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Lithium research as a plasma facing component material at the University of Illinois

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ABSTRACT

Plasma facing component (PFC) materials are critical to the development of future fusion reactor. While several different PFC materials have been considered in the past, there is an increased interest in the scientific community on the use of lithium as a future PFC material, after its initial success demonstrated by the TFTR "supershots" and more recent work performed on the CDX-U and NSTX spherical tori. The worldwide usage of lithium in tokamaks has grown rapidly over the past few years because of these results. The Center for Plasma-Material Interactions (CPMI) at the University of Illinois at Urbana-Champaign (UIUC) has been actively involved in lithium research since its foundation and currently, there are three experimental facilities dedicated to studying lithium interactions relevant to fusion conditions namely: 1. Ion surface InterAction eXperiment (IIAX); 2. Divertor Erosion and Vapor Shielding eXperiment (DEVeX); and 3. Solid/Liquid Lithium Divertor Experiment (SLiDE). One of the significant advantages of these experimental facilities is the ability to study the basic physics of the phenomenon taking place. In this review paper, a brief description of the experimental facilities and their capabilities is provided and the interested reader is advised to look in future publications for the recent results.

1. Introduction

The challenge of finding a plasma facing component (PFC) material for use in fusion reactors is an active research problem. Different solid PFC materials have been studied however there is no agreed upon solution [1]. There has been some interest in the use of liquid PFCs as a "high risk, high reward alternative to solid PFCs" [1]. Of the various liquids considered, lithium has garnered the most interest. A liquid PFC eliminates the concern of long-term erosion as it can be continuously renewed. In addition, lithium, in particular, has shown dramatic improvements in plasma performance in NSTX and also in suppressing ELMs [2]. Lithium can pump large amounts of hydrogen [3] and being a low Z material pollutes less when inside of plasma. Lithium has also shown exceptional power handling capabilities in the CDX-U experiment [4,5]. With such advantages, lithium is a strong contender in the search for a viable reactor PFC.

The worldwide usage of lithium has grown tremendously and its use has risen over the past few years (for e.g., T11-M [6], FTU [7], LTX [8], TJ-II [9] and NSTX [2]). 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. The advantages of using lithium are often overshadowed by the lack of understanding and, particularly with liquid systems, the technical complexity associated with its use. 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.

2. Experimental facilities at CPMI

CPMI continues to study lithium, following several years of tradition and experience [10–12]. The Ion surface InterAction eXperiment (IIAX) provides valuable insight into quantifying sputtering yields and evaporation fluxes that are of interest to the fusion community. The Divertor Erosion and Vapor Shielding eXperiment (DEVeX) was constructed to study the vapor shielding phenomenon of thin lithium films. The Solid/Liquid Lithium Divertor Experiment (SLiDE) has been constructed to examine the behavior of free-surface liquid lithium under fusion relevant heat load conditions. In this section, a brief summary of the experimental facilities and capabilities is provided.

2.1. Ion surface InterAction eXperiment (IIAX)

IIAX is primarily used for low-energy ion beam bombardment of samples. A Quartz Crystal Microbalance (QCM) monitors particular effects of the bombardment. Fig. 1 shows the key components of the IIAX facility: the ion gun, target assembly, secondary plasma, evaporation sources and diagnostics. The base pressures are on the order of 10^{-7} Torr. A Residual Gas Analyzer (RGA) is used as needed for measurements. IIAX uses a Colutron ion source which is capable of creating and accelerating ions of both gaseous and metal species. Gaseous ions are obtained by means of electron-impact ionization while metal ions are obtained by thermionic emission. The bombarding ions are mass-selected through an

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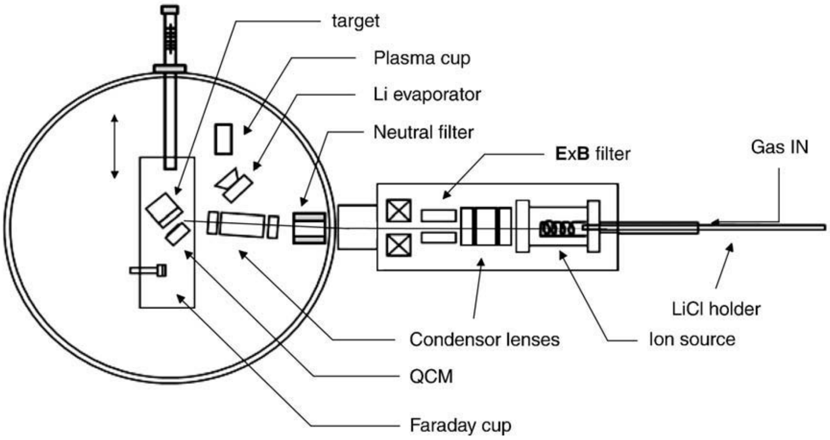

Fig. 1. Schematic of the experimental setup of IIAX.

E × B filter and decelerated near the target by a five-element, cylindrical, electrostatic lens system. A Faraday cup positioned on a translational stage is used to characterize the ion beam before any measurement is taken. The target holder is also held on the same translational stage, and is set in front of the beam as needed. The target holder consists of an ultra-high vacuum (UHV) heater (behind the sample) that can be heated by a controlled AC power supply. A type-K thermocouple is attached to the heater in order to have a temperature measurement for control purposes. The heater allows us to study evaporation rates as well as temperature dependent sputtering yields. An *in-situ* lithium evaporator is added to deposit lithium onto a target substrate. A plasma cup is also installed for deuterium saturation treatment of the target sample. Sputtered or evaporated material from the target is collected by a QCM, which measures the frequency changes due to mass deposited on the crystal. The QCM system in IIAX employs dual crystals where one crystal measures the frequency change from sputtering material while the other measures only the background signal.

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. A 36 μF capacitor bank, capable of being charged to 60 kV or 64 kJ, is connected to a conical theta-coil which is the source of energetic plasma flows in the DEVeX facility. A thin lithium film, which is deposited *in-situ* by a DC magnetron, is used as the plasma facing material though any material can be used to sputter coat the target. The key components of the DEVeX facility are thus the θ-pinch and target assembly housed inside of a vacuum chamber with the appropriate diagnostics installed as shown in Fig. 2. All the major components of the system are depicted in their relative positions (PiP source electrode, θ-coil, and the vacuum chamber). The base pressures are in the range of $(10)^{-7}$ Torr and typical operating pressures for discharges are between 1 and 5 mTorr static fill pressures of hydrogen. The control room is separated from the experiment by a 30 in. think concrete block wall for safety and houses all the electronics needed to remotely charge and discharge the capacitor bank. The entire control room is housed inside of a copper Faraday cage to shield the diagnostics and data acquisition hardware from electromagnetic interference.

All components of the main capacitor bank, charging relays, dielectric insulation, etc. have been designed with a hold-off voltage of at least 60 kV. The main capacitor bank is connected to the conical, θ-coil through a series of 15, RG-19/U coaxial cables to minimize

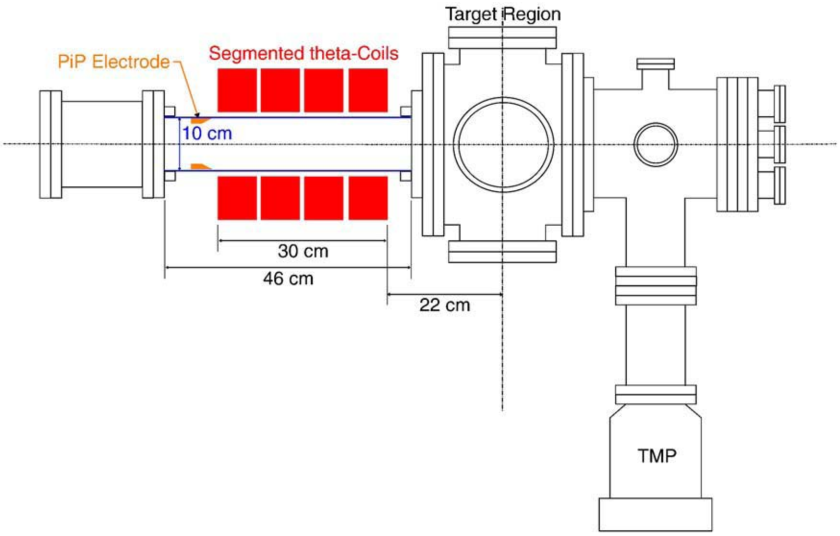

Fig. 2. Side view schematic of DEVeX facility.

inductance. The θ-coil has an inner diameter of 0.1 m at the narrow end and 0.11 m at the opposing end with an overall length of 0.36 m, which yields a calculated inductance of 35 nH.

Several plasma diagnostics characterize the plasma and measure the vapor cloud that forms during plasma interactions with the target. Triple Langmuir probe and optical emission spectroscopy are used to characterize the incident plasma and the formation of the vapor cloud. A set of filtered photodiodes are used to measure intensities of excited states of lithium and hydrogen in the vapor cloud dynamically during the discharge. Initial experiments show plasma densities on the order of 10^{21} m^{-3} in the target chamber with electron temperatures ranging from 15 to 100 eV.

2.3. Solid/Liquid Lithium Divertor Experiment (SLiDE)

The Solid/Liquid Lithium Divertor Experiment was designed, constructed and operated in order to examine the behavior of liquid lithium under fusion relevant heat loads and applied magnetic fields. A schematic of the central part of the machine is shown in Fig. 3. Within the vacuum chamber, liquid lithium is contained within a tray structure. The lithium is subject to an incident heat flux produced by a line-stripe electron beam. The tray is diagnosed with a set of thermocouples embedded within the tray which enables calculation of the heat flux distribution leaving the lithium. The magnetic field is produced by a set of external magnets which create a field which is aligned with the tray normal. Additionally, a camera is used to monitor motion of the lithium. Lithium fills are on the order of 5–20 mm. Magnetic fields range from 30 to 800 G in the present configuration.

The electron beam is designed to mimic a fusion divertor heat flux. The divertor of a fusion experiment consists of a toroidal ring where the magnetic configuration of a tokomak exhausts most of the heat and particle flux from the fusion plasma. Intense heat loads are developed here in the range of 5–20 MW/m^2. The line-stripe heat flux was designed to produce a Gaussian distribution which has a linear extent to approximate a straightened out divertor strike. As the typical radius of a fusion machine's divertor is >1 m, these strike points already look substantially linear. In order to create a fusion relevant heat flux, two parameters were considered, the peak heat flux and the peak heat flux gradient. The latter is important for thermally driven effects such as thermocapillary flows and thermoelectric effects. A 15 kW power supply sources the voltage and current for use in the machine.

The tray system was designed to be actively cooled. This is done to operate in a steady-state condition. At present, no fusion machine operates at steady-state, but is pulsed. Future reactors, however, will require near steady-state operation with pulse lengths on the order of 10^6 s. Already, ITER is planned to produce a maximum pulse length of 1000 s which will result in near-steady thermal conditions for some of the divertor components.

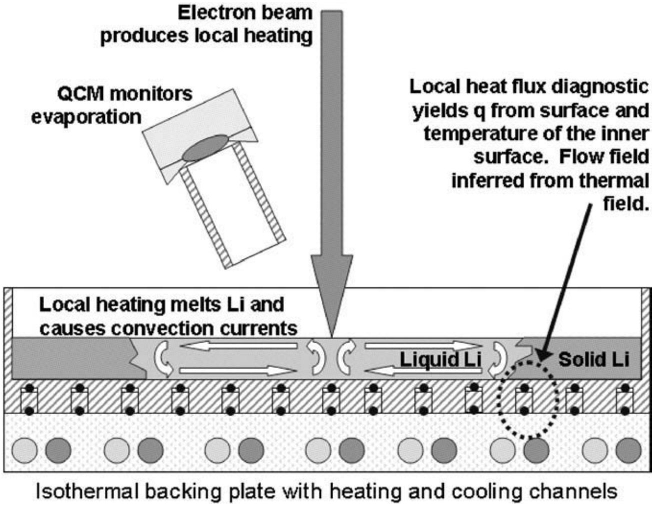

Fig. 3. Schematic of the SLiDE Apparatus.

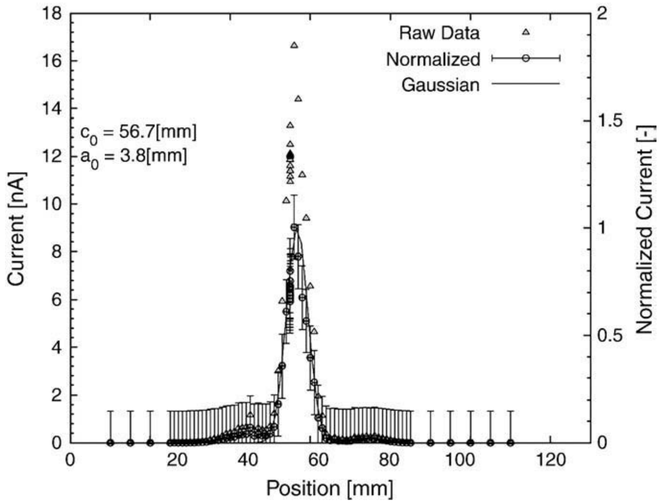

Fig. 4. Typical electron beam profile with raw current signals along with normalized data and Gaussian fit.

The electron beam current density was measured with a Faraday cup diagnostic at low power. This is done to avoid damaging the Faraday cup. These measurements provide the Gaussian decay length associated with a given magnetic field. The beam length was measured with a Beam Visualization Tool which produced a visible glow corresponding to the location of the incident heat flux. This is used instead of the Faraday cup because of a slight (~5°) rotation in the beam which varies with magnetic field. Fig. 4 shows an example Gaussian beam profile and measurement. Table 1 summarizes the projected capabilities of the SLiDE electron beam operating at 8 kW. For comparison, the peak heat flux of a typical NSTX shot is 10 MW/m^2 and the peak heat flux gradient varies from 100 to 800 MW/m^2-m and as can be seen, the SLiDE electron beam provides peak heat fluxes on the order of those currently observed in magnetic fusion experiments.

3. Summary of recent work

IIAX is currently directed toward the study of thin films of lithium on various substrates starting with ATJ graphite. A recent study in IIAX looked at sputtering and evaporation of this target material. For lithiated ATJ graphite studies, an *in-situ* lithium evaporator is used to deposit lithium onto ATJ graphite sample. The sputtering study utilized a lithium ion beam to irradiate the ATJ graphite sample and also lithiated ATJ graphite sample. The absolute sputtering yields of Li^+ on ATJ graphite and lithiated ATJ graphite before and after D saturation at 45° incidence are measured. For evaporation measurements of lithiated graphite, a significant suppression of evaporation flux of Li in graphite is observed

Table 1
Summary of electron beam capabilities operating at 10 [kV] and 800 [mA] (P0 = 8 [kW]).

Magnetic current	Magnetic field	Peak heat flux	Peak heat flux gradient (mean)
I_{mag} [A]	B_0 [G]	q_0 [MW/m^2]	$\partial q/\partial x$ [MW/m^2 m]
2	13.5	1.25	24.2 (11.3)
5	33.9	1.78	52.2 (24.3)
10	67.7	≥2.58	≥97.6 (≥45.5)
40	270	≥5.22	≥337 (≥157)
80	542	17	3830 (1790)
100	677	18.2	4330 (2020)

for surface temperatures ranging from 250 °C to 500 °C as compared to pure lithium. The recent results are reported in [13].

The phenomenon of vapor shielding is believed to protect the PFC surface from further damage and DEVeX facility will be used to study such effects. Recently, this facility was used to study bombardment of thin lithium films with energetic plasma flows. The use of lithium is encouraging in that it shows the formation of a vapor cloud under these simulated disruption conditions. The results will be reported in a future publication.

The two major effects expected in the SLiDE machine are thermocapillary flows and thermoelectric magnetohydrodynamic (TEMHD) flows [14]. In the case of a thermocapillary driven flow, surface tension variations with temperature cause flows which moves material from hot areas to cooler ones. In the case of TEMHD, the thermoelectric effect creates currents within the liquid metal and the container which, in conjunction with an external magnetic field, produces flows [15]. Both of these effects are examined from a theoretical standpoint as well as experimentally and the results are reported in the following publication [16].

The versatility of lithium research activities at CPMI can thus be seen from the summary of activities being performed. Through the myriad of experiments described here, the complex questions arising from the use of lithium are being studied in the hope of answering whether lithium will prove to be the ultimate technology for fusion PFCs.

4. Conclusions

Lithium research has been the cornerstone of CPMI's fusion research program for many years and has a large amount of experience working with it. This storehouse of past experience, and current experiments with lithium situates CPMI as uniquely capable of studying plasma–lithium interactions. Having laboratory scale experiments that are flexible and easy to upgrade are needed to answer complex questions that arise in fusion research. In this paper, a review of current experimental facilities available in CPMI and their capabilities were detailed. These experimental facilities are used to study plasma interactions with either solid thin film or liquid lithium for a variety of conditions. The interested readers are encouraged to look into future publications for results obtained in these newly developed facilities.

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