Liquid Lithium Divertor and Scrape-Off-Layer Interactions on the National Spherical Torus Experiment: 2010 – 2013 Progress Report

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Abstract

The implementation of the liquid Lithium Divertor (LLD) in NSTX presented a unique opportunity in plasma-material interactions studies. A high density Langmuir Probe (HDLP) array utilizing a dense pack of triple Langmuir probes was built at PPPL and the electronics designed and built by UIUC. It was shown that the HDLP array could be used to characterize the modification of the EEDF during lithium experiments on NSTX as well as characterize the transient particle loads during lithium experiments as a means to study ELMs.

With NSTX being upgraded and a new divertor being installed, the HDLP array will not be used in NSTX-U. However UIUC is currently helping to develop two new systems for depositing lithium into NSTX-U, a Liquid Lithium Pellet Dripper (LLPD) for use with the granular injector for ELM mitigation and control studies as well as an Upward-Facing Lithium Evaporator (U-LITER) based on a flash evaporation system using an electron beam.

Currently UIUC has Daniel Andruczyk Stationed at PPPL and is developing these systems as well as being involved in preparing the Materials Analysis Particle Probe (MAPP) for use in LTX and NSTX-U. To date the MAPP preparations have been completed. New sample holders were designed by UIUC's Research Engineer at PPPL and manufactured at PPPL and installed. MAPP is currently being used on LTX to do calibration and initial studies. The LLPD has demonstrated that it can produce pellets. There is still some adjustments needed to control the frequency and particle size. Equipment for the U-LITER has arrived and initial test are being made of the electron beam and design of the U-LITER in progress. It is expected to have these ready for the first run campaign of NSTX-U.

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1. Executive Summary

The implementation of the Liquid Lithium Divertor (LLD) in NSTX presented a unique opportunity in plasma material interaction studies. Lithium's high evaporation rates at relatively low temperatures presented a challenge to successful implementation and influences the particle pumping capabilities of the LLD. Diagnostics and studies on NSTX provided experimental data of hydrogen and lithium flux above the LLD as well as the coupling between evaporative and incident power.

UIUC contributed the electronics and data acquisition for a dense-pack array of triple Langmuir probes. The probes were fabricated at PPPL and located between the LLD tray segments. The probes ran till the end of the 2011 run campaign when NSTX was shut down for upgrades.

With NSTX being upgraded and a new divertor being installed, the HDLP array will not be used in NSTX-U. However UIUC is currently helping to develop two new systems for depositing lithium into NSTX-U, a Liquid Lithium Pellet Dripper (LLPD) for use with the granular injector for ELM mitigation and control studies as well as an Upward-Facing Lithium Evaporator (U-LITER) based on a flash evaporation system using an electron beam.

Currently UIUC has a Research Engineer/Scientist stationed at PPPL and is developing these systems as well as being involved in preparing the Materials Analysis Particle Probe (MAPP) for use in LTX and NSTX-U. To date the MAPP preparations have been completed. New sample holders were designed by UIUC's Research Engineer at PPPL and manufactured at PPPL and installed. MAPP is currently being used on LTX to do calibration and initial studies. The LLPD has demonstrated that it can produce pellets. There is still some adjustments needed to control the frequency and particle size. Equipment for the U-LITER has arrived and initial test are being made of the electron beam and design of the U-LITER in progress. It is expected to have these ready for the first run campaign of NSTX-U.

2. Background

The highlights of the previous collaboration include the successful design and installation of the "joint PPPL-UIUC High-Density Langmuir Probe (HDLP) array". The HDLP array is installed at one of the toroidal breaks in the liquid lithium divertor (LLD) and has been successfully used in making spatially resolved measurements of edge number density, electron temperature, and floating potential in real-time. The HDLP array was also used to monitor the scrape-off-layer currents, including the PFC linked currents as well as machine linked currents. The highlights of the work could be best summarized through the following journal publications. Also, the results were reported at various conferences:

V. Surla, M.A. Jaworski, V. Soukhanovskii, T.K. Gray, R. Kaita, J. Kallman, H. Kugel, A. McLean, D. N. Ruzic, F. Scotti, "*Characterization of transient particle loads during lithium experiments on the National Spherical Torus Experiment*," Fusion Eng. Design, 87 (2012) 1794 – 1800.

M.A. Jaworski, M.G. Bell, T.K. Gray, R. Kaita, J. Kallman, H.Kugel, B. LeBlanc, A. McLean, S.A. Sabbagh, V. Soukhanovskii, D.P.Stotler, V. Surla, "*Modification of the electron energy distribution function during lithium experiments on the National Spherical Torus Experiment*" Fusion Eng. Design, 87 (2012) 1711 – 1718.

J. Kallman, "*Effective Sheath Heat Transmission Coefficient in NSTX discharges with Applied Lithium Coatings,*" Ph.D. Dissertation, Princeton University, 2011

M.A. Jaworski, J. Kallman, R. Kaita, H. Kugel, B. LeBlanc, R. Marsala, and D.N. Ruzic, "*Biasing, acquisition and interpretation of a dense Langmuir probe array in NSTX*," Review of Scientific Instruments, 81, 2010.

J. Kallman, M. A. Jaworski, R. Kaita, H. Kugel, and T. K. Gray, "*High density Langmuir probe array for NSTX scrape-off layer measurements under lithiated divertor conditions,*" Review of Scientific Instruments, 81, 2010.

3. Research Progress

3.1. Summary of LLD results

In the last-run campaign, NSTX has implemented the LLD to modify the edge recycling behavior. In order to study the effect of LLD on pumping, it will be necessary to monitor changes in electron temperature and edge number density. The previous diagnostics on NSTX covered the mid-plane thoroughly but were limited in the edge-region, which motivated the development of HDLP array. As a result of previous funding effort, the HDLP array is successfully installed between LLD plates to provide proximate measurements.

Below is a summary of the capabilities of HDLP array

- Several key measurements including local n_e and T_e at outer divertor target.
- Probes can be run in various modes: triple, single swept, I_{sat}, floating
- Spatial resolution is 2.5 mm radially, and 7.5 mm toroidally
- DAQ and electronics allow for 250 K-samples/sec/channel simultaneously
- Additional probes to monitor scrape-off-layer currents directly
- Strike point could be determined from floating potential measurements and target plasma profiles

While the details of the probe are presented in the publications listed in the previous section, some specific results are shown here demonstrating the above listed capabilities. Figure 1 shows sample probe data collected using HDLP array for shot #137622 on NSTX. A comparison of the raw IV characteristic and the resulting analysis against the dual probe method with circuit resistance corrections are presented in figure 1. An option for measurement made possible by the electronics is the use of a "dual probe" method where the floating potential measured on the adjacent triple probe is subtracted from the bias on the swept probe to account for fluctuations and plasma perturbation effects [1]. This shows that the implemented HDLP array allows a high degree of flexibility in measurement location and type.

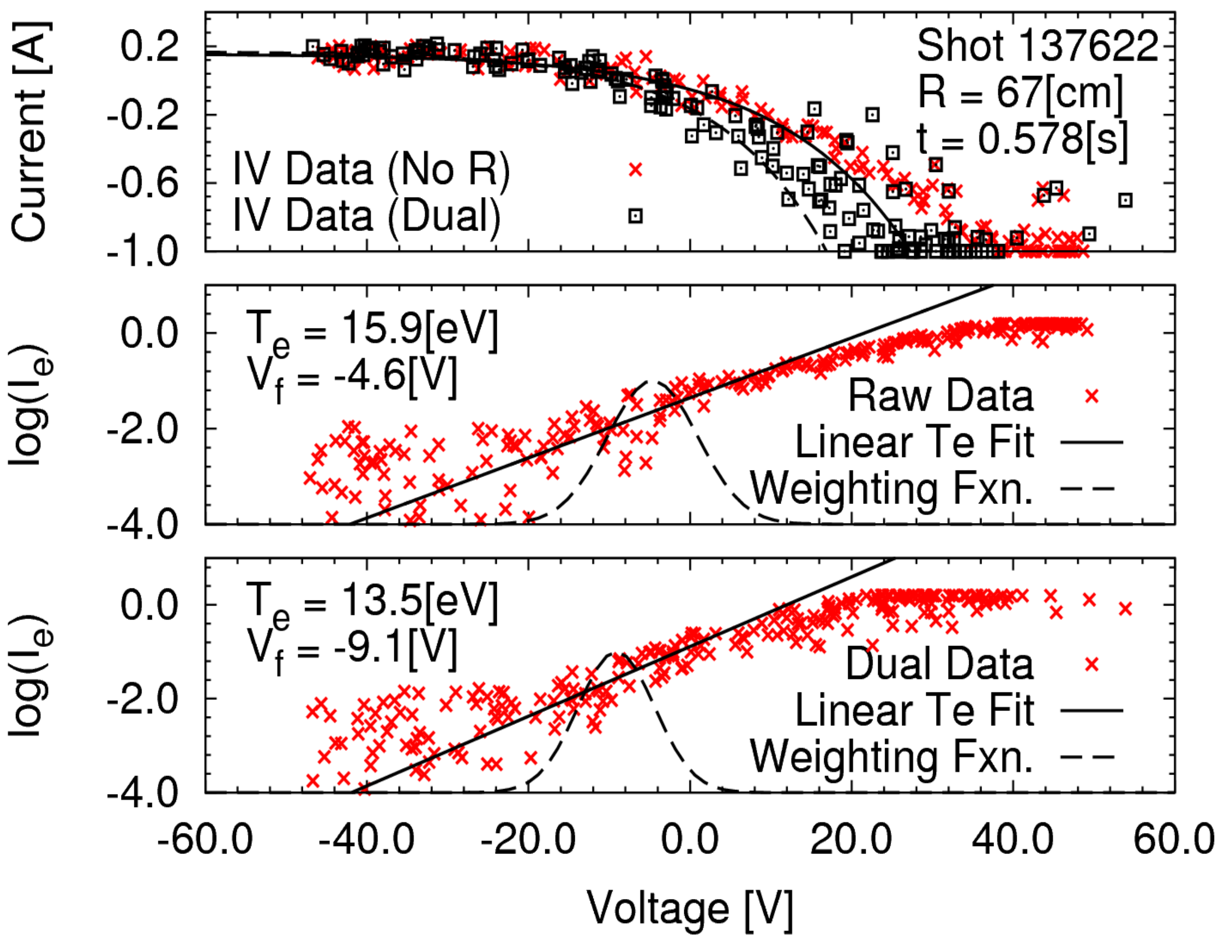

Figure 1: Sample probe data for NSTX shot #137622.

A standardized interpretation has been implemented for the Langmuir probes providing a comparison to dual- and triple-probe methods. On average, all three temperature calculation methods yield results within 25% of one another. Upon mapping to midplane, the calculated temperatures are not inconsistent with those measured by Thompson scattering [2].

An additional capability of the HDLP array is to monitor the scrape-off-layer currents that are flowing through the PFC and machine linked currents [3-6]. Figure 2 shows measurements of the machine-linked currents in a 900 kA, 2MW NBI, ELM-free discharge in NSTX. The strike point sweeps over the inner two probes at about 0.5 s and was held at the nominal set-point location after this time. The measurements indicate significant spatial gradients in SOLC in the vicinity of the strike-point and a typical magnitude of order 10–20 kA/m^2. Figure 2 also shows initial measurement of the PFC-linked SOLC in NSTX. The two probes were initial set at the same radial location with a toroidal gap of 500 µm for testing during two 900 kA discharges with the strike point approximately 10 cm inboard of the probe location. In order to demonstrate that a real current was being measured, the toroidal order of the two probe tips was reversed and the measured current reversed as well.

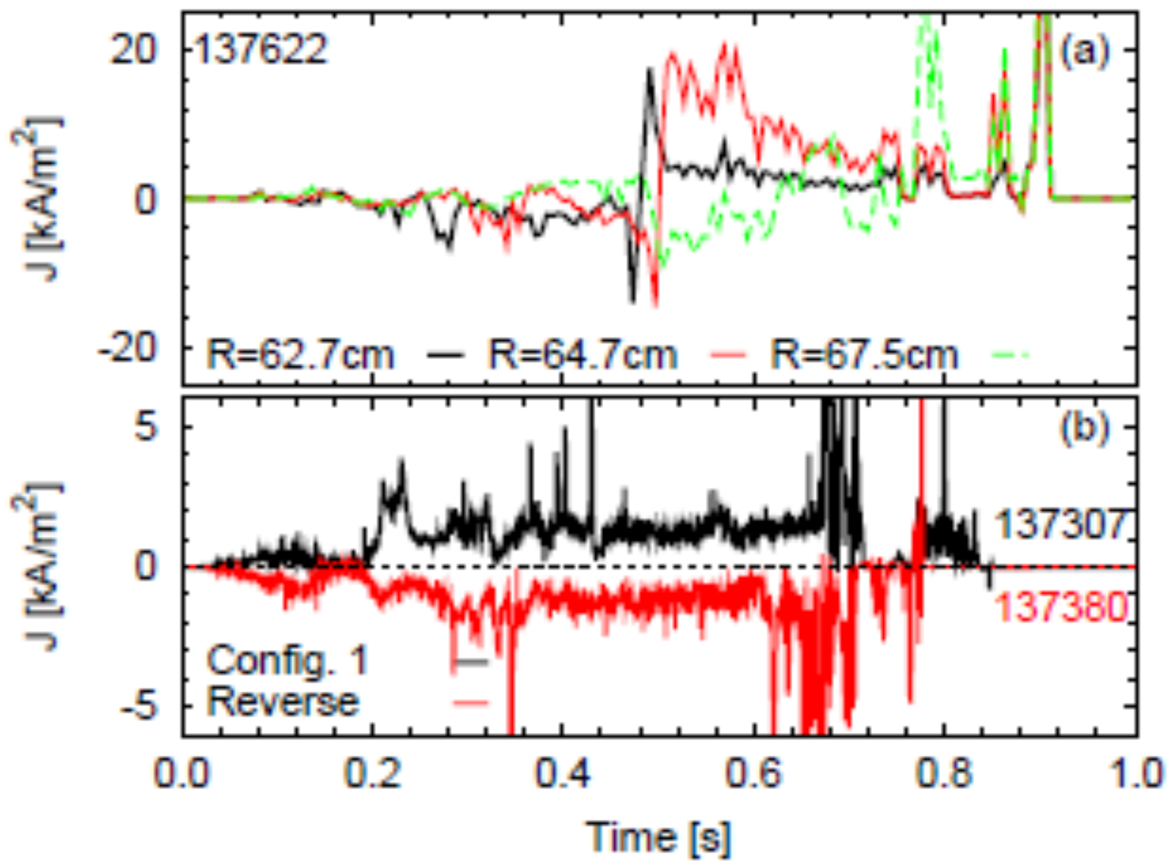

Figure 2: Measurements ofm(a) machine linked and (b) PFC linked SOLC in NSTX. In (a) the strike point sweeps over the inner two probes at about 0.5s. In (b) two similar discharges are compared with the probe configuration reversed to confirm the signal is reliable. Data has been smoothed for reliability [2].

The motion of liquid metal plasma facing components under interaction with divertor plasmas is analyzed by M. Jaworski using the HDLP array [2]. SOLC are divided into machine- and PFC-linked currents which result in orthogonal motion of the liquid metal. In addition to currents entering from the plasma, thermoelectric effects between the liquid and solid substrate will also create currents when temperature gradients are present. PFC-linked currents in the radial direction will be capable of producing vertically destabilizing forces. Linear stability theory utilizing these external Lorentz forces is provided indicating when the fluid layer will go unstable and a simple non-linear model is provided to estimate the maximum droplet radii for thin-layers of fluid [2]. In all cases, thin layers are more resistant to motion and this is consistent with observations made in NSTX to date.

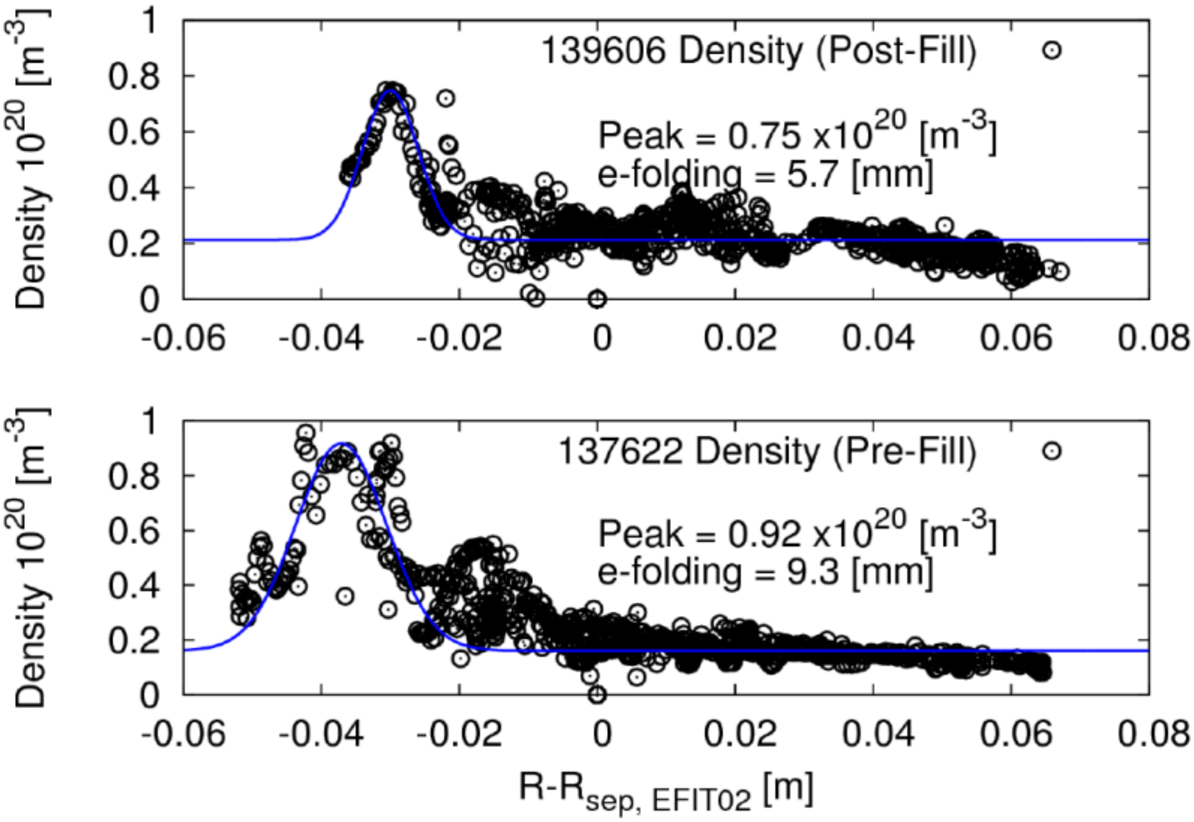

Figure 3: Variation of number density profiles for lithium post fill and pre-fill conditions.

The variation in SOL profiles before and after LLD fill were also studied using the HDLP array. A key finding is that there is a significant variation in density profile (as shown in figure 3), while the temperature profiles remained almost similar.

The HDLP array, in general, has been used to support several XPs during the previous run campaign. Some of them include LLD characterization XPs (XP 1000, XP 1059, XP 1041 a), XP 1001 for recycling & pumping of LLD, XP 1021 for halo currents during disruptions, XP 1031 for MHD ELM stability & dependence and XP 1034 for CHI start-up experiment.

3.2. Summary of New Technology Development for NSTX-U

3.2.1. Materials Analysis Particle Probe (MAPP)

The MAPP, though not a UIUC diagnostic is part of the over all PPPL suite of diagnostics being developed for material testing and analysis on NSTX-U. New sample holders needed to be designed and the UIUC Research Engineer was tasked to do this.

The sample holders are manufactured form molybdenum and have a design where by there is a wave spring that ensures a goof thermal contact is made between the actual sample materials with the actual sample holder. There are locking screws used to make sure that the whole system will not come apart during operation.

Currently the sample holder has been manufactured and installed on MAPP and the MAPP is installed and being tested on LTX. Figure 4 shows a photo of the MAPP probe head with the new sample holders.

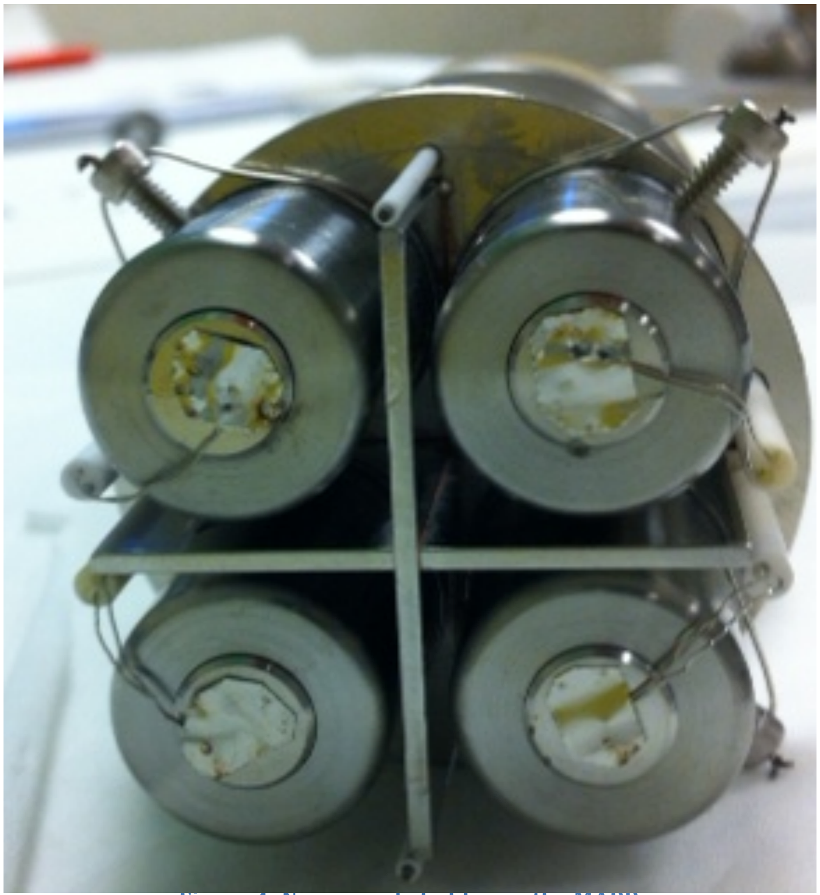

Figure 4: New sample holder on the MAPP

3.2.2. Liquid Lithium Pellet Dripper (LLPD)

A granular injector has been developed at PPPL for launching small pellets ($d \sim 1$ mm) into a discharge with the intention of triggering small ELM like events. Currently the PI uses a pellet dropper, physical pellets that are shaken through a small opening and drop down a guide tube where they then are impacted by a rotating impeller and injected into the plasma. However the pellets come down at irregular intervals and have an impurity layer on them. A new method for producing clean pellets of lithium is being investigated through a Liquid Lithium Pellet Dripper (LLPD).

The LLPD has the liquid lithium in a reservoir, where by a pressure or force is applied to push the liquid through a small orifice ($d_{orofice}$ = 300 μm). The idea being that spheres of lithium will form at a regular frequency and size. The big advantage of this method is that the spherical pellets are made from clean lithium.

Two methods are being investigated a gas driven system and a electromagnetic driven system. The former uses high-pressure gas to force the liquid lithium through the orifice where as the later uses a $\boldsymbol{J}\times\boldsymbol{B}$ force to push the metal. Initial test are being conducted with both systems at PPPL by UIUCs Research Engineer/Scientist. However with these test rather than lithium, Wood's metal is being used in stead. The reason being it has a low metling temperature, 70 ^{o}C, its surface tension is similar to lithium's and it does not require a glove box to be handled. Any test using lithium will be performed at UIUC.

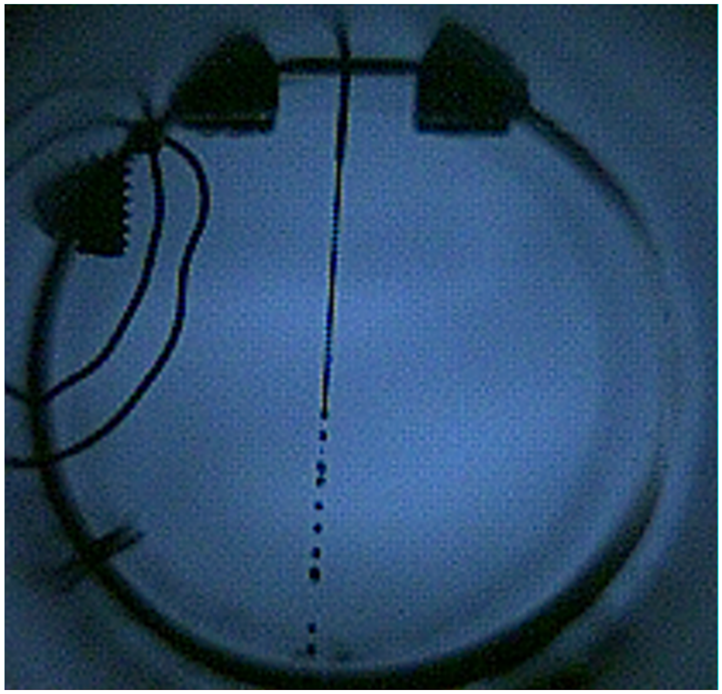

Figure 5: High-speed camera image of the Wood's metal LLPD at work.

Initial results are encouraging. The gas driven system was able to produce drops at a certain sizes and frequencies. These very much are dependent on the pressure and density being used and are coupled together. Figure 5 shows an image from a high speed camera of the pellets being formed from the woods metal.

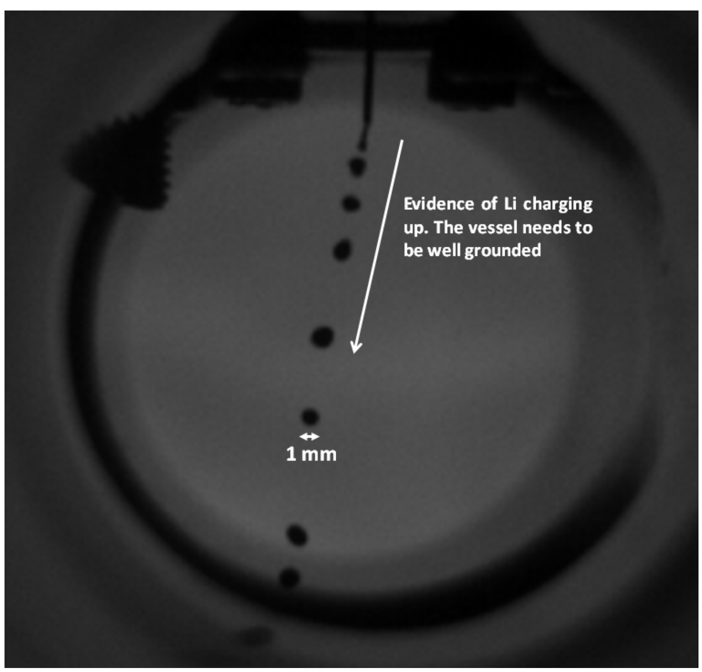

Figure 6: High-speed camera image of the Lithium LLPD at work. The vacuum vessel needs to be grounded well otherwise the Li pellets charge up and can be deflected very easily.

The gas driven system was tested at UIUC and similar results were seen with lithium pellets being formed. One issue that care needs to be taken with is grounding of the vacuum chamber, charging up of the lithium means that its very susceptible to any other space charges and can be deflected. This can be seen in figure 6.

Figure 7 shows results for the gas driven LLPD the frequency and drop size for Wood's metal and lithium. It was found that the pellets do not exit the nozzle at a constant rate and can also come together to form larger droplets down the guide tube.

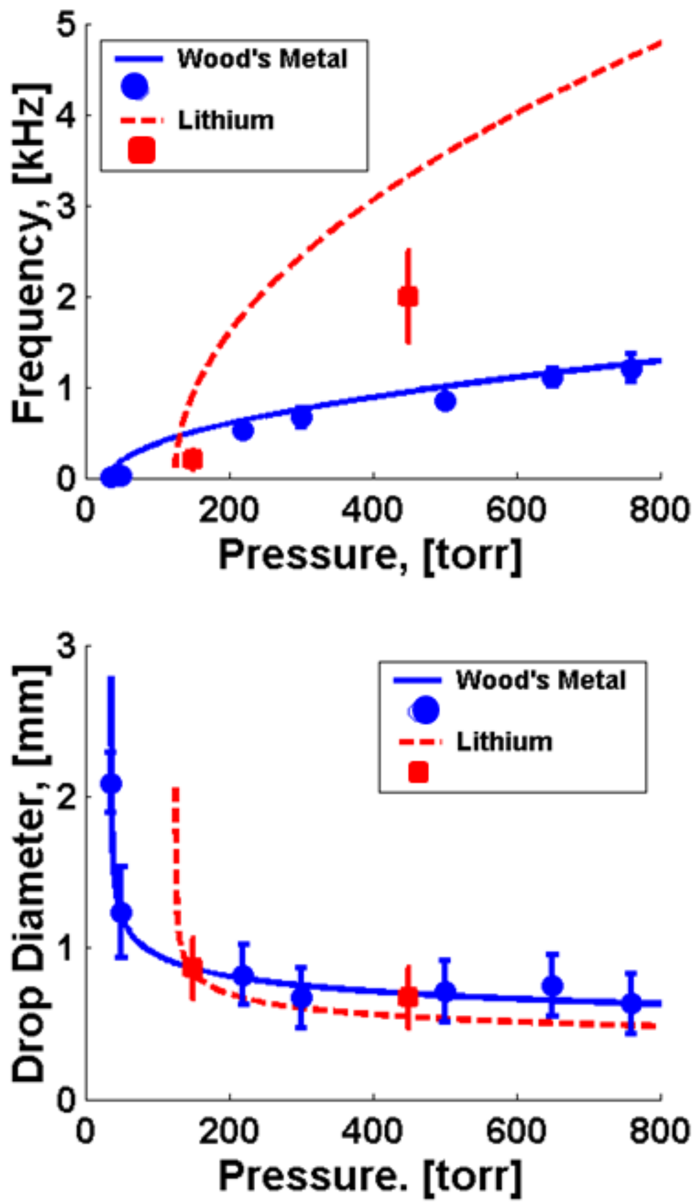

Figure 7: Scan of the LLPD for Wood's metal and Lithium for different pressures and (a) frequency and (b) drop size.

Am electromagnetic system is being tested and these experiments will be complete by the end of August 2013. Here the current will be modulated setting the frequency while the amplitde will set the force or pressure thus determining the pellet size.

3.2.3. Upward-Facing Lithium Evaporator (U-LITER)

With double null operation expected on NSTX-U, the upper divertor will play a role. Currently the lower divertor has lithium deposited via the lithium evaporator (LITER). An upward facing system is being developed by PPPL and UIUC to coat the upper divertor with a directed beam of lithium.

The system will use an electron beam of known voltage and current to evaporate lithium from a crucible that is pointed towards the upper divertor. The upward facing lithium evaporator (U-LITER) will sit outside the plasma boundary and is intended to deposit lithium just before a discharge, ensuring as fresh as possible layer of lithium before operation.

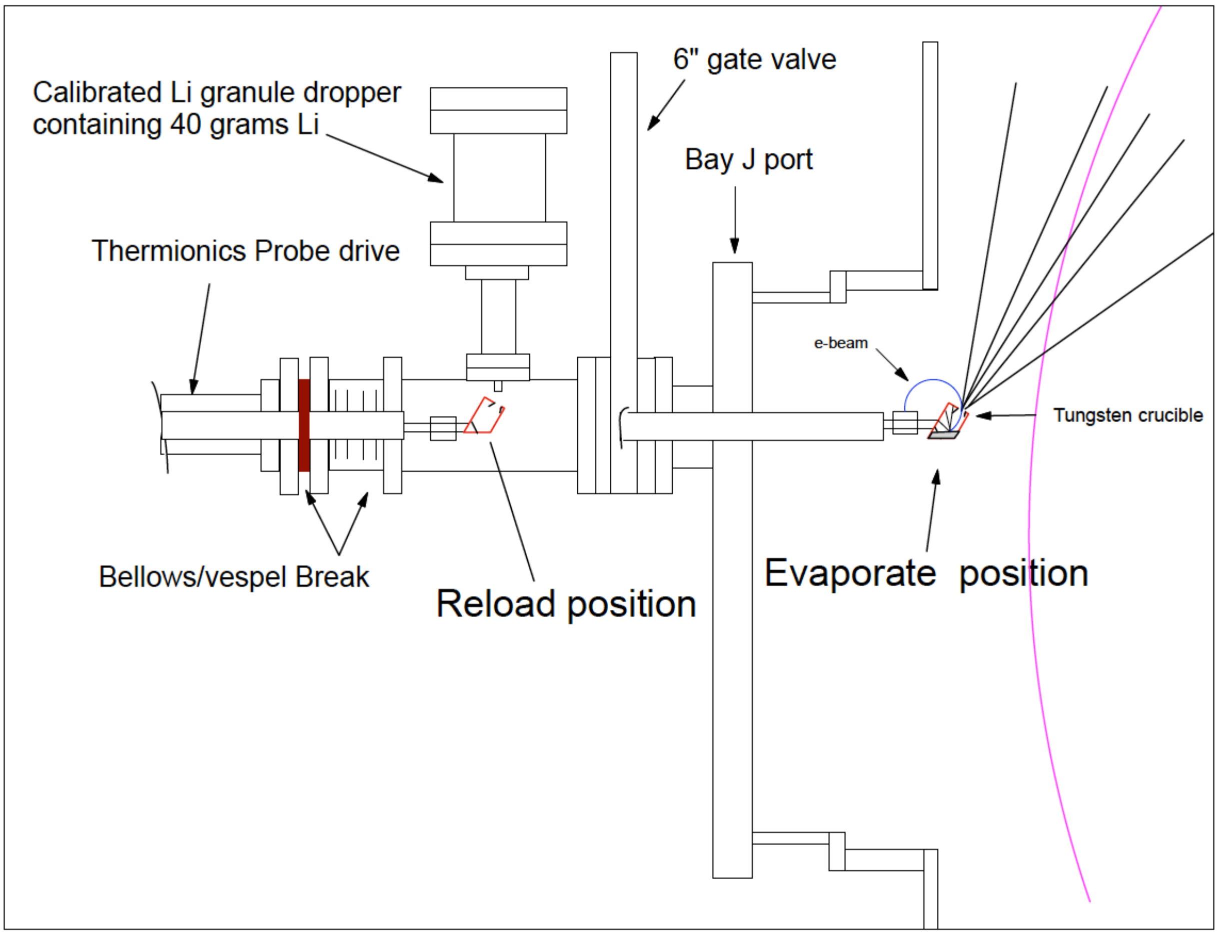

Figure 8: Schematic of U-LITER design for NSTX-U

Figure 7 shows a schematic of the initial U-LITER design. Currently the e-beam has arrived and is being tested. Work on designing the U-LITER is also under way.

4. Future Work Plan

The work at PPPL will involve the UIUC research engineer/scientist continuing to develop the LLPD and U-LITER. The LLPD is in its last stage of development before being implemented with the granular injector. The gas driven LLPD has been shown to work however frequency and pellet size control is difficult. An electromagnetic driven LLPD is in its last stages of development. A decision will be made which system will be the best to move forward. This will be complete by August 2013. From there a design will be produced to be integrated with the granular injector.

The U-LITER is being developed to evaporate lithium on to the upper divertor for double null operation. The e-beam has been delivered and tested and the U-LITER is being designed and will be manufactured in the next couple months. UIUCs research engineer/scientist will be integral in the design of the U-LITER and its implementation on NSTX-U.

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