A Method to Produce Lithium Pellets For Fueling and ELM Pacing in NSTX-U

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Abstract

A device has been developed that produces spherical lithium pellets for the controlled excitation, or pacing, of ELMs and replenishing lithium coating on PFCs during a plasma shot. The device is based on a dripper design, where the lithium is forced through a small orifice with gas pressure. It is envisaged to use the dripper in two ways: first it is used in conjunction with the lithium granular injector developed at PPPL for ELM pacing and the second for replenishing lithium PFC coatings during a plasma discharge by "dripping" liquid lithium drops into the plasma edge and vaporization will redistribute the lithium to recoat the PFC during the shot. A theory has been developed for the drop formation and frequency using high-pressure gas. Experiments have been performed initially with Wood's metal and subsequently lithium. Using Wood's metal at a backing pressure of $\Delta P > 600$ torr, frequencies up to $f = 1200$ Hz have been achieved with droplet diameters $d > 600$ μm. These agree well with theory. Measurements using lithium also show that the frequency does not quite match the theory with $\Delta P = 450$ torr, a frequency of $f = 2$ kHz and but the diameters are in good agreement with $d = 0.8$ mm.

Introduction

One of the most significant issues facing fusion is to control impurities and recycling of hydrogen from the walls of the confinement vessel. These have a significant impact on the performance of the plasma influencing the confinement time and edge temperatures and densities. It is now known that lithium is a powerful getter of these impurities and 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 densities have been achieved[3]. Most notably it has been observed that the amplitude of Edge Localized modes

Princeton Plasma Physics Laboratory (PPPL) is a leader in lithium research and the primary method for depositing lithium in the National Spherical Torus Experiment (NSTX) is via a lithium evaporator (LITER)[4] or a lithium aerosol[5]. With NSTX being upgraded (NSTX-U) longer plasma discharges (up to 5s) will be possible and it will be desirable to be able 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[6]. The granular injector uses spheres of lithium that are released from a dropper[5] and then impact a rotating impeller that launch the pellets into the plasma and are able to trigger an ELM in a controlled fashion. Supplying the correct size of pellets is important and pellets with diameter approximately 1 mm are required for proper ELM control.

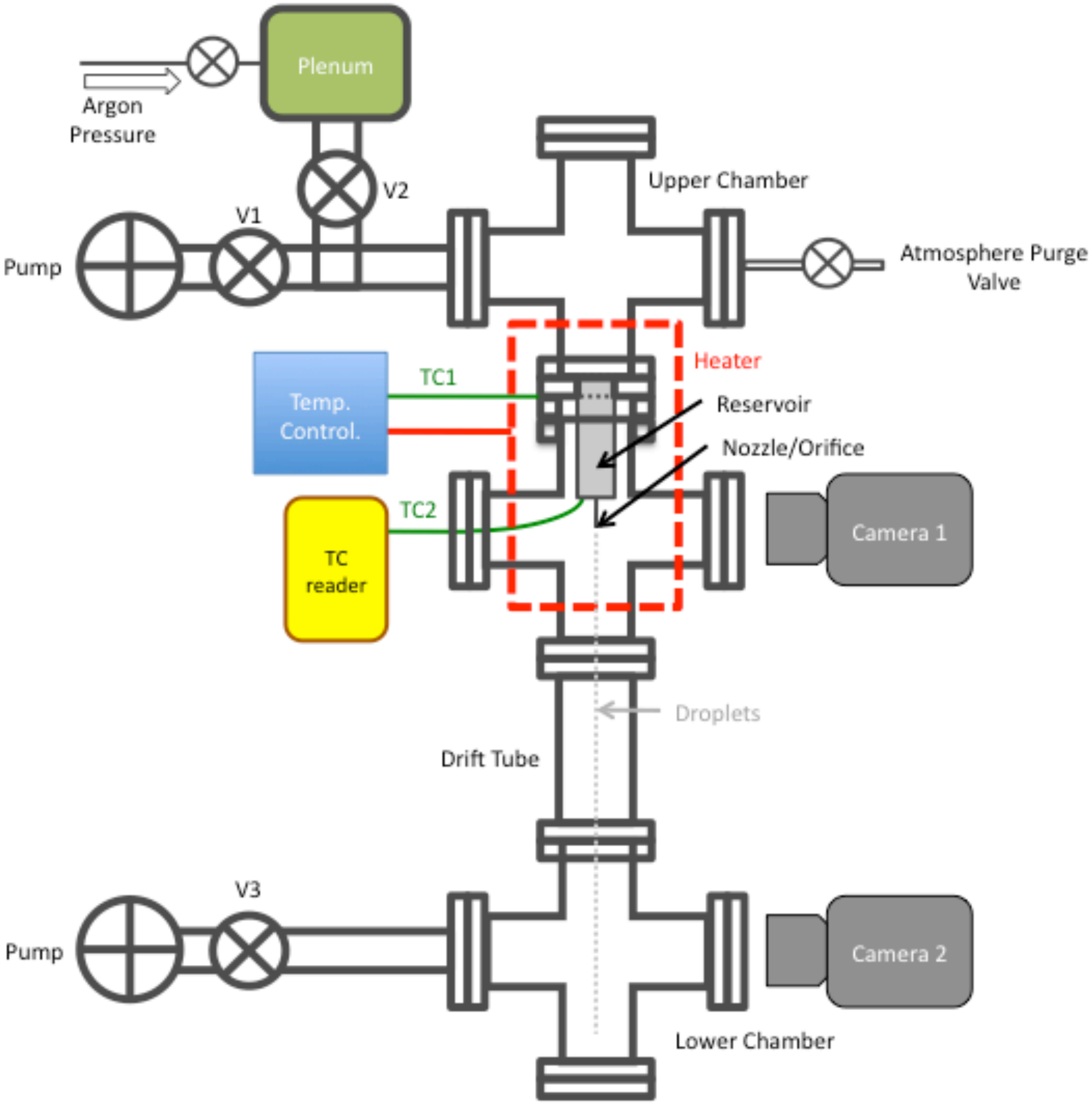

Figure 1: Schematic of the liquid lithium dripper developed at PPPL.

To have a method for producing pellets of regular size would be of great benefit for the granular injector. It is envisioned that the dripper would essentially replace the dropper in the granular injector design. By forming lithium pellets at a desired frequency and size and have then drop towards the rotating impeller whilst cooling and becoming a hard pellet they can then be injected into the plasma. This paper presents a design for a device being developed at PPPL that can form small spheres of liquid lithium. Initial tests at PPPL have been performed with Wood's metal and subsequently with lithium at the Center for Plasma Material Interactions (CPMI) at the University of Illinois at Urbana-Champaign (UIUC). The result is an inexpensive tool that can produce pellets and the frequency and diameter they are ejected in a controlled way.

Experiment

Description

A schematic of the experimental set up is shown in figure 1. There are two sections that make up the dripper. The Upper chamber is designed to house a reservoir for the intended liquid metal, The Reservoir is made up of a mini con-flat re-entrant port welded to a larger 2 ¾" CF zero length adapter. At the bottom of the mini con-flat reservoir is a flange that has a stainless steel capillary tube soldered into it with a high temperature solder (T_{melt} = 226 °C). The tube has an inner radius of R_0 = 0.3 mm and has an overall length of l_0 = 5 mm.

A six way cross above this provides the gas reservoir needed to push the liquid metal through the orifice and this is attached to a plenum reservoir. This is plenum has a large volume many times that of the upper chamber and is designed so that the plenum is filled to the required pressure and then when a valve is open between it and the upper chamber quickly fills the volume to the desired pressure without losing the backing pressure. The reservoir and surrounding chamber is heated using a heating tape and in conjunction with a thermocouple (TC1) and temperature controller the temperature is maintained at a desired level.

Just below the upper chamber is another 5-way cross that allows an internal thermocouple (TC2) to monitor the temperature of the actual reservoir and thus the liquid metal. The droplets once formed fall down a drift tube of length l = 0.390 m where the land in the lower chamber. There are two high-speed cameras that view the drops being formed out of the nozzle and travel down the drift tube.

Procedure

The procedure for producing the drops is quite simple and is as follows: The whole system needs to be pumped out. Valves, V1, V2 and V3 are all open. The pumps used are backing pumps and the base pressure is several 10 torr. While pumping down the heating tape is switched on and the temperature controller set to the desired temperature V2 is then closed and the plenum pressurized to the desired pressure.

Once the reservoir reaches the required temperature via monitoring TC2 where the metal melts, valve V1 is closed and the cameras are readied to be triggered when the drop form. With V1 still closed the, V2 is opened charging the upper chamber and pushing out the liquid metal through the nozzle, at the same time the cameras are triggered to capture the droplet formation. V2 is opened for approximately 2 seconds and then closed and V1 opened so as to pump out the upper chamber to conserve the liquid metal. The reservoir holds enough metal for up to 10 experimental runs.

Theory

The theory for the formation of liquid metal droplets has been developed by Fiflis *et al.*[7], at UIUC. When a fluid exits a nozzle as a jet the Plateau-Rayleigh instability drives the jet to break up into droplets[8]. 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. The radius of the jet is assumed to have the following form:

$$R = R_0 + \varepsilon e^{i(kz+\omega t)} \tag{1}$$

where, R_0, is the unperturbed column radius and will be defined as the orifice radius, ε, is the perturbation amplitude, k, is the wave number, ω, the frequency which also can be considered the growth rate for a given instability and, R, is the perturbed column radius

Once entered into the Navier-Stokes equation[1,7] one finds that the maximum growth rate occurs at kR_0 = 0.697 which yields a frequency of[7]

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

with, ρ, being the fluid density and, γ, the surface tension of the fluid. Assuming that the jet exiting the orifice in the nozzle is cylindrical, the volume of the liquid encapsulated by one wavelength of the instability, V_{liq}, is

$$V_{liq} = \pi\lambda_{\max} R_0^2 = 28.32 R_0^3 \tag{3}$$

As pinch off happens, then the volume of the drop will be some number of wavelengths, n, of the instability. The value of, n, is in fact dependent on the backing pressure, ΔP, and using the Young-Laplace equation for ΔP across a capillary surface, $\Delta P = (2\gamma/R)$ one can find that

$$n = \frac{v_{liq}}{3.067\sqrt{\frac{\Delta P}{\rho}}} \tag{4}$$

where, v_{liq}, is the velocity of the column of liquid exiting the orifice. Thus the volume for the droplet can be determined and subsequently the radius for the droplet as well

$$V_{droplet} = 9.2338\frac{v_{liq} R_0^3}{\sqrt{\frac{\Delta P}{\rho}}} \tag{5}$$

Results

When a stream of liquid exits a capillary in a vacuum it undergoes a break up through some applied disturbance[9]. This has been studied extensively since the late nineteenth century[10]. The Pattern of these droplets is in fact not as uniform as hoped but has an initial break up into carrier droplets which have a distance and velocity separation[11,12]. 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 extensively described by Orme et al.[9,11,12,13]

Wood's metal is a eutectic of 50% bismuth, 26.7% Lead, 13.3% tin and 10% cadmium. It has a melting point of $T_{liq,woods}$ = 70 °C, density when melted ρ_{woods} = 9700 kgm^{-1} and surface tension γ_{woods} = 0.42 Nm^{-1}. Lithium is the lightest of all metals and has a melting point of $T_{liq,Li}$ = 180.54 °C, density of ρ_{Li} = 512 kgm^{-1} when liquid and a surface tension of γ_{Li} = 0.32 Nm^{-1}.

Wood's metal is initially used since it has similar surface tension properties to lithium and also is not reactive with air when hot, allowing for fast refilling of the reservoir. Table 1 summarizes the properties of both Wood's Metal and Lithium.

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

	ρ, [kgm^{-3}]	γ, [Nm^{-1}]	T_{melt}, [^{o}C]
Wood's Metal	9700	0.42	70
Lithium	512	0.32	180.54

Wood's Metal

Figure 2 shows the flow of Wood's metal through a nozzle where the orifice has a 300 µm inner diameter and 500 µm outer diameter. The background pressure is approximately ΔP = 500 torr. As described in the theory, 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 = 15 mm before it breaks up into the carrier droplets.

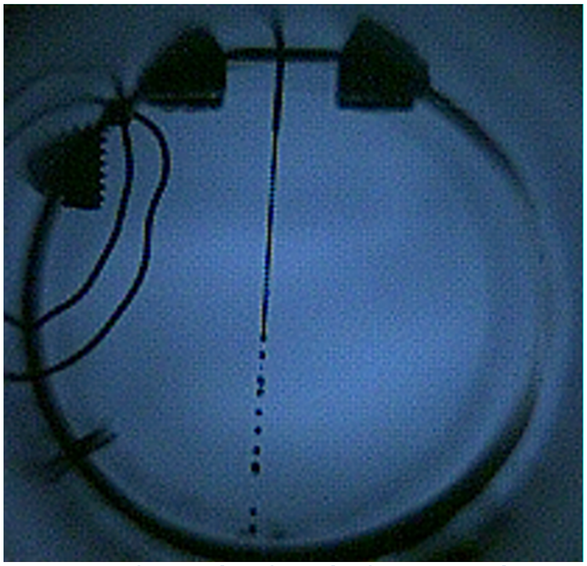

Figure 2: A frame taken from the fast camera showing the stream of liquid Wood's metal and then its break up into the carrier droplets.

For these measurements, we were not so concerned about the carrier and modulating drops, as eventually this phenomenon will be eliminated, as discussed later. The frequency of the droplets is taken to be at the point a drop forms at the end of the column. In one second, that is 4000 frames, the drops are counted and this is defined as the frequency.

Lithium

With the Wood's metal experiments showing some success, experiments with the dripper were performed with lithium at the University of Illinois. Figure 3 shows drops of lithium that are produces with the dripper. The same nozzle is used and the length of the column before the lithium breaks up is h = 2 mm. This is for a pressure approximately ΔP = 150 torr. It was observed that the lithium was charging up significantly as it passed through the nozzle. Any space charges in the chamber would affect the path the lithium takes. Thus it is important that the whole chamber is grounded well so that the lithium is ejected straight down.

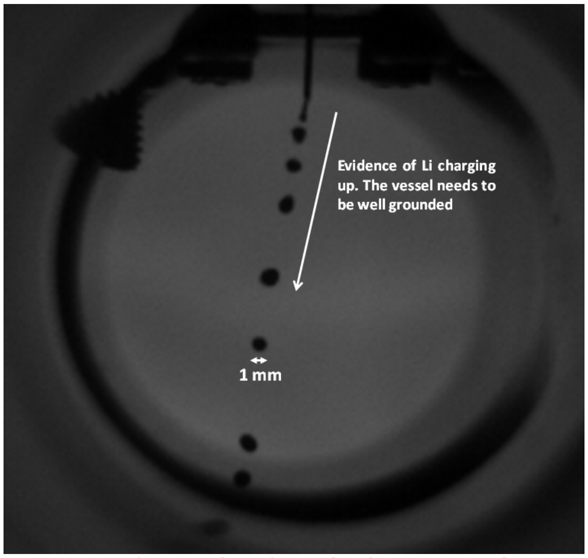

Figure 3: A frame taken from the fast camera showing the stream of liquid lithium metal. Note the angle the Li exits showing that it is charging up.

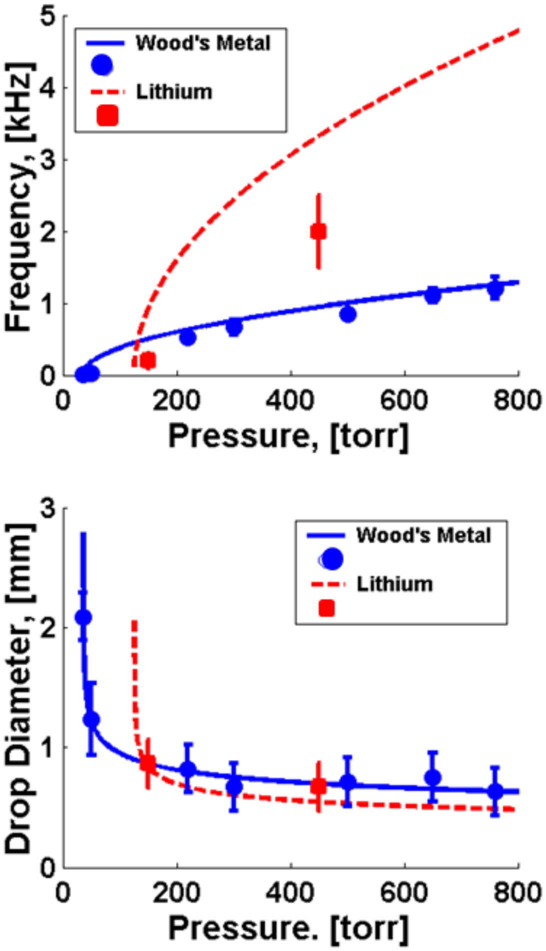

Figure 4: Results with Wood's metal and lithium. The top plot shows the frequency of drops. Bottom shows the drop diameters.

Figure 4 shows the plots for frequency and drop diameter for Wood's metal and lithium as a function of the backing pressure. Frequencies up to nearly 1200 Hz have been achieved at pressures close to an atmosphere. The gas used is argon since ultimately an inert gas needs to be used with lithium. It is clear to see that the Wood's metal frequency agrees well with theory. However with lithium, though the frequency is much higher than that of Wood's metal, is much lower than expected from theory. The diameter of the drops is between 0.8 mm < d < 1 mm in lithium.

Discussion

Though, using high pressure to form drops has been successful, the control of the drop spacing is not acceptable in the current form. 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. It is clear that the carrier droplets produce an uneven distribution and thus using them at a set frequency would be problematic. This is unacceptable with the granular injector and thus for use in NSTX.

Thus a new method of producing the drops has been devised and is currently under development. An electro-magnetic pulser based on the J×B force is being built. The set up two copper electrodes brazed to a 10 mm wide stainless steel tube. Two Samarium-Cobalt permanent magnets are then mounted perpendicular to the electrodes with vesspel liner to separate them from the metal, which will have a high current passing through it. The SmCo magnets and vesspel are chosen since the whole apparatus is to be heated to 200 oC to melt lithium. At each end there are min CF flanges and at the lower flange the nozzle is mounted. Inside the tube it is filled with enough metal to fill it up past the electrodes when melted. A modulated current is passed through the liquid metal. The induced force should then provide the pressure to push out the liquid metal through the nozzle. Since the current is modulated at a set frequency then the drops of the metal will come out at the set frequency, the strength of the current would then set the size of the droplets.

The dripper, in it current form can also be used as a method for refueling, or replenishing, lithium into a plasma while the discharge is in progress. A machine such as NSTX-U will deposit lithium before a discharge to take advantage of the beneficial effects of lithium, however as a discharge progresses these diminish. The dripper would allow the liquid lithium drops 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.

Conclusions

A liquid lithium dripper has been designed to be used as an alternative to the dropper used with the granular injector. The drops that have been produced are the correct size that needs to be used however though high frequencies up to 2 kHz have been produced the spacing between the drops as they are produced are irregular. With a redesign of the way the drops are formed the dripper does provide a means of producing drops and eventually pellets for ELM control. 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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