Characterization of a Liquid Lithium Pellet Delivery (LLPD) system for ELM Pacing and Lithium Replenishment in NSTX-U

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Abstract

A new liquid lithium pellet delivery system has been developed that will be used in several Li delivery schemes on NSTX-U. The LLPD is based on dripping Li out of a 300 µm nozzle. A high pressure gas is used to drive the formation of droplets which sets the frequency, up to 2 kHz, and drop size, 0.6 mm < d_{drop} < 2.0 mm. An alternative method for drop production uses a modulating current and permanent magnets to provide a $\boldsymbol{J}\times\boldsymbol{B}$ force that drives the formation of droplets. It is suggested that the current amplitude sets the size of the drops and modulation sets the frequency that the drops come out of the nozzle. It is intended to use the LLPD to deliver solid Li pellets for the granular injector system, fill the upward facing LITER (U-LITER) being developed and maintain fresh Li during a discharge by injecting Li drops into the plasma, ablating the Li and replenishing the coatings on the PFCs.

Droplet and Pellet Production

- High pressure gas (Ar, He), forces liquid lithium through a small orifice.
- Liquid exits the nozzle as a jet.
- Sinusoidal perturbation is set up and ultimately pinches off an amount of liquid to form a droplet.
- From the dispersion equation the frequency of the drops being formed can be determined.
- Volume of the the droplet using the Young-Laplace equation for pressure.
- Surface tension pulls the liquid into a sphere with diameter D_{sphere}.
  - h_{liq} → height of the column of liquid exiting nozzle
  - R_o → nozzle radius
  - ΔP → Pressure change
  - ρ → density of liquid metal
  - ω → frequency
  - D_{sphere} → diameter of the droplet
  - γ → surface tension
  - k → wave number
  - g → gravity
  - l → length of tube
  - θ → capillary contact angle
- Wood's metal (50% Bi, 26.7% Pb, 13.3% Cd, 10% good surrogate for lithium, γ, very similar
- Ideal pellet production with synchronous pellets at $kR_o = 0.697$

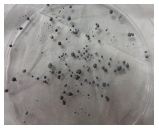
$$\omega^2 = \frac{\gamma}{\rho R_0^3} kR_0 \frac{I_1(kR_0)}{I_0(kR_0)}\left(1-(kR_0)^2\right)$$

$$\omega = \frac{0.34\,gl}{4\pi\gamma\cos(\theta)}\sqrt{\Delta P\rho}$$

$$D_{sphere} = 2.603\left(\frac{h_{liq}\omega R_0^3}{\sqrt{\frac{\Delta P}{\rho}}}\right)^{\frac{1}{3}}$$

Fiflis *et al.*, Rev. Sci. Instrum. **84**, 063506 (2013)

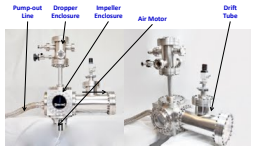
	Lithium	Wood's Metal
T_{melt} [°C]	180.51	70
ρ [kg•m^{-3}]	512	9700
γ [N•m^{-1}]	0.4	0.42
μ [N•s•m^{-2}]	5.03×10^{-4}	0.291
R_e 300 µm	3050	100
R_e 500 µm	5090	200

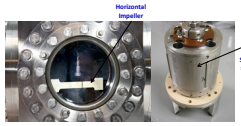


- Shown above is a selection of lithium pellets formed by the LLPD.
- Initially experiments have been performed with Wood's metal since it's a good surrogate for lithium.
- Lithium studies were performed at the University of Illinois, Urbana-Champaign.

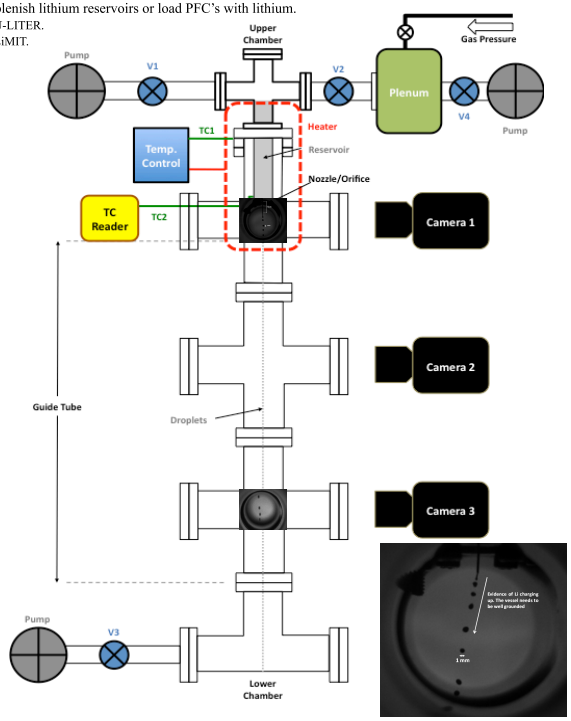
Motivation

- ELM pacing as well as replenishing beneficial lithium during a single shot.
- Lithium has beneficial effects for fusion reactor operations.
  - R. Maingi *et al.* Nucl. Fusion **52** (2012) 083001.
- Formation of Pellets.
  - Mitigates potential future supply problems if manufacturer decides to stop making them.
  - Safety aspect, no powder used.
- Supply pellets for Granular Injector.
  - Want to make synchronous.
  - Solidify before hitting paddle for vertical dropping.
  - ELM pacing and control?
  - Horizontal Launch.
- Drop into plasma
  - During a discharge, useful lithium gets passivated.
  - Replenish lithium during a shot.
- Replenish lithium reservoirs or load PFC's with lithium.
  - U-LITER.
  - LiMIT.

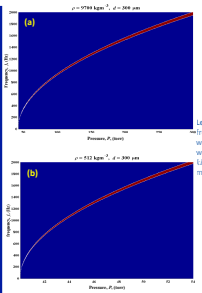




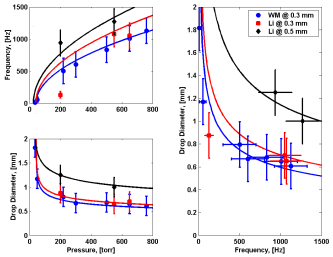
Above: Images of the Granular Injector developed at PPPL with the original dropper and paddle shown.

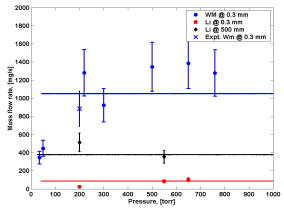


Comparison of Theory and Experiment



Left: The ideal pressure and frequency relationship where the pellets produced would be synchronous at kR_o = 0.697, (a) Wood's metal and (b) lithium.





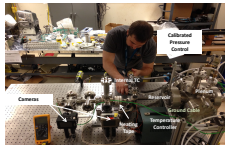
Above: Frequency and pellet diameter are dependent on the pressure. Plotting them against each other allows for them to be calibrated against each other.

Left: Curves based on modeling for the liquid metal flow rate using the experimental data from frequency and drop size as well as the model and a measurement using a 3 second burst. • Wood's metal with a 300 µm diameter orifice, ■ Lithium with a 300 µm diameter orifice, ◆ Lithium with a 500 µm diameter orifice and ✕ Wood's metal with a 300 µm diameter orifice done with a 3 second burst.

Future Paths Forward

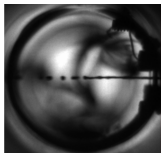
Horizontal Injection

- Launching of the pellets horizontally has demonstrated dependence on pressure, similar to vertical.
- With Wood's metal travel a distance of about 13 cm.



Left: Photo of the set up for the horizontal LLPD .

Right: Photo of some of the pellet formation and break up with the horizontal set up.



Electromagnetic Pulsing

- An external regular impulse can force the breaking up of the Liquid metal to be regular.

M. Orme *et al.* Rev. Sci. Instrum. **58**(2), Feb 1987.
M. Orme *et al.* Phys. Fluids A **2** (7), July 1990.
M. Orme et al. Phys. Fluids A **5** (1), January 1993.

- Electromagnetic pulsing has been tried.
  - Modulating current sets the frequency
  - Amplitude i.e. the pressure generated, determines the drop/pellet size.
  - Permanent magnets.
  - SmCo High temperature (up to 500 °C)
  - B = 0.3 T
- Current
  - Modulated BoP
  - I < 100 A

Below Right: The electromagnetic pulser developed for the LLPD.

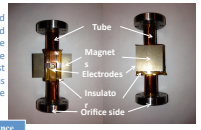
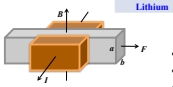


Table: A list of the conductivity and resistance of the stainless and liquid metals for the volumes inside the pulser tube. It shows that half the current with Wood's metal is lost through the stainless steel wall. Thus not allowing enough force to be produced.

Metal	Conductivity [σ, Sm^{-1}]	Resistivity [ξ, $1/\sigma$, Ωm]	Volume [V, m^{-3}]	Resistance [R, Ω]
Stainless Steel	1.45×10^6	6.90×10^{-9}	3.06×10^{-7}	2.14×10^{-4}
Wood's Metal	1.13×10^6	885×10^{-9}	1.20×10^{-6}	2.285×10^{-4}
Lithium	3.52×10^6	284×10^{-9}	1.20×10^{-6}	73.32×10^{-6}

No droplet formation observed means higher currents and B-field needed.

E. M. Borges *et al.* Thermal Eng. **Vol 5** No 2, December 2006 pp. 16 - 23.



Schematic showing the principle behind the EM pump system.

Piezoelectric Crystal

- Use a piezo-crystal to set frequency.
- Pressure set to have ideal Rayleigh condition $kR_0 = 0.697$
- Produce synchronous drops

J. M. Algots *et al.* Proc of SPIE **Vol 5751**, pp 885-891