



A method to produce lithium pellets for fueling and ELM pacing in NSTX-U[☆]



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HIGHLIGHTS

- A new method for delivering lithium to the lithium granular injector has been developed.
- Frequencies up to 1.5 kHz achieved.
- Droplet/pellet sizes down to 0.6 mm in diameter have been achieved.
- Aim is for ELM control and pacing.
- This has the potential for replenishing lithium coating during a plasma discharge.

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ABSTRACT

A device for producing small, high frequency spherical droplets or pellets for lithium or other liquid metals has been developed and could aid in the controlled excitation or pacing of edge-localized plasma modes (ELMs). The Liquid Lithium/metal Pellet Injector (LLPI) could also be used to replenish lithium coatings of plasma-facing components (PFCs) during a plasma discharge. With NSTX-U having longer pulse lengths (up to 5 s), it is desirable to be able to inject lithium during the discharge to maintain the beneficial effects. Using a nozzle injector design and a surrogate to lithium, Wood's metal, the LLPI has achieved droplet diameters between $0.6 \text{ mm} < d_{\text{drop}} < 1 \text{ mm}$ in diameter and frequencies up to 1.5 kHz with argon gas driving the formation. This paper presents the LLPI being developed with initial results mainly using Wood's metal and some lithium, using high pressure argon to force the liquid lithium through the nozzle.

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1. Introduction

Some of the most pressing issues facing fusion are the ability to control impurity accumulation and the recycling of hydrogen from the walls of the confinement vessel. These have an impact on the performance of the plasma, influencing the confinement time, edge temperatures and densities. It is known that lithium is a getter of these impurities and reduces recycling as well as controlling instabilities such as edge localized modes (ELMs). By depositing the lithium at strategic points within a fusion reactor, for example the divertor [1,2] higher energy confinement times, higher edge temperature and lower densities have been achieved [3]. Most notably

it has been observed that the amplitude of ELMs is reduced and even completely mitigated [4].

Princeton Plasma Physics Laboratory (PPPL) is a one of the leaders in lithium research and the primary method for depositing lithium in the National Spherical Torus Experiment (NSTX) is via a lithium evaporator (LITER) [5] or lithium aerosol [6]. With NSTX being upgraded (NSTX-U), longer plasma discharges (up to 5 s) will be possible and thus will require the ability to inject lithium during the discharge to maintain the beneficial effects of the lithium.

More recently a granular injector has been developed for ELM pacing at PPPL and it has been tested on EAST in China and RFX in Italy [7]. The granular injector uses pre-formed spheres of lithium that are released from a dropper [6] and impact a rotating impeller that launches the pellets into the plasma, thus triggering an ELM in a controlled fashion. Supplying the correct size of pellets is important, currently the correct size is unknown and experiments need to be performed to establish this. Pellets with diameter approximately 1 mm were chosen for the ELM control test.

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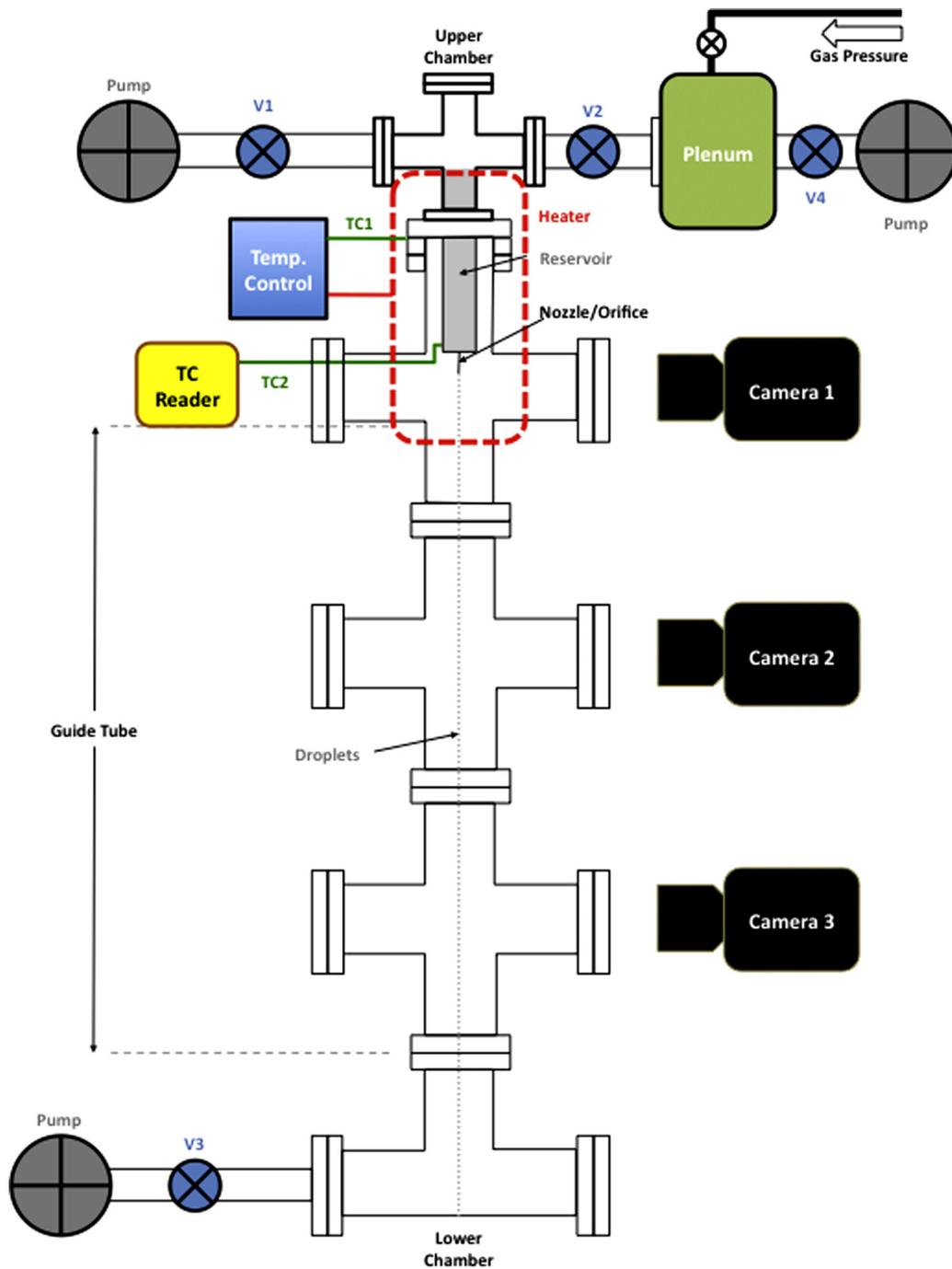


Fig. 1. Schematic of the liquid lithium Pellet Injector showing the different components of the LLPI.

It would be a great benefit to the granular injector if a method for controlling the pellet size could be developed. It is intended that the liquid lithium pellet injector (LLPI) would essentially replace the dropper in the granular injector design. By forming clean lithium pellets at a desired frequency and size and have them drop towards the rotating impeller whilst cooling and becoming a solidified pellet, they can then be injected into the plasma. This paper presents a design for a LLPI being developed at PPPL that can form small spheres of clean liquid lithium. Initial tests at PPPL have been performed using Wood's metal (a eutectic of 50% bismuth, 26.7% lead, 13.3% tin and 10% cadmium) which has been found to be a good surrogate for lithium with similar surface tension, less chemically reactive and has a lower melting point. Subsequently, some initial lithium experiments have been performed at the Center for Plasma

Material Interactions (CPMI) at the University of Illinois at Urbana-Champaign (UIUC). The end result is an inexpensive tool that can produce pellets with a frequency and diameter in a controlled way.

2. Experiment

A schematic of the experimental set up is shown in Fig. 1. There are two sections that make up the LLPI, the upper and lower chambers. The upper chamber is a reservoir for the liquid metal and is separated from the lower chamber via a nozzle. The nozzle consists of an orifice manufactured from a stainless steel capillary tube. Two capillary tubes have been used, one with an inner radius of $R_0 = 0.3$ mm and another $R_0 = 0.5$ mm and both have an overall length of $l_0 = 20$ mm.

To push the liquid metal through the orifice the upper chamber is attached to a high-pressure plenum reservoir. This plenum has a large volume many times that of the upper chamber and has a valve separating the plenum from the upper chamber. This allows the upper chamber to be pumped down to a base pressure of, $P_0 \sim 2$ Pa, through another valve, V1. Both upper and lower chambers are pumped down to the same base pressure, P_0 . The plenum is filled to the required pressure ($P_{\text{plenum}} < 101.3$ kPa). When valve, V1, is closed and valve, V2, is open between the plenum and the upper chamber, the upper chamber quickly fills to the desired pressure and pushes the liquid metal through the orifice. The reservoir and surrounding chamber is heated to a temperature between $80^\circ\text{C} < T < 200^\circ\text{C}$ which ensure that the Wood's metal or lithium is liquid. The temperature is monitored by two thermocouples. TC1 is used in conjunction with a temperature controller to maintain the desired temperature while TC2 monitors the temperature at the orifice.

A high-speed camera (Vision Research MIRO 4) is used to image the droplets as they exit the orifice in the nozzle. The camera can be used to measure the rate that the droplets are injected, the size and velocity. The droplets fall down a guide tube and can be imaged at different position along the tube with the camera or multiple cameras. Typical experimental runs vary from 2 s to 5 s.

3. Theory

Formation of liquid metal droplets has been described by Fiflis et al. [8], at UIUC. When a fluid exits a nozzle as a jet the Plateau-Rayleigh instability drives the jet to break up into droplets [9]. The flow is unstable due to the fluid pressure and surface tension competing with each other. This grows along the length of the jet and eventually breaks off forming the droplet.

When solved with the Navier–Stokes equation [1,8] one finds that the ideal growth rate occurs at a dimensionless wave number $kR_0 = 0.697$ which yields a frequency of [8],

$$\omega = 0.34 \left(\frac{\gamma}{\rho R_0^3} \right)^{1/2} \quad (1)$$

with, ρ , being the fluid density and, γ , the surface tension of the fluid and, R_0 , is the diameter of the orifice. Capillary effects need to be taken into account and this is modified such that the frequency is given by

$$f = \frac{0.34gl}{4\pi\gamma \cos(\theta)} \sqrt{\Delta P \rho} \quad (2)$$

The contact angle, θ , has been measured by Fiflis et al. for lithium on different surfaces [10]. Pinch off happens at some length of the liquid column, h_{liq} , which is dependent on the exit velocity of the liquid from the nozzle's orifice, v_{liq} . The term ΔP refers here to the pressure difference between the backing pressure, P_0 , and the pressure required to overcome surface tension given by $P_\gamma = (2\gamma/R)$. If $\Delta P = P_0 - P_\gamma$, one can find that the diameter of the droplet, D_{drop} ,

$$D_{\text{drop}} = 2.603 \left(\frac{h_{\text{liq}} f R_0^3}{\sqrt{\Delta P / \rho}} \right)^{1/3} \quad (3)$$

4. Results

When a stream of liquid exits a capillary in a vacuum it undergoes a break up through some applied disturbance [11] and has been studied since the late nineteenth century [12]. The distribution of these droplets is in fact not uniform but has an initial break up into carrier droplets which have a distance and velocity

Table 1
Summary of Wood's metal and lithium parameters.

	ρ [kg m^{-3}]	γ [N m^{-1}]	T_{melt} [$^\circ\text{C}$]	$(\sigma, \text{S m}^{-1})$
Wood's metal	9700	0.42	70	1.13×10^6
Lithium	512	0.40	180.54	3.52×10^6

separation [13,14]. These then come together to form a modulation drop due to the difference in speed that has been acquired at break up. This has been observed in both the Wood's metal and lithium streams in these experiments and is described by Orme et al. [11–15].

Wood's metal has a melting point of $T_{\text{liq,woods}} = 70^\circ\text{C}$, density when melted $\rho_{\text{woods}} = 9650 \text{ kg m}^{-3}$ and surface tension $\gamma_{\text{woods}} = 0.42 \text{ N m}^{-1}$. Lithium is the lightest of all metals and has a melting point of $T_{\text{liq,Li}} = 180.54^\circ\text{C}$, density of $\rho_{\text{Li}} = 512 \text{ kg m}^{-3}$ when liquid and a surface tension of $\gamma_{\text{Li}} = 0.40 \text{ N m}^{-1}$.

Wood's metal is used since it has similar surface tension properties to lithium [16–18], has a much lower melting temperature than lithium and also is not reactive with air when hot, allowing for fast refilling of the reservoir and much easier to work with. Table 1 summarizes the properties of both Wood's Metal and Lithium.

Fig. 2 shows the flow of Wood's metal through a nozzle where the orifice has a $300 \mu\text{m}$ inner diameter. The background pressure is up to $\Delta P = 101.3$ kPa. As described above, there is a column of liquid metal and it is clear to see the oscillating instability on it. The height of this column is approximately $h_{\text{liq}} = 15$ mm before it breaks up into the droplets. The frequency of the droplets is taken to be at the point a drop forms at the end of the column. In one second, the drops are counted and this is defined as the frequency.

The nozzle diameter during the Wood's metal experiments was 0.3 mm and a range of pressures were used from just above the required pressure to break surface tension to atmosphere, $5.6 \text{ kPa} < \Delta P < 101.3 \text{ kPa}$. Fig. 4 shows the results for the Woods' metal experiments. Frequencies over 1 kHz can be achieved at higher pressures shown in Fig. 4a and subsequently drop diameters are between $0.6 \text{ mm} < d_{\text{drop}} < 2 \text{ mm}$, seen in Fig. 4b. The relationship between the drop diameter and frequency can be seen in Fig. 4c, which clearly shows that that higher frequencies lead to smaller drops.

With the encouraging results using Wood's metal, experiments were performed with lithium at the University of Illinois. Fig. 3

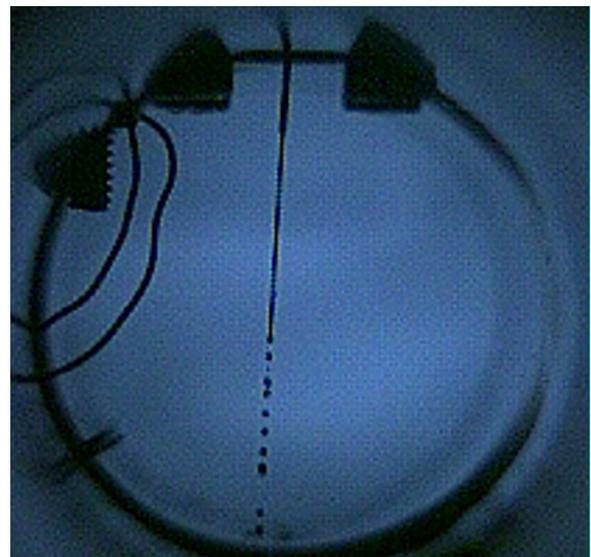


Fig. 2. A frame taken from the fast camera showing the stream of liquid Wood's metal and then its break up into the carrier droplets.

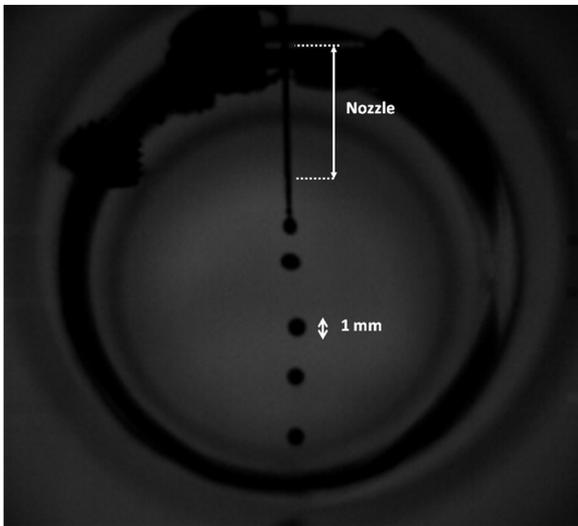


Fig. 3. A frame taken from the fast camera showing the stream of liquid lithium metal. Note the angle the Li exits showing that it is charging up.

shows drops of lithium that are produced with the LLPI. There are two nozzles used with different orifice diameters, 0.3 mm which is the same nozzle as used with the Wood's metal and a 0.5 mm diameter nozzle.

It can be seen in Fig. 4a–c that the frequency and drop diameter increases with pressure. The results with lithium show that the frequency is higher than wood's metal, due to the difference

in density but the drop diameters are similar at the 0.3 mm orifice diameter where surface tension plays a greater role. It can also be seen that the theoretical predictions come close to predicting the results from the LLPI validating that the Wood's metal is a sufficient surrogate material for lithium.

5. Discussion

Though, using high pressure to form drops has been successful, the control of the drop space uniformity has some issues. Carrier drops with a spatial and velocity distribution are clearly seen, with grouping of 3 to 4 carrier drops. If the dripper is to be used with the granular injector at frequencies greater than 500 Hz then the droplets need to be evenly spaced. Thus a method for seeding a coherent instability to form the drops needs to be devised. Such methods are currently under development. Coherent, stable drops will only form when the ratio of the driving frequency over the exiting velocity is matched such that $kR_0 = 0.697$. Fig. 5 shows the ideal pressure range that would be needed to meet this condition for a given driving frequency.

One such method is an oscillating rod placed within the liquid metal and close to the orifice. The vibrations in the rod can be stimulated using a piezo-stack and can induce a regular instability in the exiting liquid metal.

Another method uses an electro-magnetic oscillator based on the Lorenz force. This uses two copper electrodes brazed to the reservoir wall. Two samarium–cobalt permanent magnets are then mounted perpendicular to the electrodes with a vespel liner to separate them from the metal. A modulated current is passed through the liquid metal. The induced oscillating force, which depends on

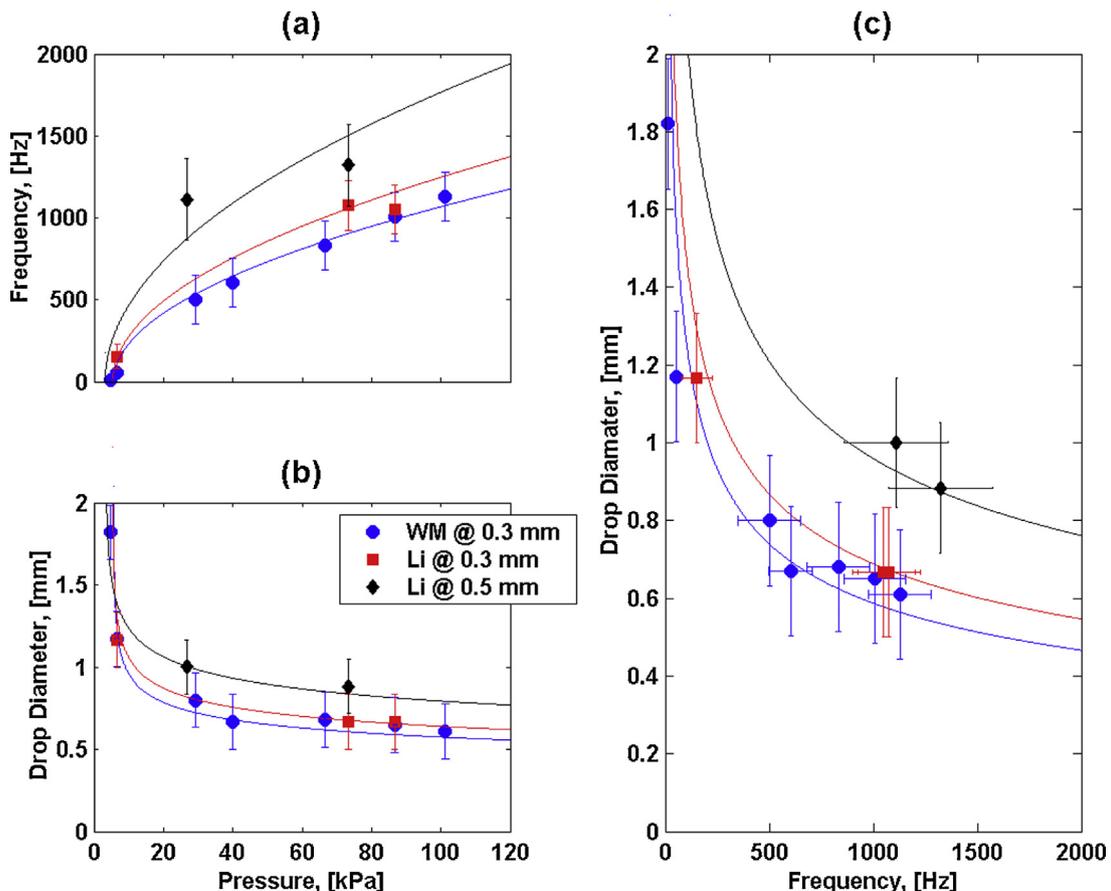


Fig. 4. Results with Wood's metal and lithium. (a) Shows the drop frequency data with respect to pressure compared to the curve from Eq. (2). (b) Shows the drop diameter data with respect to pressure and compared to curves from Eq. (3). (c) The frequency and drop diameter plotted against each other.

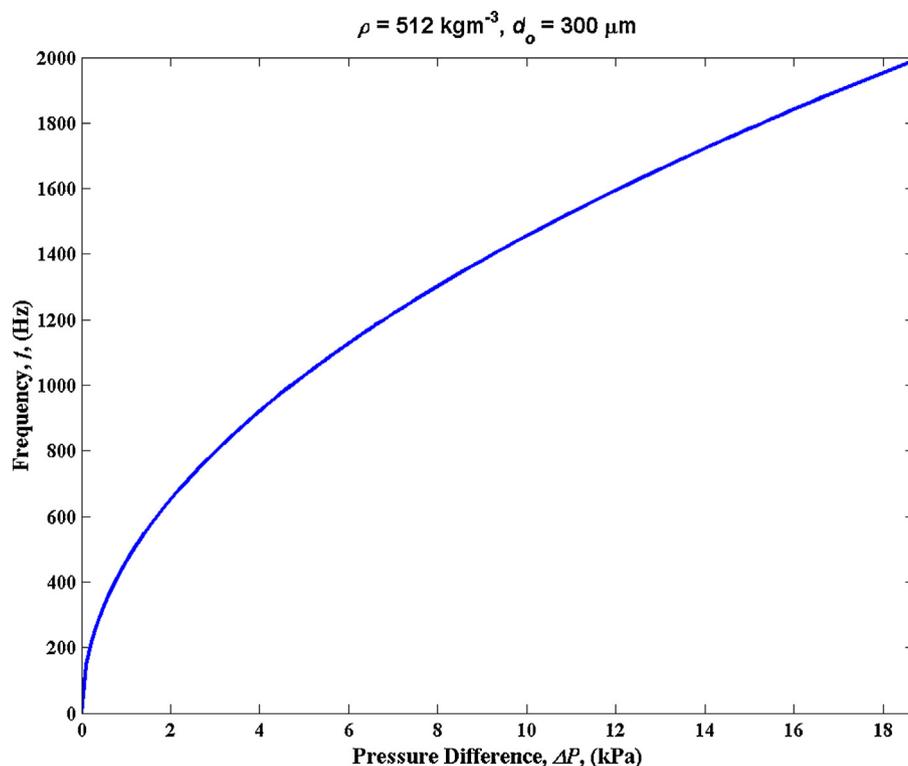


Fig. 5. The curve for the ideal liquid lithium case over a range of pressure differences, ΔP , that would be needed to meet the resonant condition to give a driving frequency.

the liquid metals conductivity, σ , will provide the disturbance in the exiting liquid metal through the nozzle to form coherent drops.

The LLPI, in its current form can also be used as a method for refueling, or replenishing, lithium into a plasma while the discharge is in progress. Currently, NSTX-U deposits lithium before a discharge to take advantage of the beneficial effects; however as a discharge progresses these advantages diminish. The LLPI would allow the liquid lithium droplets to fall into the scrape off layer of the plasma. The plasma would evaporate and distribute the lithium around the wall of the vacuum vessel. The current design of the dripper would be acceptable for such a use.

6. Conclusion

A liquid lithium pellet injector has been developed as an alternative to the dropper used with the granular injector. The drops that have been produced are between 0.6 mm to 2 mm. However, though high frequencies up to 1.5 kHz have been produced the spacing between the drops is irregular. With a redesign of the way the drops are formed the dripper will provide a means of producing drops and eventually pellets for ELM control. Seeding of the frequency with an external source will help to make the production of the pellets more uniform. In its current form the dripper can be used to refuel the lithium in NSTX-U while a discharge is in progress, allowing the beneficial effects of lithium to be utilized through the whole discharge.

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