbon and benchmarked modeling codes.
- Shown that divertor detachment can significantly reduce net carbon erosion in DIII-D.
- Identified the potential erosion/redeposition (E/R) contributions from the first wall.
- Identified the importance of chamber wall aging to chemical sputtering.
- Quantified the E/R and deuterium (as a proxy for tritium) uptake of carbon and different metallic coatings.
- Identified the critical issue of MHD interaction between liquid lithium and SOL plasma.

A description of the DiMES experiment, its operation in DIII-D, its experimental methods and its diagnostics support are presented in Refs. [3–7]. In the last two years, the DiMES program responded to selected fundamental scientific and International Tokamak Physics Activities (ITPA) identified needs while making use of the new capability of temperature control of the DiMES sample. Recent results summarized in this paper include the study of carbon deposition in gaps [8] and on metallic mirrors [9,10] as a function of temperature, study of dust migration from the divertor [11], study of methane injection to benchmark chemical sputtering diagnostics [12], and the measurement of charge exchange neutrals with a hydrogen sensor. In concert with the modification of the lower divertor of DIII-D, the DiMES sample vertical location has been modified to match the raised divertor height. The new MiMES design will allow the study and measurement of erosion and redeposition of relevant materials at the outboard mid-plane of DIII-D.

2. Tile-Gap experiments

Tritium co-deposition/retention is one of the most critical issues for ITER. One of the most troublesome carbon deposition regions for trapping tritium is in the narrow tile gaps that are not accessible to many of the proposed T-recovery methods. These deposits tend to be the 'soft', H/D/T-rich hydrocarbon layers, rather than the 'hard', leaner layers that occur on plasma-contacting surfaces. Fortunately, such soft deposits may be more manipulable than hard ones, and it may be possible to control and reduce the formation of such deposits by changing the tile temperature. In particular, increased chemical erosion by cold hydrogenic atoms at elevated temperature [13] can inhibit the growth of hydrocarbon deposits in tile gaps.

We studied co-deposition of deuterium (as a proxy for tritium) in DIII-D using a special DiMES sample [designed and fabricated at Sandia National Laboratories (SNL), Livermore] featuring a simulated tile gap 2 mm wide and 15 mm deep (Fig. 1). The sample was exposed in the DIII-D divertor to a number of highly reproducible ohmic discharges. Two separate exposures of nine discharges each were performed. In the first exposure, the sample was at the ambient temperature (~30 °C), while in the second exposure it was heated up to 200 °C by an internal heater. In both cases, the discharges were lower single–null (LSN) with outer strike point (OSP) kept at the DiMES radial location from 0.9–4.4 s into the discharge. The line-average density flattop was at $4.5 \times 10^{13}\ cm^{-3}$ for about 3 s, and the OSP was detached most of the time. The discharges were terminated by current ramp-down, there were no large transients or disruptions. The total exposure time in both cases was about 30 s.

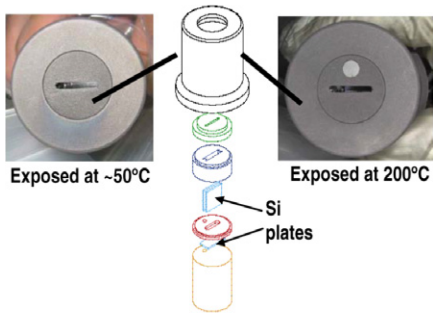

Fig. 1. DiMES tile gap sample after exposure to plasma.

In order to obtain the best possible resolution of the deposition down the gap, the sample was equipped with silicon wafers (catcher plates) installed down the sides of the gap and at the bottom. After being exposed in DIII-D, the wafers were shipped to Max-Planck-Institut für Plasmaphysik (Garching, Germany) for analysis of the deposits by ellipsometry and ion beam analysis (IBA).

Both ellipsometry and IBA analyses of the catcher plates from the non-heated exposure showed measurable amounts of deposited carbon on all plates. The deposit thickness on the side plates decreased exponentially with the distance from the plasma facing side of the gap, with a decay length of about 1–3 mm. The shapes of the deposit thickness profiles from ellipsometry were in good agreement with the carbon number density from IBA. Measured D/C atomic ratio from IBA was 0.4–0.7.

IBA analysis of the carbon deposition on the catcher plates from the heated exposure revealed a slightly smaller amount of deposited carbon compared to the non-heated exposure. However, the amount of co-deposited deuterium was reduced by about an order of magnitude in the heated exposure. These results confirm the observed differences between hydrocarbon deposition in gaps at ASDEX Upgrade and TEXTOR and agree very well with the observed temperature dependency of hydrocarbon deposition at remote surface [8]. This is possibly due to the observation that the sticking probability at least of CH_3^+ hydrocarbons does not vary significantly in the relevant surface temperature range, while the D and C are still deposited with approximate constant ratio of $D/C \approx 0.7$ and an exponential fall-off length from the gap entrance of ≈3 mm [8]. This is a very encouraging result for ITER, suggesting that moderately elevated temperature can significantly reduce tritium accumulation in tile gaps. Ellipsometry analysis of the carbon deposition on the heated wafers failed to resolve the deposition thickness. This may indicate that the carbon reacted with silicon to form a thin Si:C layer rather than a 'normal' a-C:H film. Further analysis is underway at Max Planck IPP. For the heated DiMES sample, a graphite button with implanted Si was added to the exposed surface (Fig. 1), which was not installed in an earlier experiment. At 200 °C, the net carbon erosion rate was measured with IBA at ∼3 nm/s, whereas normally net deposition was observed at the condition of plasma detachment when the surface was at ambient temperature [8].

3. Exposure of mirrors

Optical mirrors are foreseen for ∼50% of ITER diagnostics, and they will be used in infrared, visible and ultraviolet wavelength ranges. Mo, W and stainless steel are among the main candidate mirror materials to be used in ITER. However, the optical properties of mirrors will change due to erosion, deposition of contaminants and particle implantation. Mirrors in the ITER divertor will likely suffer from deposition of carbon and other impurities [14].

First ever tests of ITER-relevant molybdenum mirror surfaces in a tokamak divertor were successfully performed during the last two weeks of DIII-D operations in 2005. This experiment was conceived and performed as a collaborative effort between DIII-D and IPP Forschungszentrum Jülich. The mirrors were positioned about 2 cm below the floor tiles in the lower divertor of DIII-D using DiMES (Fig. 2).

Three sets of two mirrors each were exposed. The first set was exposed in a piggyback mode over two days to 72 plasma discharges with varying parameters, producing significant semi-transparent deposits on the mirror closest to the leading edge of the floor tile. The second set of mirrors was exposed at ambient temperature (∼30 °C) to six identical partially detached (PDD) ELMing H-mode discharges for a total of ∼25 s. Visible deposits were found on both mirrors and holder elements upon removal. The third mirror set was exposed to 17 PDD H-mode discharges similar to those of the second exposure for a total of ∼70 s. The holder with mirrors was exposed at elevated temperature, changing from 140 °C to 80 °C in the course of the experiment. Upon removal, virtually no deposits were visible on the mirrors, and some of the deposits formed on the mirror holder elements in the previous exposures were gone. This is potentially another encouraging result for ITER since it indicates that a very

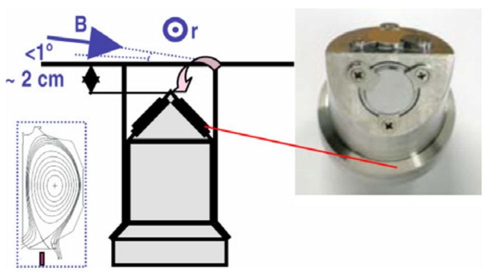

Fig. 2. Illustration and picture of DiMES mirror sample.

moderate temperature increase could strongly inhibit or suppress net carbon deposition on the diagnostic mirrors. However, the drop of total reflectivity was still observed from the heated mirrors, with the main effect in the wavelength range of 300–1500 nm. Results also show that C deposition has a dramatic impact on the mirror polarization characteristics. The mirrors are currently going through detailed post-exposure analyses in Germany, Switzerland and SNL, Albuquerque [9].

4. Dust exposure at the divertor

Micron-size dust is commonly found in tokamaks and stellarators. Though generally of no concern in present-day machines, dust may pose serious safety and operational concerns for the next generation of fusion devices such as ITER. Dust accumulation inside the vacuum vessel can contribute to tritium inventory rise and cause radiological and explosion hazards [15]. In addition, dust penetrating the core plasma can cause increased impurity concentration and degrade performance.

We studied the migration of pre-characterized carbon dust in a tokamak environment by introducing ~30 mg of dust flakes 5–10 μm in diameter at the lower divertor of DIII-D using the DiMES sample holder (Fig. 3). In two separate experiments, dust was exposed to high power ELMing H-mode discharges in the LSN magnetic configuration with the strike points swept across the divertor floor [11]. In the initial stage of the discharges, the dust holder was located in the private flux zone, and the dust presence did not manifest itself in any way. When the OSP passed over the dust holder exposing it to high particle and heat fluxes, part of the dust was injected into the plasma. In about 0.1 s following the OSP pass over the dust, 1–2% of the total dust carbon content ($2–4 \times 10^{19}$ carbon atoms – equivalent to a few million dust particles) penetrated the core plasma, raising the core carbon density by a factor of 2–3. When the OSP moved inboard of the dust holder, the dust injection continued at a lower rate. Individual dust particles were observed moving at velocities of 10–100 m/s, predominantly in the toroidal direction for deuteron flow to the outer divertor target, consistent with the ion drag force. The dust velocities were estimated by dividing the observed track lengths by the exposure time recorded by standard (60 f/s) cameras [11]. The observed behavior of the dust is in qualitative agreement with modeling by the 3D Dust Transport (DustT) code, which calculates trajectories of test dust particles in a realistic plasma environment.

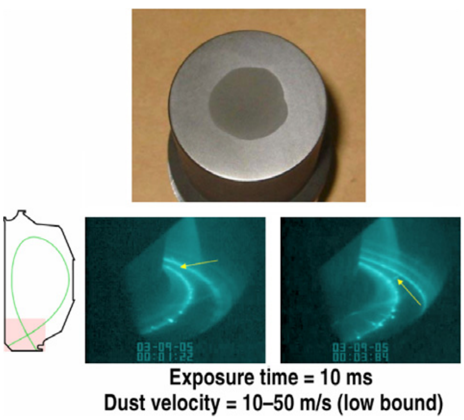

Fig. 3. Loaded carbon dust on DiMES and dust tracks in DIII-D.

5. Porous plug

In the study of the evolution of carbon release from the DIII-D lower divertor tiles, we found a gradual decrease of chemical erosion yield [16] over time. This could be caused by long-term conditioning via boronization. For further quantification of the measurement of chemical sputtering from lower divertor tiles, a self-contained gas injection system for the DiMES on DIII-D has been successfully employed for in situ study of chemical erosion in the tokamak target environment. The Porous Plug Injector (PPI) injects methane, a major component of molecular influx due to chemical sputtering of graphite, from a location flush with the lower divertor tile surface into the plasma above it at a controlled rate via a porous graphite surface. This reduces the local plasma perturbation due to the puff to a minimum, while also simulating the immediate environment of methane molecules released from a solid graphite surface by chemical sputtering. The release rate was chosen to be of the same order as natural chemical sputtering of ~100 eV deuterium on graphite as measured in laboratory experiments. An investigation of the resulting interaction between the injected CH_4 and the local plasma was made using the calibrated Multichord Divertor Spectrometer (MDS) and the Reticon spectrometer, in addition to collecting data on the parameters of background plasma by the full complement of DIII-D divertor diagnostics.

The injection of methane at a known and well controlled rate allows for the determination of photon efficiencies of CD molecules for measured local plasma conditions in a tokamak environment. The contribution of chemical versus physical sputtering as the source of C^+ at the target was determined through simultaneous measurement of a CII line and CD band emission both during a release of CH_4 from the PPI and during intrinsic-only emission [12].

6. Hydrogen sensor

In addition to the erosion of surface material from the divertor, charge exchange neutrals impinging on the chamber wall could also lead to a significant amount of eroded material, since the chamber wall surface area is much larger than that of the divertor. However, the amount of charge exchange neutrals has not been measured at the chamber wall. To test such a measurement at the divertor, a DiMES sample with built-in solid-state hydrogen micro-sensors was developed by SNL, Livermore, and successfully tested in DIII-D. The sensor assembly is embedded in the probe and consists of two collimating apertures, a four-element hydrogen sensor chip, a thermocouple, and a small internal heater for the sensor. The hydrogen sensor was successfully exposed in DIII-D, and consistent capacitance and biased voltage curves were obtained. Results are being analyzed at SNL, Livermore.

7. DiMES modification

To enhance the plasma shaping capability, the lower divertor of DIII-D was modified in 2006 [17]. Correspondingly, the upper surface of the DiMES sample level relative to the new lower divertor surface had to be raised by a vertical height of 11.23 cm. In order to reduce the contribution of carbon erosion from adjacent tiles, the vertical alignment between tiles was set at the demanding criteria of <0.1 mm. To achieve these design requirements, the DiMES hydraulic cylinder was modified to accommodate the additional vertical delivery, and a new sample alignment mechanism was designed, fabricated and installed in DIII-D. The DiMES mechanism was re-assembled and we demonstrated that the DiMES sample can be delivered to the new lower divertor surface with alignment meeting the new DIII-D requirements.

8. MiMES

The magnetic divertor is to provide heat and particle exhaust and has been projected to shield the main plasma from impurity contamination. Our dust experiment shows that carbon from the divertor can move into the plasma core. At the same time considering the eroded edges and arc-tracks from the chamber wall, we can project that some core contaminants could also be coming from the chamber wall. This possibility is further emphasized with the projection and experimental observation of intermittent radial convection [18]. Taking advantage of the modification of the outboard mid-plane fast probe in DIII-D, with the addition of an airlock for the exchange of fast probe hardware, we have designed and will modify the graphite shield of the fast probe, such that material samples can be installed (Fig. 4).

The design and operational approach of MiMES will be modeled after the DiMES program. The goal is to provide material erosion and redeposition experimental data for different relevant materials at the chamber wall of DIII-D. The additional key contribution of this work will involve benchmarking the SOL modeling code.

9. Future plan

For the DiMES and MiMES programs, we will continue to address divertor surface and chamber wall material erosion and redeposition issues related to advanced tokamak experiments and power reactors. In the near term, we will continue to address ITER-critical issues identified by ITPA, perform additional tile gap, metallic mirror, methane injection, and surface materials exposure experiments as a function of temperature. We will analyze exposed MiMES material samples and study the impacts from radial transport. We will also perform additional controlled exposure of carbon dust and

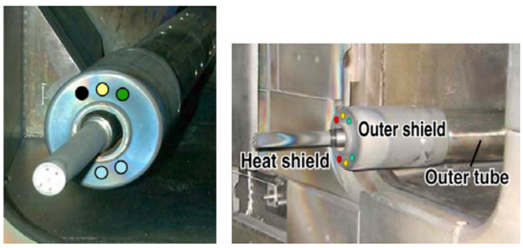

Fig. 4. MiMES location and possible installation of material samples on the graphite shield of the mid-plane fast probe.

support the development of advanced diagnostics: hydrogen sensor, advanced mass micro balance and innovative PMI surface designs. Benchmarking of modeling codes is also a key objective of our program.

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