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DiMES PMI research at DIII-D in support of ITER and beyond

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HIGHLIGHTS

- Net erosion of high-Z PFC materials in DIII-D divertor is reduced by short scale re-deposition.
- Positive electrical biasing locally suppresses erosion of high-Z PFC materials.
- Local injection of methane gas suppressed Mo erosion by forming in-situ carbon coating.
- Measurements of Mo and W erosion on DiMES samples are well reproduced by ERO-OEDGE modeling.
- Migration of W in and out of DIII-D divertor was studied using DiMES and MiMES collector probes.

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ABSTRACT

An overview of recent Plasma-Material Interactions (PMI) research at the DIII-D tokamak using the Divertor Material Evaluation System (DiMES) is presented. The DiMES manipulator allows for exposure of material samples in the lower divertor of DIII-D under well-diagnosed ITER-relevant plasma conditions. Plasma parameters during the exposures are characterized by an extensive diagnostic suite including a number of spectroscopic diagnostics, Langmuir probes, IR imaging, and Divertor Thomson Scattering. Post-mortem measurements of net erosion/deposition on the samples are done by Ion Beam Analysis, and results are modelled by the ERO and REDEP/WBC codes with plasma background reproduced by OEDGE/DIVIMP modelling based on experimental inputs. This article highlights experiments studying sputtering erosion, re-deposition and migration of high-Z elements, mostly tungsten and molybdenum, as well as some alternative materials. Results are generally encouraging for use of high-Z PFCs in ITER and beyond, showing high redeposition and reduced net sputter erosion. Two methods of high-Z PFC surface erosion control, with (i) external electrical biasing and (ii) local gas injection, are also discussed. These techniques may find applications in the future devices.

1. Introduction

Control of plasma-material interactions (PMI) is one of the main challenges facing ITER and future magnetic fusion devices. The

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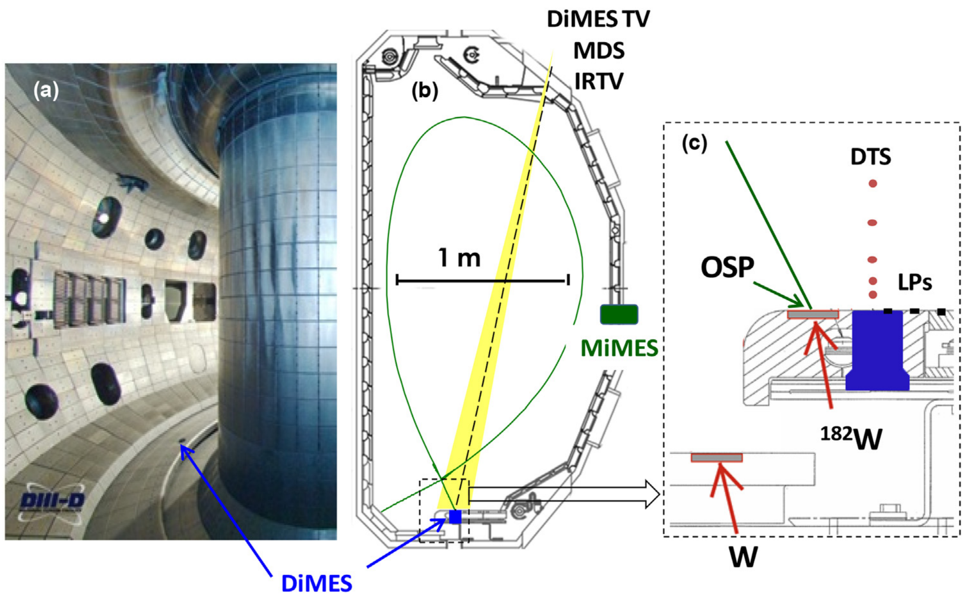

Fig. 1. Experimental arrangement on DIII-D. Poloidal locations of DiMES, MiMES and main diagnostics are shown in (b). Locations of shelf LPs, DTS scattering volumes, W-coated tile inserts, and OSP during W short-range transport experiment (see Section 4.6) are shown in (c).

Divertor Material Evaluation System (DiMES) [1] has been the main diagnostic for PMI studies in the lower divertor of DIII-D tokamak [2] since 1992. The Midplane Material Evaluation Station (MiMES) [3,4] was added in 2007 to study PMI at the outer main chamber wall. Since plasma-facing components (PFCs) in DIII-D are made of graphite, a lot of effort in 1990s and 2000s was devoted to studies of erosion and re-deposition of carbon (see, e.g. [4] and references therein). When the decision was made to go with an all-W divertor in ITER, the DiMES program shifted focus to strengthen studies of PMI with metallic PFCs in support of ITER. Since background levels of metallic impurities, particularly those of high-Z elements like tungsten (W) and molybdenum (Mo), are typically very low in DIII-D, it is possible to study erosion/re-deposition and migration of these elements without background contamination. Generally, erosion of high-Z materials in DIII-D is significantly due to low-Z ions, such as carbon (C) and nitrogen (N), similar to the earlier report from ASDEX Upgrade [5]. Here we provide an overview of DiMES experiments and analysis accomplished in the last four years.

2. Experimental arrangement on DIII-D

Fig. 1 shows a poloidal cross-section of DIII-D with a typical Lower Single Null (LSN) last closed flux surface (LCFS) and the outer strike point (OSP) on top of DiMES. Poloidal locations of DiMES, MiMES and the main diagnostics used in the experiments described below are also shown. DiMES is imaged by the DiMES TV filtered camera (employing commercial analog or digital CMOS, or specialized radiation-hardened CMOS detectors over the years) and a high resolution Multi-chord Divertor Spectrometer (MDS). In some experiments, a direct view of DiMES with an infrared camera (IRTV) was also available. Another IRTV measures the incident heat flux profile in a different toroidal cross-section. Divertor plasma density, n_e, and electron temperature, T_e, are measured by Divertor Thomson Scattering (DTS) while target fluxes and near target plasma temperatures

are measured by Langmuir probes. Locations of the lowermost DTS scattering volumes and LPs closest to DiMES are shown in Fig. 1(c), which also shows locations of W-coated metal tile inserts (See Section 4.6). DiMES samples are typically inserted so that their top surface is flush with the divertor tiles. The OSP can be swept over DiMES or dwell on it for part or most of the exposure discharge. When longer exposure times are desired, reproducible repeat discharges are used. L-mode discharges are typically used to benchmark modeling, in order to avoid transient excursions of the divertor plasma parameters caused by Edge Localized Modes (ELMs). During most of L-mode experiments described below plasma density, n_e, and electron temperature, T_e, in the vicinity of the OSP were in the range $n_e = 1 \times 10^{19}$–$1.2 \times 10^{20}\,m^{-3}$, $T_e = 10$–35 eV.

3. Sample preparation and analysis

Fig. 2 shows top views of a few DiMES heads used in recent experiments. Samples employed for studies of erosion/re-deposition feature thin films of metals deposited either on silicon (Si) substrate (some over a C inter-layer as in Fig. 2(a)) or on polished graphite (Fig. 2(b and c)). Metallic coatings are usually deposited in a magnetron sputter deposition system and pre-characterized by Rutherford Backscattering (RBS) at Sandia National Laboratories (SNL Albuquerque). By comparing pre- and post-exposure RBS measurements, net erosion of metals is measured. Re-deposition of metals on initially uncoated parts of the samples is also measured by RBS. Areal density of deposited C and hydrogenic species (H, D, T) on exposed samples is measured by Nuclear Reaction Analysis (NRA) at SNL. Surface morphology changes are typically characterized by comparing pre-and post-exposure Scanning Electron Microscopy (SEM) images. Other analyses such as Focused Ion Beam SEM, optical and contact profilometry, confocal microscopy, etc., are used when required.

4. Overview of experiments and results

4.1. Reduction of net erosion of Mo and W by short-scale redeposition

A total of five experiments have been performed in reproducible LSN L-mode discharges with Mo and W coatings [6–8]. All samples featured 1 cm diameter Mo or W films 15–40 nm thick deposited on a Si substrate. Net erosion and redeposition of Mo and W were measured by RBS. In the first two experiments, samples with 1 cm