Laboratory-Scale Lithium Research's Relevance to Fusion Devices

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Abstract: Lithium is a low Z-material which offers huge benefits as a wall or divertor target material: low recycling, high edge temperatures, improved plasma confinement, suppressing ELMs etc. However, to gain universal acceptance as a material for use in DEMO or other future experiments, several issues must be addressed. Namely, will a lithium surface be able to withstand erosion, heat fluxes, and J x B forces in a tokomak environment? Three laboratory-scale experiments are underway at the Center for Plasma Material Interactions at the University of Illinois designed to address those points. The Ion Surface InterAction eXperiment (IIAX) examines the physical sputtering, chemical erosion, and vapor pressure of lithium on various materials, including lithiated graphite as used in NSTX. The Divertor Erosion and Vapor Shielding eXperiment (DEVeX) looks at material erosion and vapor shielding due to energetic plasma flows similar to disruptions or ELMS striking the target. The Solid/Liquid Lithium Divertor Experiment (SLiDE) studies the flow of liquid lithium driven by thermoelectric magnetohydrodynamic (TEMHD) effects and thermocapillary magnetohydrodynamic (TCMHD) effects.

I. Introduction:

The worldwide usage of lithium has grown tremendously and its use has risen over the past few years (for e.g., T11-M (1), FTU (2), LTX (3), TJ-II [4] and NSTX [5]). However, several fundamental questions need to be addressed regarding the lithium-plasma interactions in a fusion relevant environment before its applicability to a DEMO-like machine can be assessed. Namely, will a lithium surface be able to withstand erosion, heat fluxes, and J x B forces in a tokomak environment? For this purpose, the Center for Plasma Material Interactions (CPMI) at UIUC has three dedicated facilities to study both liquid lithium systems and solid lithium thin films.

The first experiment developed at CPMI is the Ion Surface InterAction eXperiment (IIAX). This facility was built in order to study erosion of plasma facing component (PFC) materials of interest to the fusion community. While this has become a great resource for sputter erosion measurements in the past, recent studies involved studying lithium and its usefulness as a coating on graphite. Studies include thermal evaporation and sputtering studies of the lithiated graphite system. In another experiment called the Divertor Erosion and Vapor Shielding eXperiment (DEVeX), harsh phenomena such as edge-localized modes (ELMs) or plasma disruptions are planned to be simulated using pulsed plasma based on theta pinch. Such hot plasma-material interactions are important and have not been clearly analyzed. Lithium as a thin coating is applied to see its effect on the vapor shielding. In yet another experiment, as an alternative to solid PFC materials, liquid metal like liquid lithium as a PFC material is being studied. The goal of this study is to investigate the flow of liquid lithium in a divertor related environment, which is possible in the Solid/Liquid Lithium Divertor Experiment (SLiDE) facility.

II. Experimental Facilities at CPMI:

Recently, an overview of the three experimental facilities in the center for plasma material interactions at the University of Illinois that study lithium are described [6]. In this proceeding, only the experimental updates are provided.

2.1. Ion Surface InterAction eXperiment (IIAX):

In the past, IIAX is primarily used for low-energy ion beam bombardment of samples [7-9] and the facility is described elsewhere [6]. In this paper, a new experimental chamber for obtaining chemical erosion measurements is presented. The key components of the experimental setup are the main chamber and detection chamber separated by a gate valve and differential pumping scheme as shown in Fig. 1. The main chamber consists of the plasma producing apparatus, target holder, and the lithium evaporator; and the detection chamber contains an ion gauge and a Residual Gas Analyzer (RGA). Each chamber is pumped to low pressures (10^{-7} torr with no gas flow) individually using turbomolecular pump backed by a mechanical pump. Plasma is produced in the main chamber using RF antenna coil when pressure in the main chamber reaches the mtorr range (with gas flow), while the RGA requires the detection chamber pressure to be maintained at least in the range of ~10^{-5} torr for its better operation. This pressure difference is experimentally achieved using differential pumping scheme with three orifices (~2 mm dia. holes) placed in line between the two chambers. The ion gauge on the detection chamber allows for RGA partial pressure signal calibrations.In addition, the effect of temperature on chemical erosion of ATJ graphite is investigated by mounting target on a button heater which is controlled by a temperature controller. Also, the ability to bias the target is provided so as to increase the energy of the incoming ions striking the target, from which energy dependent sputtering measurements are possible.

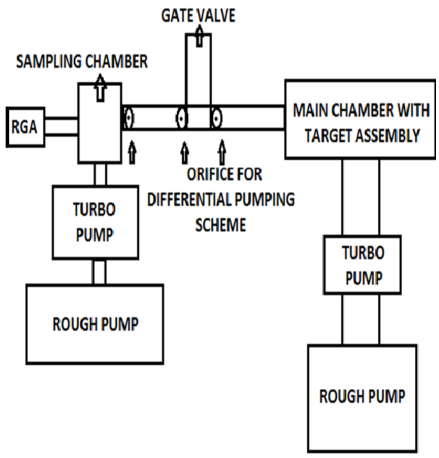

Figure 1. Schematic of the experimental setup for chemical erosion measurements.

2.2. Divertor Erosion and Vapor Shielding eXperiment (DEVeX):

DEVeX is constructed to study how plasmas similar to Edge Localized Modes (ELMs) found in tokamaks interact with PFC materials. For this purpose, the facility has to have a device that is capable of producing plasmas relevant to ELMs in as many parameters as possible and a target chamber that can house all the required diagnostics to study plasma material interactions. The pulsed plasma in DEVeX is produced using a theta pinch as reported earlier [10, 11]. Here the upgrades to the experimental setup are presented. At one end of the quartz tube, a ring-shaped preionization electrode is connected to DC power supply as shown in Fig. 2. Also, unlike earlier experiments, the target is moved into the quartz tube in order to bombard the target with a higher flux. A new

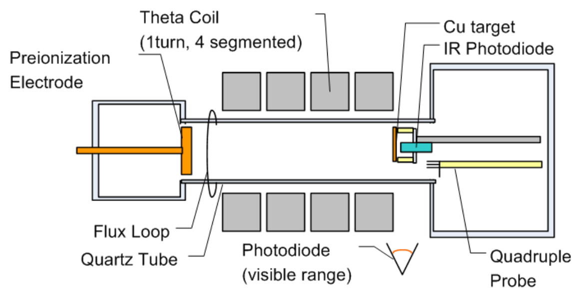

Figure 2. Experimental set up of DEVeX facility.

quadruple Langmuir probe, which is discussed in detail in Ref. [12, 13], is also located in the quartz tube to measure electron temperature, plasma density, and plasma flow velocity. To carry out temperature and IR photodiode measurements, an infrared photodiode PVM-10.6 from Boston Electronics that has 1MHz bandwidth is used. A K-type thermocouple is also used to measure the temperature rise from the target and is cross-checked with the photodiode. Another photodiode, which can detect band-filtered visible light, is located near the quartz tube to monitor various hydrogen lines as a function of time. JEOL-6060 general purpose SEM is used to take SEM images of the target surface. Weight loss measurements are also performed to estimate target erosion.

2.3. Solid/Liquid Lithium Divertor Experiment (SLiDE)

The purpose of SLiDE apparatus is to create a high heat flux and high magnetic field environment to examine the behavior of liquid lithium. The experimental details are presented elsewhere [14, 15]. Briefly, to mimic the heat flux, a linear electron beam normal to the surface of the lithium is used. The magnetic field is generated through two magnet coils ranging from 0 to about 800 G and the direction of the magnetic field is also normal to the surface of the lithium. The recent upgrade includes addition of an infrared camera (Inframetrics 760) to measure the surface temperature of lithium [16]. The control program of the IR camera provides the ability to set an emissivity map and correct the temperature measurement according to the map. Setting an appropriate emissivity of the lithium is important to this experiment. The emissivity of the lithium was measured to be 0.45 to 0.48 when temperature ranges from 200 ˚C to 400 ˚C.

III. Summary of recent work

A new facility was developed for chemical erosion measurements and the results are reported in the PSI paper [17]. In summary, qualitative measurements are possible using a residual gas analyzer. It was shown that the chemical erosion products are dominated by CD_4, and “mass 28” peaks. Furthermore, it was shown that lithium treatments help suppresses the chemical erosion of graphite in the form of CD_4, but the “mass 28” signal remains inconclusive. This is a very intriguing result and requires future investigation to quantify “mass 28”. The “mass 28” signal has interference with CO, N_2 and C_2D_2 signals and to resolve this, in future experiments, C_2D_2 will be observed at “mass 24” (from cracking pattern). Qualitatively, it was shown that both temperature and energy of incoming ions enhances the chemical erosion of ATJ graphite.

DEVeX is now fully operational and has shown that the vapor shielding effect is seen with the use of lithium as a thin film. Based on the measurements of the incident plasma parameters, it is shown that the device produces 10^{21}-10^{22} /m^3 and 10-25 eV plasma parameter with good reproducibility. While the recent results are reported elsewhere [18], several upgrades are being considered to make this a fusion-relevant device.

The two major effects expected in the SLiDE machine are thermocapillary flows and thermoelectric magnetohydrodynamic (TEMHD) flows [15]. Both of these effects are examined from a theoretical standpoint as well as experimentally and the results are reported elsewhere. While the recent are presented here [19], in summary, the surface temperature of TEMHD driven swirling liquid lithium is measured at different magnetic fields and beam currents. An increase of beam current (increase of input power to the lithium) causes a significant surface temperature rise, while a higher heat flux gradient with a constant input power can be efficiently mitigated by the Li flow. This is consistent with the 3D convection model which shows the center which has a lower velocity is easier to overheat. In a fusion device environment, the heat flux gradient mostly happens in the x-y plane which can be lowered by the TEMHD driven flow. But the input power (or the cooling of the lithium) would still need to be controlled carefully to prevent overheating or dry-out. In the future, a 3D convection flow model with a specified TEMHD source term will be built to look into how the magnetic field and boundary conditions will affect the flow and heat transfer.

Conclusions

Having laboratory scale experiments that are flexible and easy to upgrade are needed to answer complex questions that arise in fusion research. Three laboratory scale experimental facilities are used to study plasma interactions with either solid or liquid lithium for a variety of conditions. The interested readers are encouraged to look into references for the results obtained in these newly developed facilities.

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