High-temperature liquid lithium divertor targets and implications for advanced power cycles

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Liquid metal plasma-facing components (LM-PFCs) provide a potential alternative material for fusion experiments and future reactors. Liquid metals in general would separate neutron effects from plasma-material interaction effects, eliminate stress-induced fatigue of the plasma-facing surface, and eliminate net-reshaping of the components due to long-term plasma-transport of eroded material throughout the vessel. Liquid lithium PFCs in particular could provide a very low-Z material reducing concerns related to core radiation. Criticism of liquid lithium in a fusion reactor scenario focus on three issues: surface temperature limitations, loss of thermal efficiency due to reduced surface temperatures and tritium retention in the interior of the vessel.

Modeling efforts found wall temperature limits of 380C for low-recycling conditions whereas due to computational difficulties, only a lower bound of 300C was found for high-recycling [1]. Criteria based on impurity influx rates suggest 450C as a temperature limit [2]. Experiments on the FTU tokamak have indicated a temperature limit for a liquid lithium limiter of 550C [3]. Such a range of temperature limits suggests the importance of exploring the question of the operational limits of a liquid lithium divertor target though this has not yet been accomplished on any device. Transport of material throughout the scrape-off layer is at least partially determined by momentum balance and an alternative temperature limit can be calculated on the basis of lithium vapor pressure compared to upstream plasma conditions [4]. A comparison of a wide range of existing and future fusion experiments and reactors indicates that temperatures between 750-850C will be required to balance target vapor pressures with plasma pressures calculated with a heuristic drift-based model of the scrape-off layer [5].

Experiments have been conducted on the Magnum-PSI linear plasma device [6] to begin an assessment of high-temperature liquid lithium PFCs in a divertor-like plasma environment. Experiments were conducted by depositing thin layers (1 micron thickness) of lithium onto a high-Z substrate (TZM-alloy of molybdenum) and subjected to a plasma discharge at normal incidence that resulted in heating of the substrate from room temperature to over 1300C. The plasmas simulated NSTX divertor conditions with densities ~$2 \times 10^{20} m^{-3}$ and electron temperatures ~2eV. During exposure, a stable cloud of intense lithium emission is developed directly in front of the target, shown in figure 1.

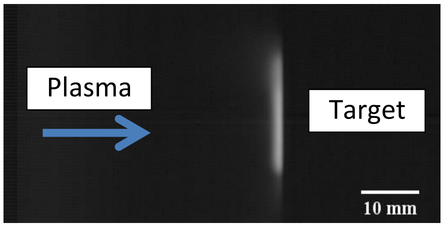

Figure 1: Filtered fast-camera image of lithium emission directly in front of the target. The camera view is tangential to the target surface with the plasma source to the left of the image. Li-I emission is shown. The observed vapor cloud is stable over a wide temperature range.

This cloud persists for nearly 4s (corresponding to the presence of a macroscopic lithium layer) despite a surface temperature exceeding 1000C by that time (see figure 2). During the period of time the cloud is present, an increased electron density 4-7mm in front of the target is observed, alongside increased hydrogen optical emission. No deleterious effects of the high-temperature lithium exposures were observed upstream indicating confinement of the lithium near the target. The absence of lithium emission in subsequent experiments on lithium-free targets indicates lithium did not travel up the plasma stream and contaminate the source despite surface temperatures violating the previous flux-based temperature limits. These provide an initial viability demonstration for liquid lithium vapor-shielded targets consistent with current cooling technologies that must then be integrated into a global power-cycle.

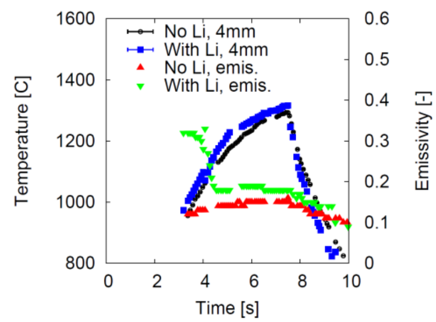

Figure 2: Surface temperature and surface infrared emissivity evolution during plasma discharges in Magnum-PSI. Transition at ~4s indicates removal of the lithium layer. Similar transition is observed in spectroscopic signals and camera imaging.

Liquid metal PFC technologies based on advanced cooling systems, including the use of supercritical CO_2 power cycles, have been proposed [4]. A modified Brayton power-cycle with recompression is compatible with cooling of the LM-PFC by diverting a fraction of the recompressed gas to cool the divertor. Such gas cooling results in surface temperatures above 700C under a 10 MW/m^2 heat flux without additional radiative cooling of the scrape-off layer plasma. The recompression cycle had previously been shown to provide a thermal efficiency of 45% for a turbine inlet temperature of only 550C for Gen-IV fission reactor studies [7]. The impact of modifying the recompression power cycle for use with a liquid lithium PFC is presented addressing concerns of reduced cycle efficiency with the use of a liquid lithium PFC.

The use of liquid lithium systems as a means of tritium inventory control was previously proposed [8]. This feature of liquid lithium is a unique capability unavailable to refractory metals and carbon. The power-cycle implications of a tritium-controlling wall is presented.

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