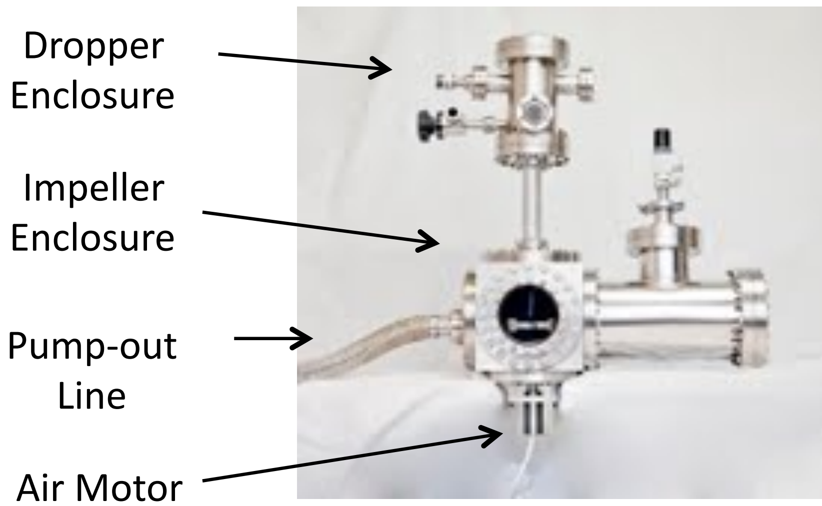
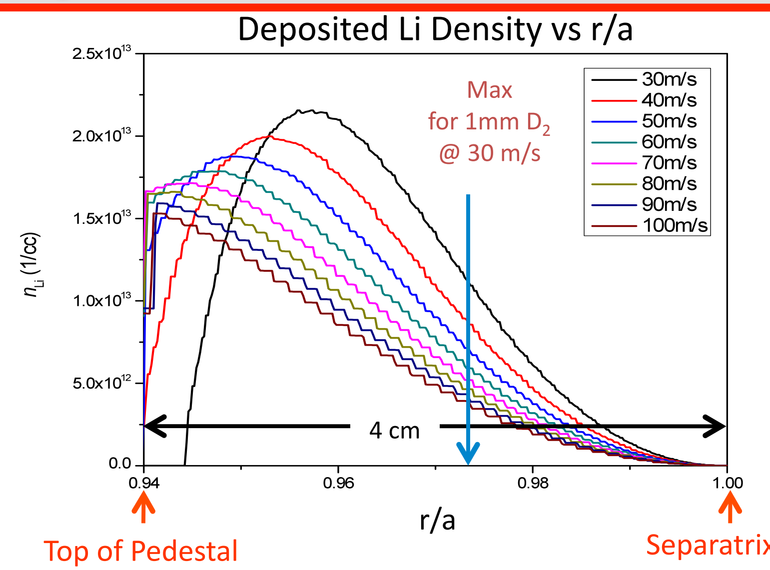
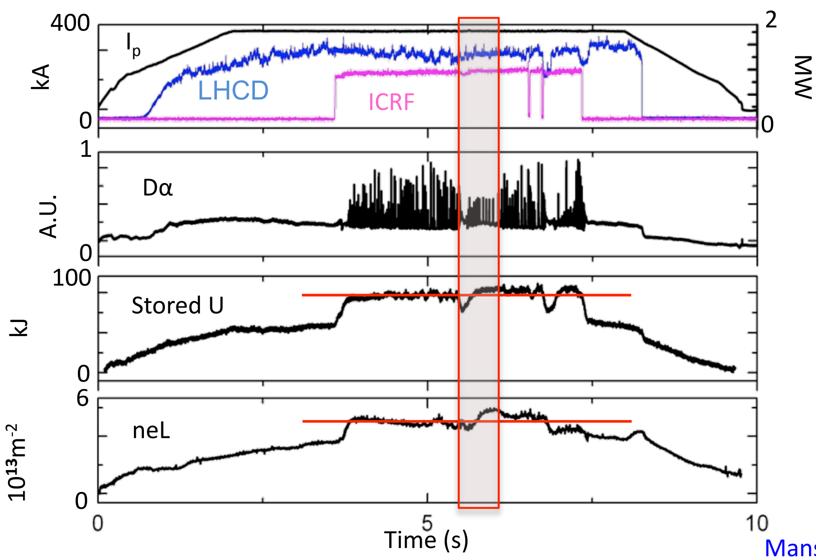
ELMs Triggered by Li Granules

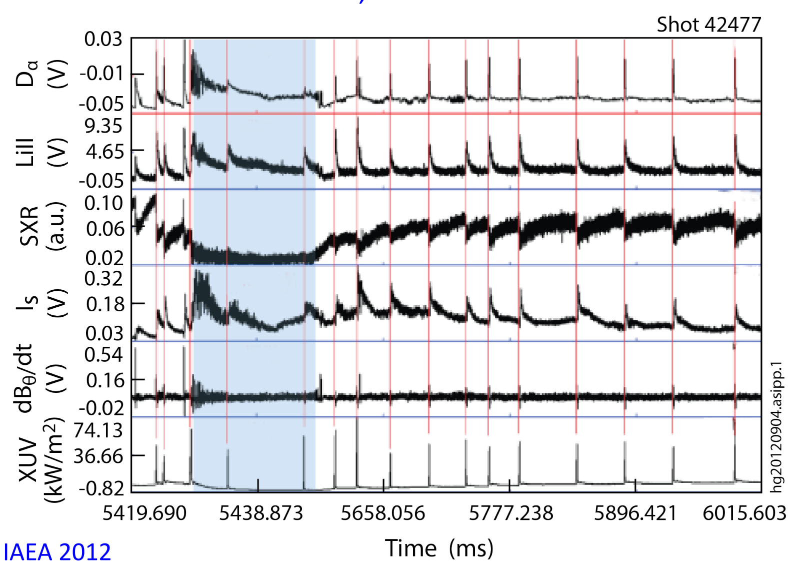




Mansfield et al., IAEA 2012

Paul Parks, Wen Wu





Mansfield et al., IAEA 2012

Motivation to Build a LLPI

- Lithium as a plasma facing component (PFC) material shown to improve the plasma performance.
- More recently Li pellets injected into the edge of EAST have been able to trigger and control edge localized modes (ELM) using a granular injector (GI).

D. K. Mansfield *et al.* 2012,2013

- The GI is intended to be used on the National Spherical Torus Experiment Upgrade (NSTX-U) to pace ELMs with small ($d_{pellet} \leq 1$mm) Li pellets.
- Operation of NSTX, it has been observed that an operating regime with small, yet high frequency ELMs allows a high performance in the operating plasma.

R. Maingi *et al.* 2005, 2006, 2011

- The pellets are supplied to the GI using a powder dropper that "shakes" solid granules or powder down a flight tube and then a rotating impeller injects the falling granules into the plasma.

D. K. Mansfield *et al.* 2010

- A liquid lithium/metal Pellet Injector (LLPI) has been designed based on concepts whereby a liquid metal is pushed through a small orifice to eject a liquid jet.
  - Inject the droplets directly into the plasma, vertically or horizontally, to trigger ELM
    - Solidify the ejected droplets into solid pellets and use with the GI directly
    - Possible uses for refilling other lithium PFC technologies being developed.
  - Clean lithium exits the LLPI
  - Safety
  - Availability

Droplet Formation

- Surface tension causes a laminar break up of the jet into droplets.
- Jet not only undergoes a break up but there is also a coalescence of the drops.
- Linear analysis of the drop break up and have a characteristic growth rate, β.

$$\beta^2 + \frac{3\mu k^{*2}}{\rho r_0^2}\beta = \frac{\gamma}{2\rho r_0^3}\left(1 - k^{*2}\right)k^{*2}$$

- where, β, is the growth rate of the disturbance, γ, is the surface tension μ, is the viscosity, ρ, is density, r_0, orifice radius and , k^*, is a dimensionless wave number which is given by:

$$k^* = \frac{2\pi r_0 f}{v_0}$$

- β, is a maximum when $k^* = 0.697$. The radius of the drop is determined by

$$r_d = \left(\frac{3 r_0^2 v_0}{4 f}\right)^{\frac{1}{3}}$$

Rayleigh 1878, Weber *et al.* 1931, Sterling *et al.* 1975, Orme *et al.* 1987, 1990, 1991, 1993, Algots *et al.* 1990, Gao *et al.* 2007

Basic Parameters

- The initial velocity, v_o, is found simply by the relation,

$$v_0 = \left(\frac{2\Delta P}{\rho}\right)^{\frac{1}{2}}$$

- where, ΔP, is the pressure difference and is simply given by the relation $\Delta P = P_0 - P_\gamma$. Here P_γ is the pressure due to the surface tension at the orifice.

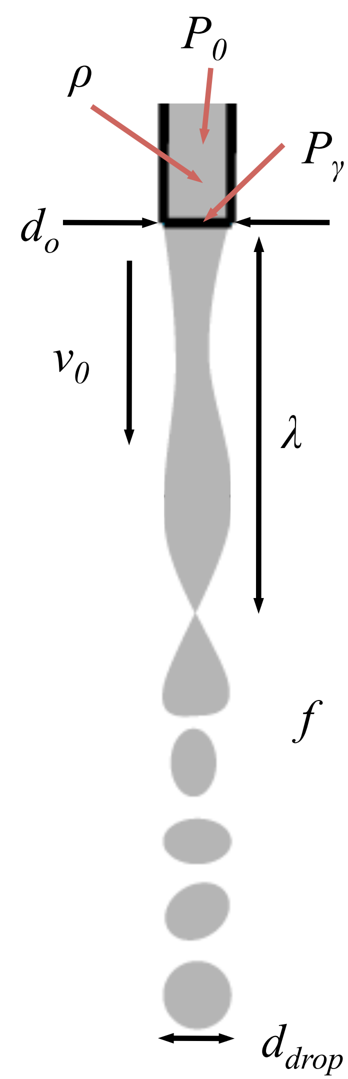
$$P_\gamma = \frac{2\gamma}{r_0}$$

- Without stimulation the carrier drops will break up with different velocities

- The wavelength that the drops break up at is found using, $\lambda = v_0/f$, and the optimum break up wavelength, λ^*, is

$$\lambda^* = \sqrt{2}\pi d_0 \sqrt{1 + \frac{3\mu}{\sqrt{\rho\gamma d_0}}}$$

- d_0 here is the diameter of the orifice. One finds that $\lambda^* \sim$ 1.33 mm for lithium.



Wood's Metal a Lithium Surrogate

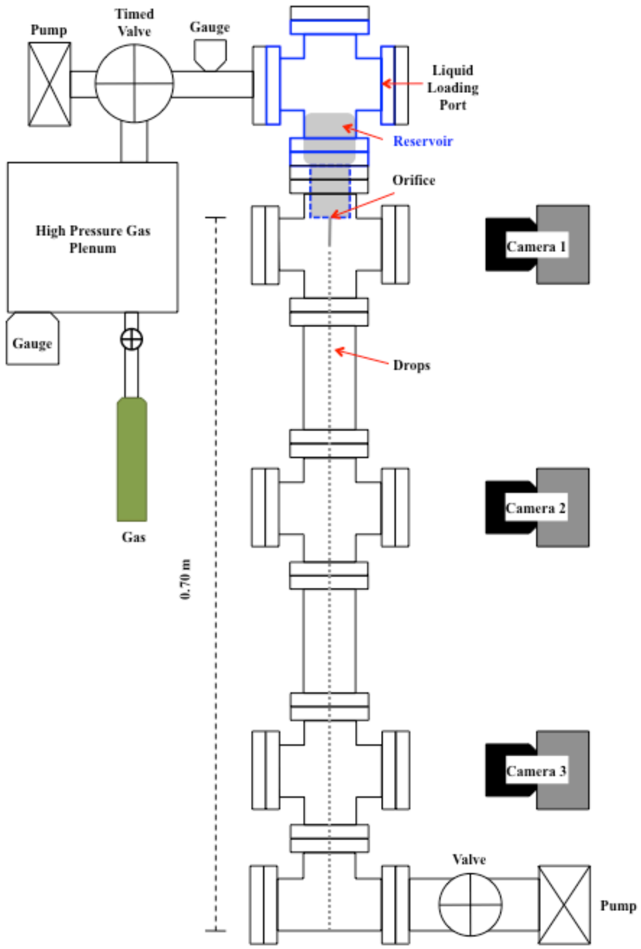
- Two liquid metals:
  - Lithium.
  - Wood's metal (Bi 50% Pb 26.7% Sn 13.3% Cd 10%).
- Wood's metal makes a good surrogate for lithium.
  - Safety
  - Negligible impurity formation with air.
  - Surface tension is similar to lithium.
- Li measurements performed at University of Illinois.
- Several methods for generating droplets have been looked at.
  - Gas pressure only
  - Vibrating Rod
  - $J \times B$ pump – **Not Successful to date**

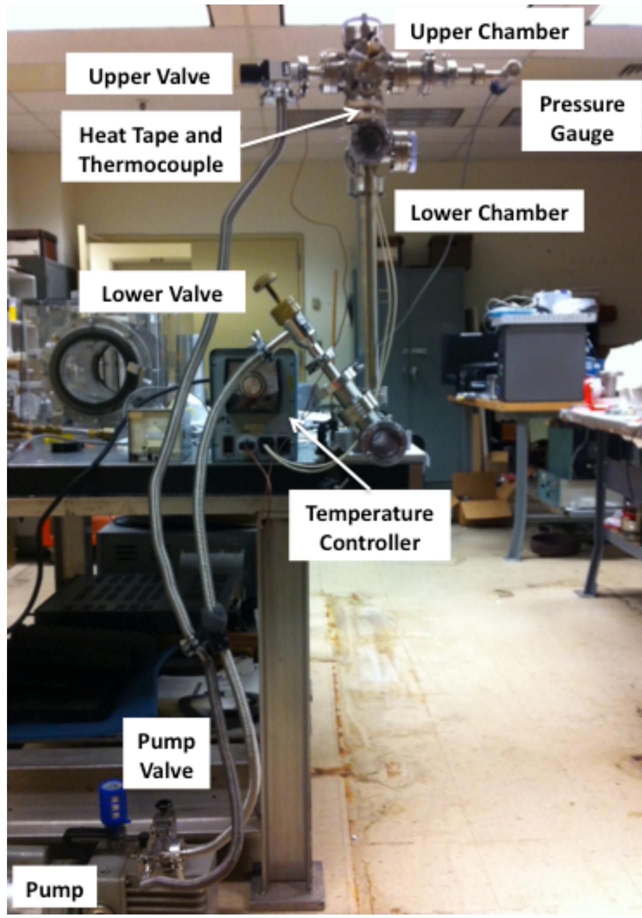
	Lithium	Wood's Metal
Solid Density [ρ_S] (kg.m^{-3})	534	9730
Liquid Density [ρ_L] (kg.m^{-3})	512	9650
Melting Temp. [T_{melt}] (K)	180.54	70
Specific Heat [C_P] (J.kg^{-1}K^{-1})	3570	147
Thermal Conductivity [k] (W.m^{-1}K^{-1})	85	12.8
Thermal Diffusivity [α] (m^{2}s^{-1})	4.45×10^{-5}	8.96×10^{-6}
Dynamic Viscosity [μ] (Pa.s)	5.69×10^{-4}	3.26×10^{-3}
Surface Tension [γ] (N.m^{-1})	0.4	0.42

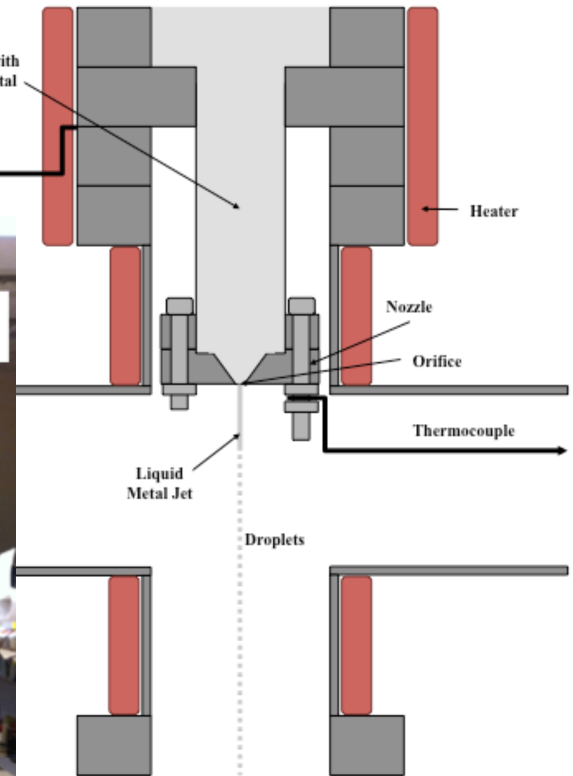
Camera Type	Vision Research MIRO-4
Resolution	144 × 144
Frames Rate (*frames/s*)	3000 - 4000
Calibration (*mm/pixel*)	0.25
Record Time (*s*)	~ 10
Typical Pulse Length (*s*)	~ 1 - 5

D. W. Jeppson *et al.* 1978, B. B. Alchagirov *et al.* 2009, M. Iguchi and O. J. Ilegbusi ISBN: 978-1-4419-7478-5, H. A. Khun et al. 1962, C. Uher and D. Morelli ISBN 1-56676-806-3.

Gas Pressure

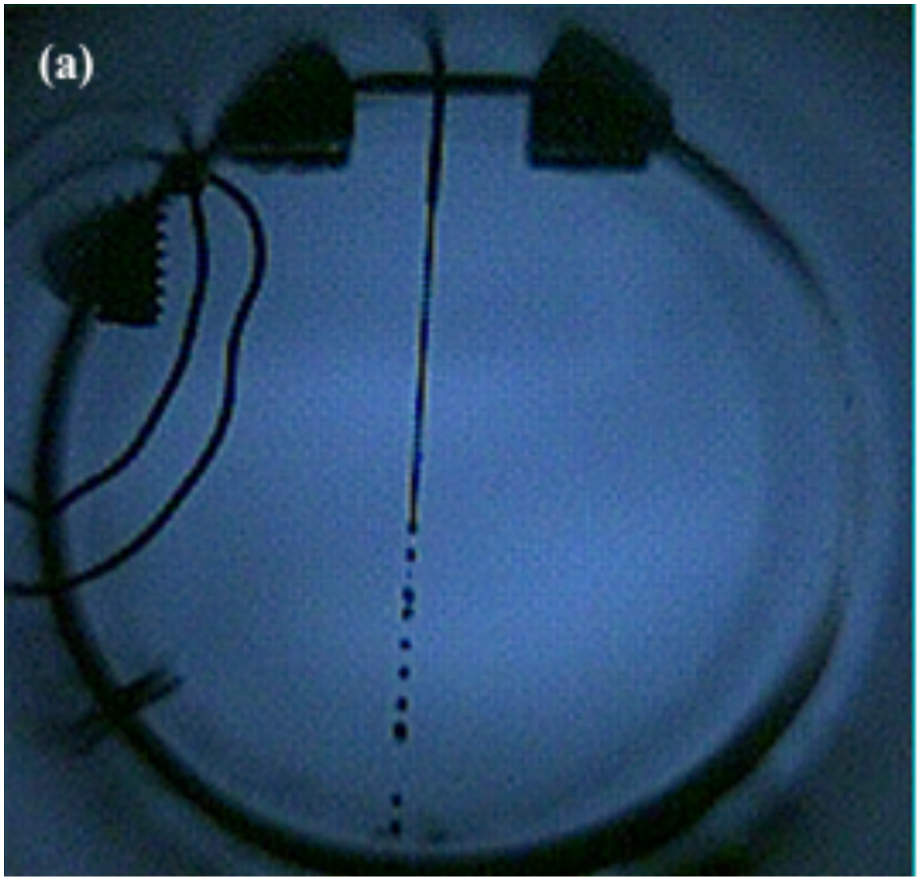




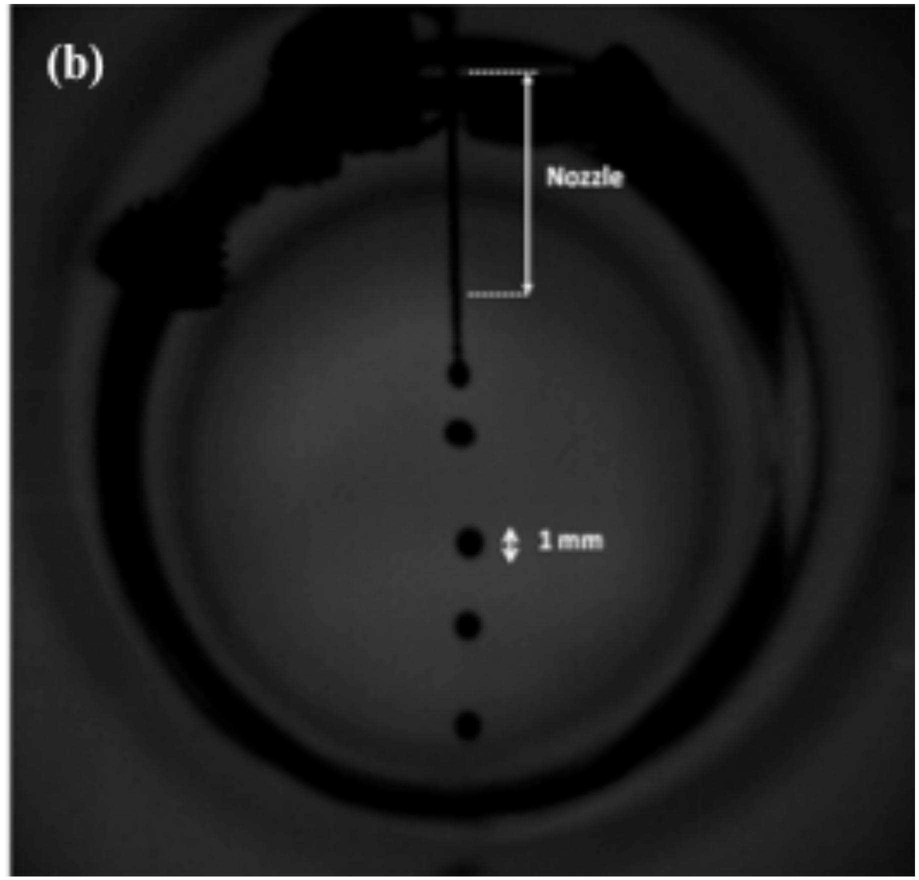


Coalescence of Droplets

Wood's Metal

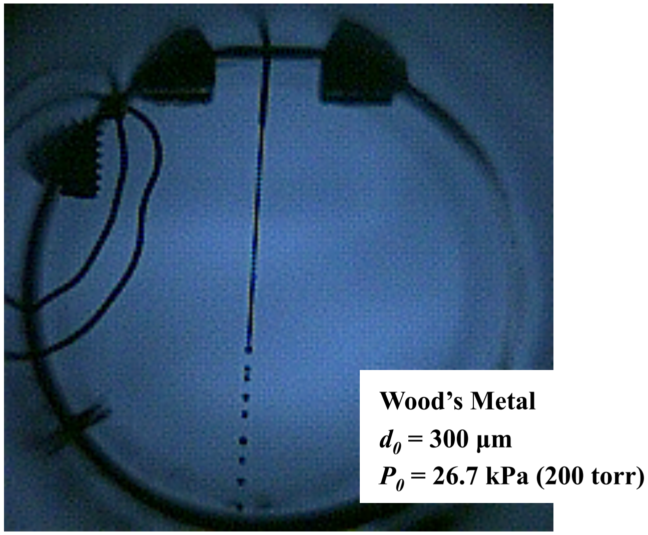


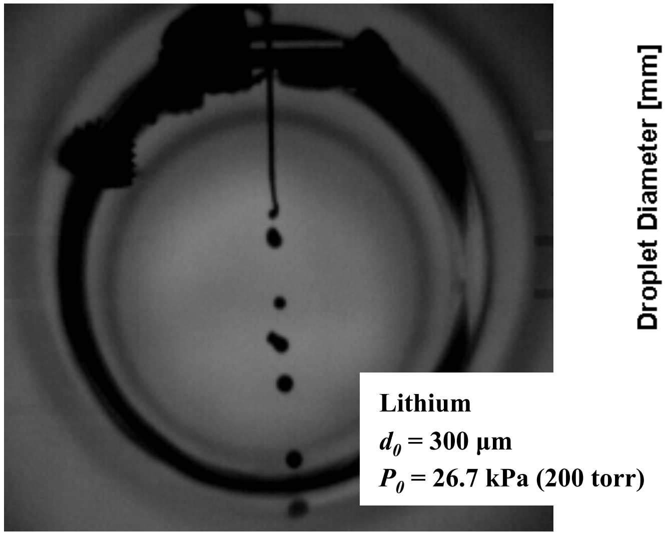
Lithium

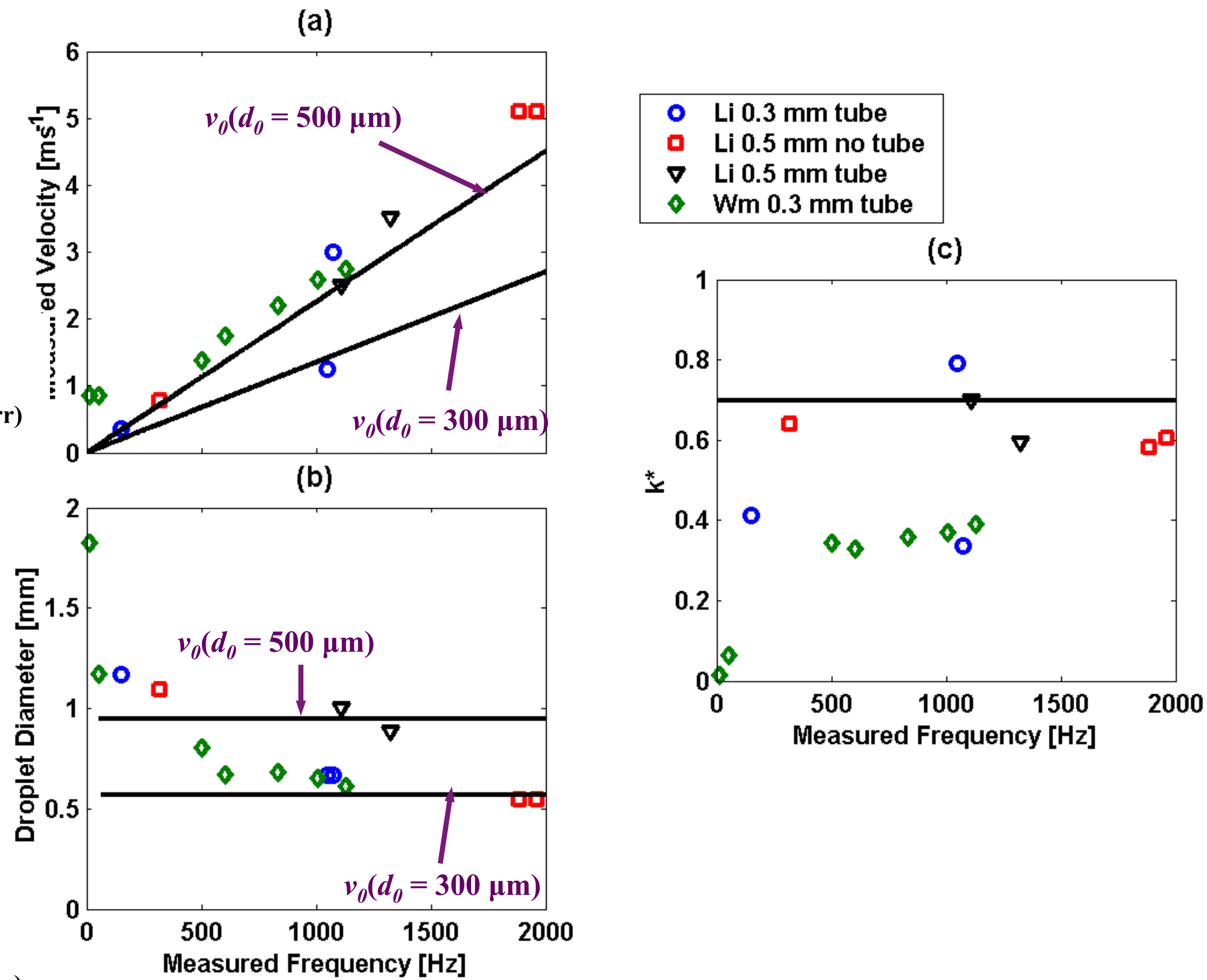


Andruczyk *et al.,* FED (under review) 2014

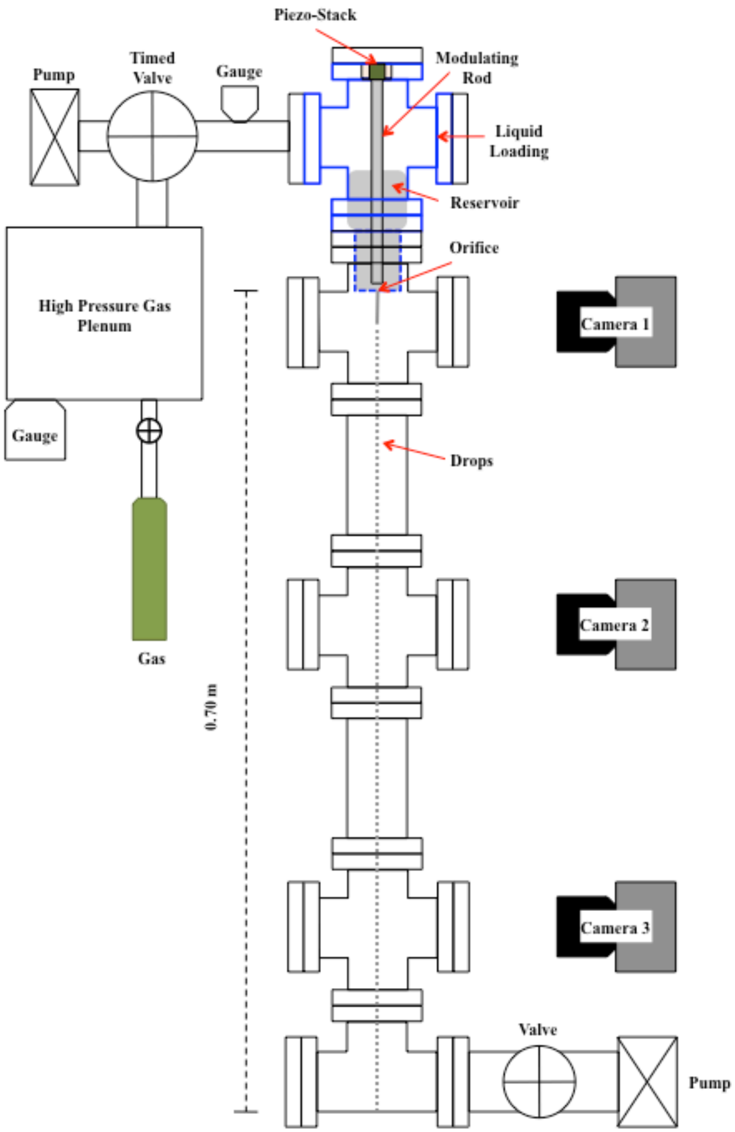
Frequencies and Drop Diameter

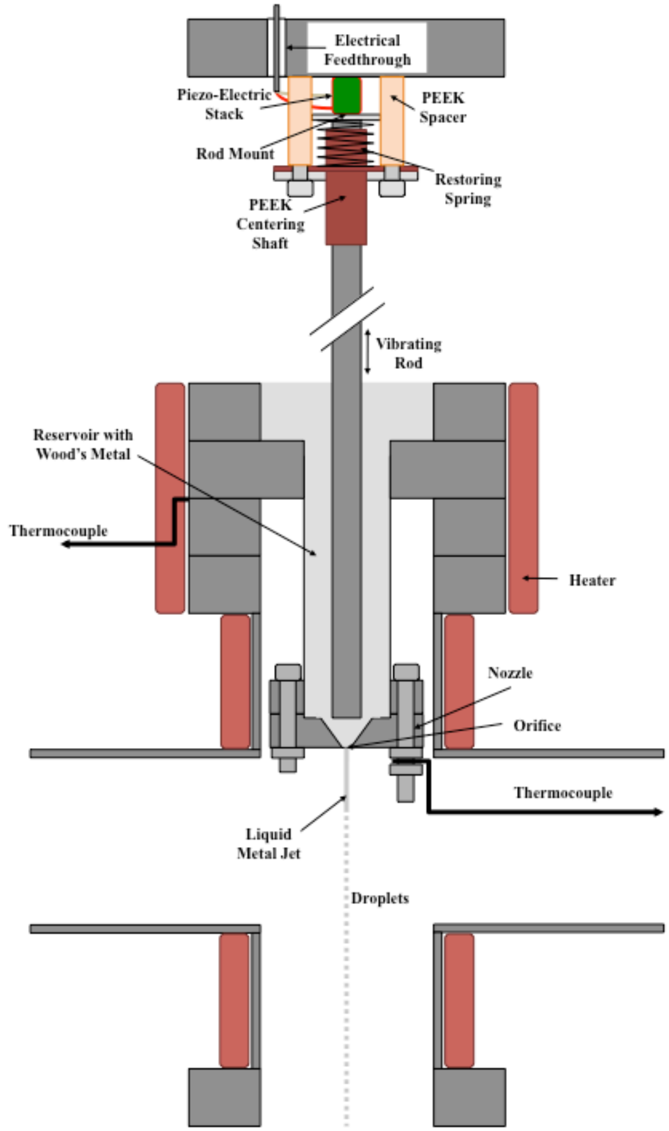


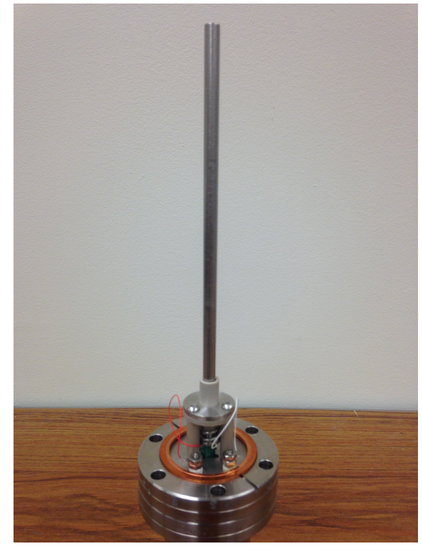




Vibrating Rod





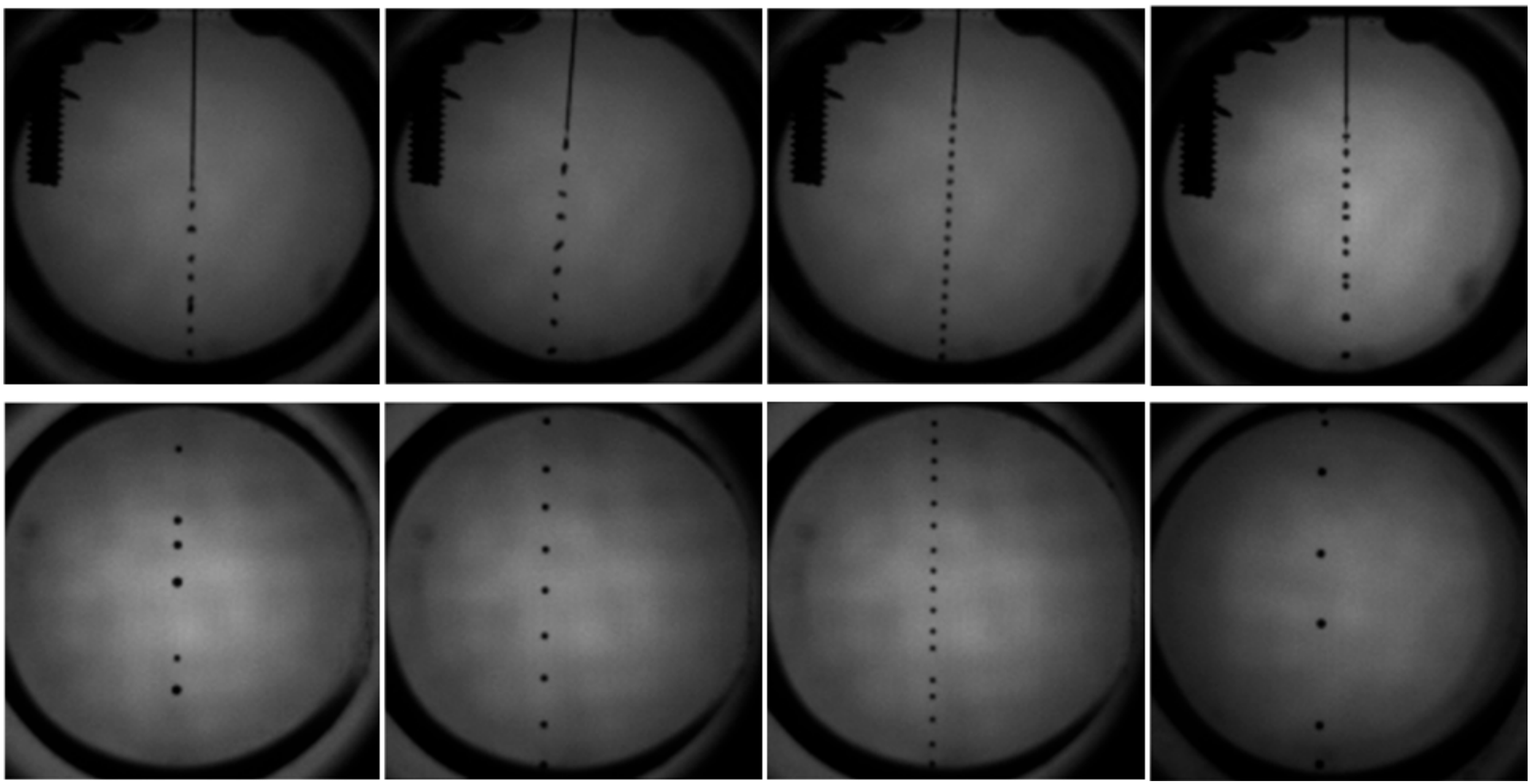


Evenly spaced droplets when $k^* = 0.697$

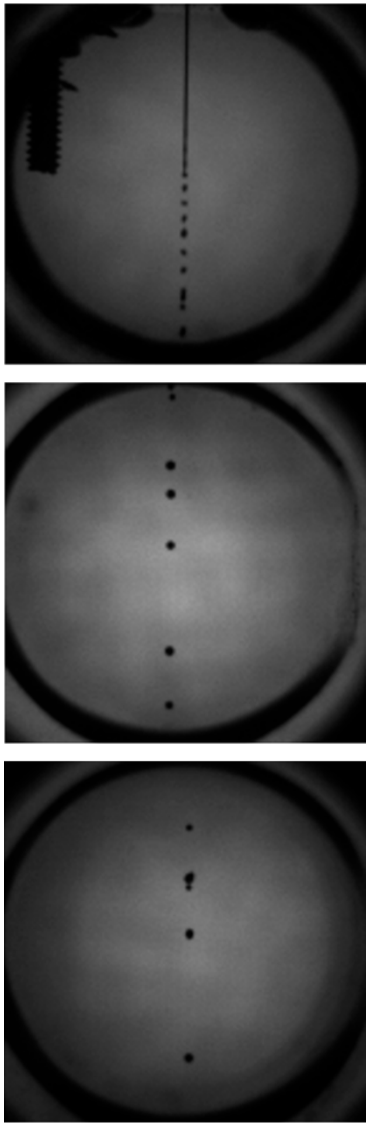
Wood's Metal

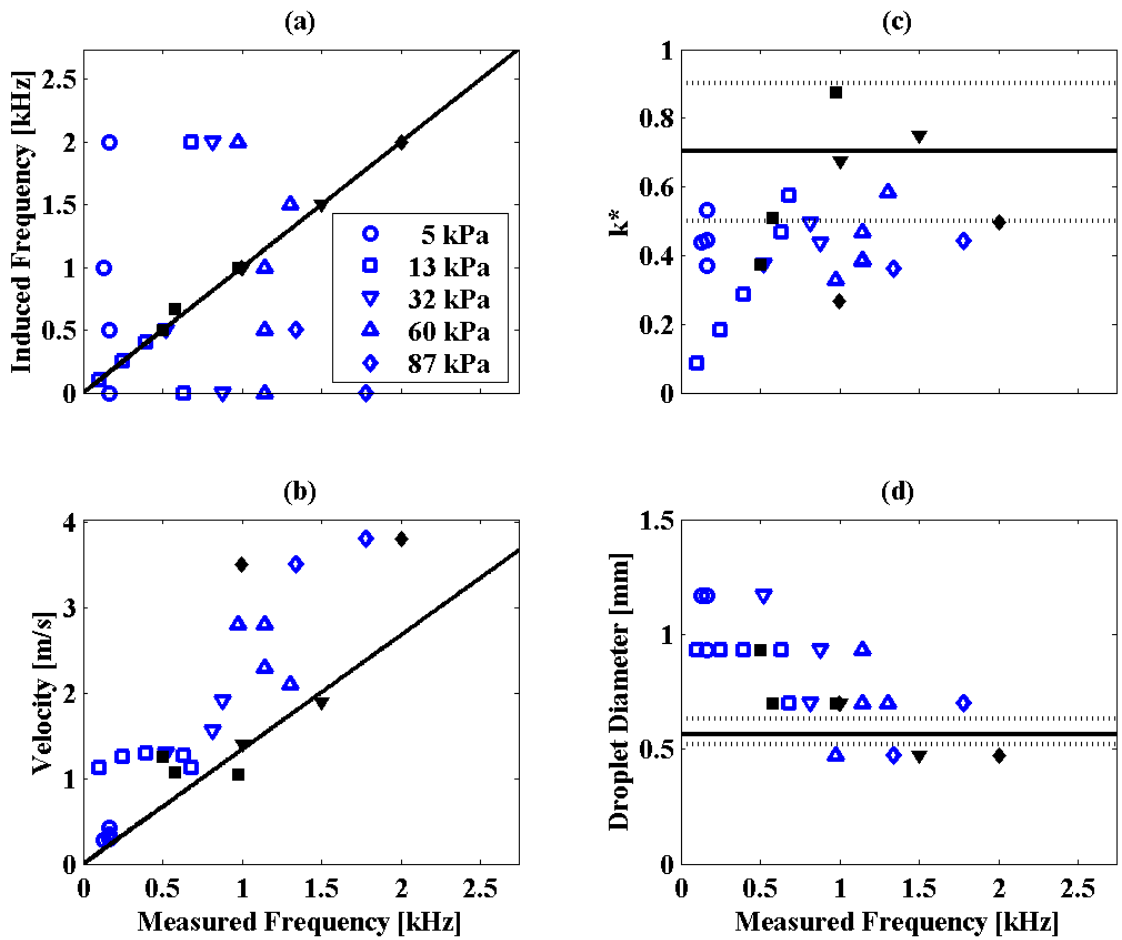
Pressure: 13 kPa

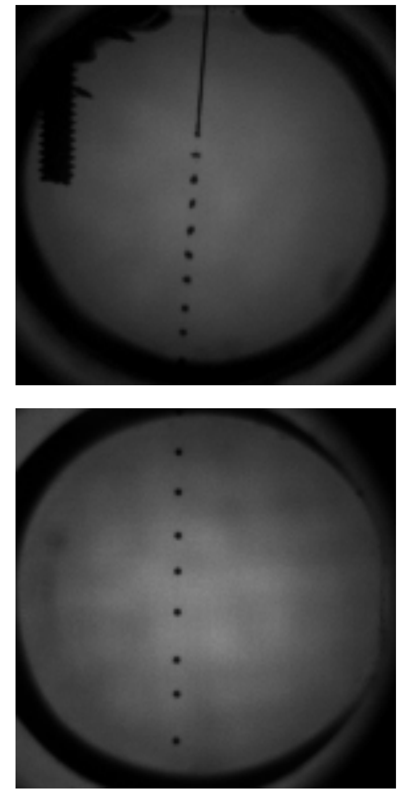
$f_{induced} = 0.0$ kHz | $f_{induced} = 0.5$ kHz | $f_{induced} = 1.0$ kHz | $f_{induced} = 2.0$ kHz



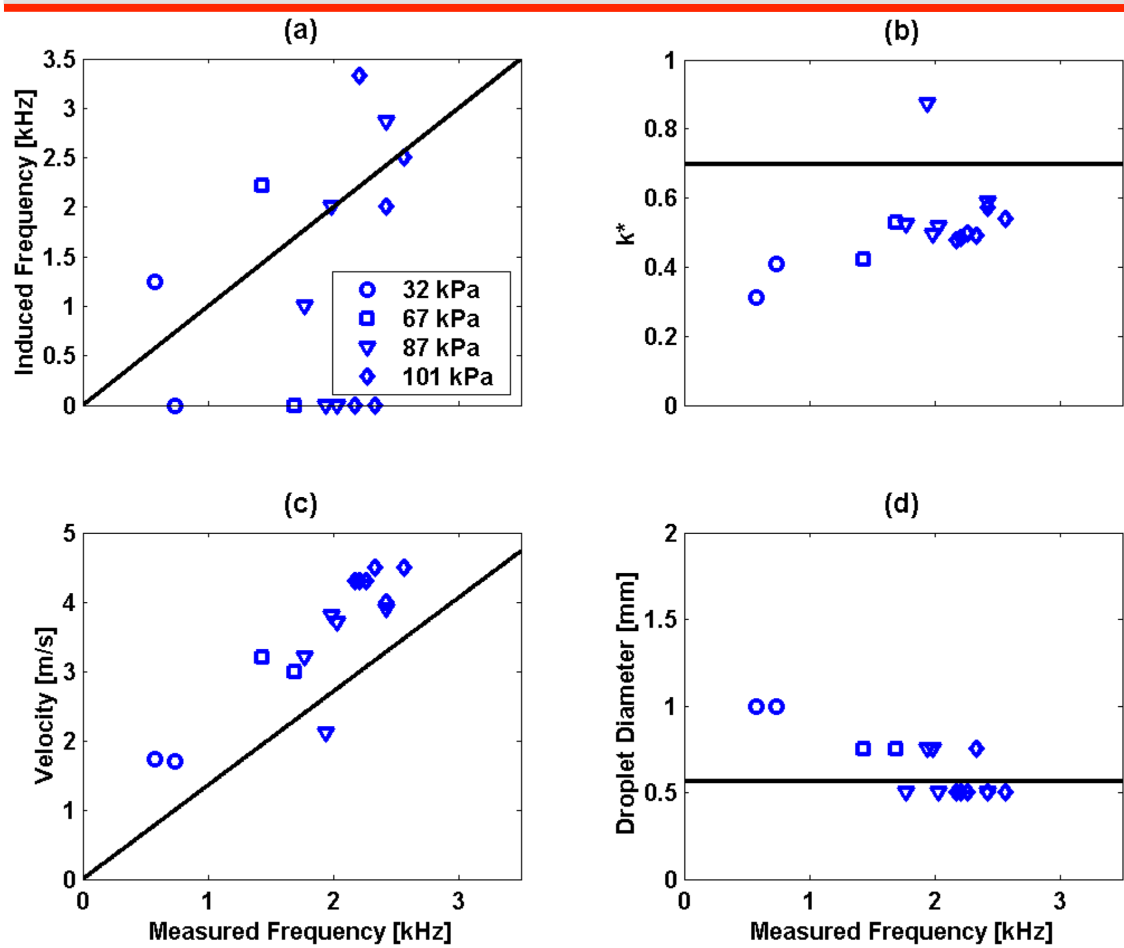
Build up a Picture of Ideal Conditions



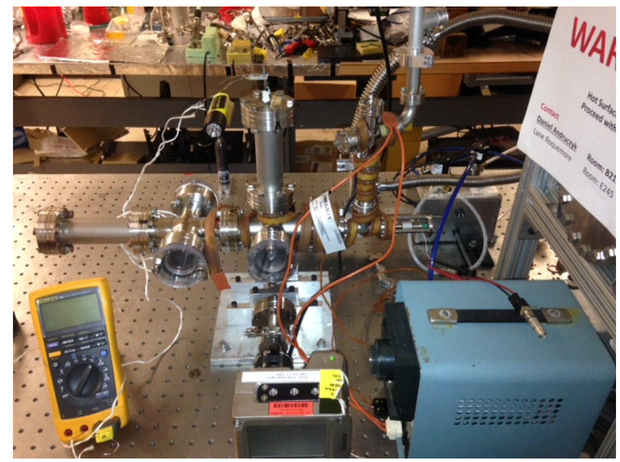


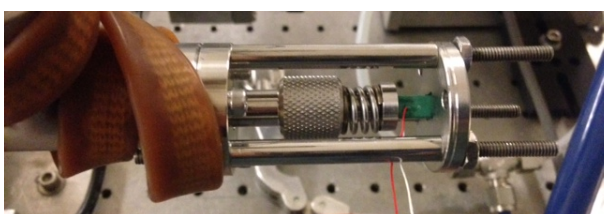


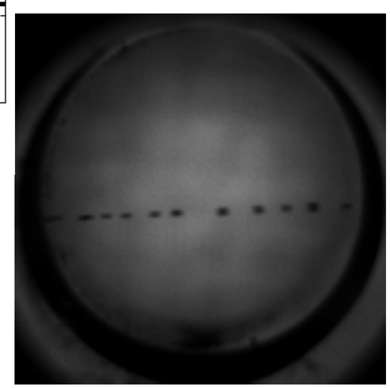
Horizontal Injection

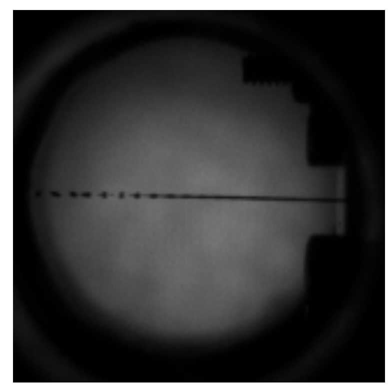


- Direct injection of droplet/pellets into plasma edge.
- Replacement of Granular injector.
- ~ 15 cm distance needed from the NSTX-U wall.



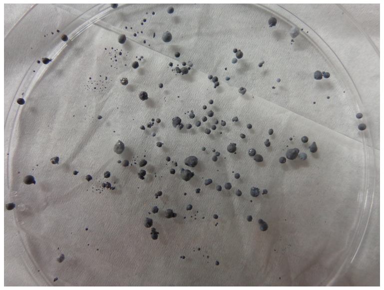




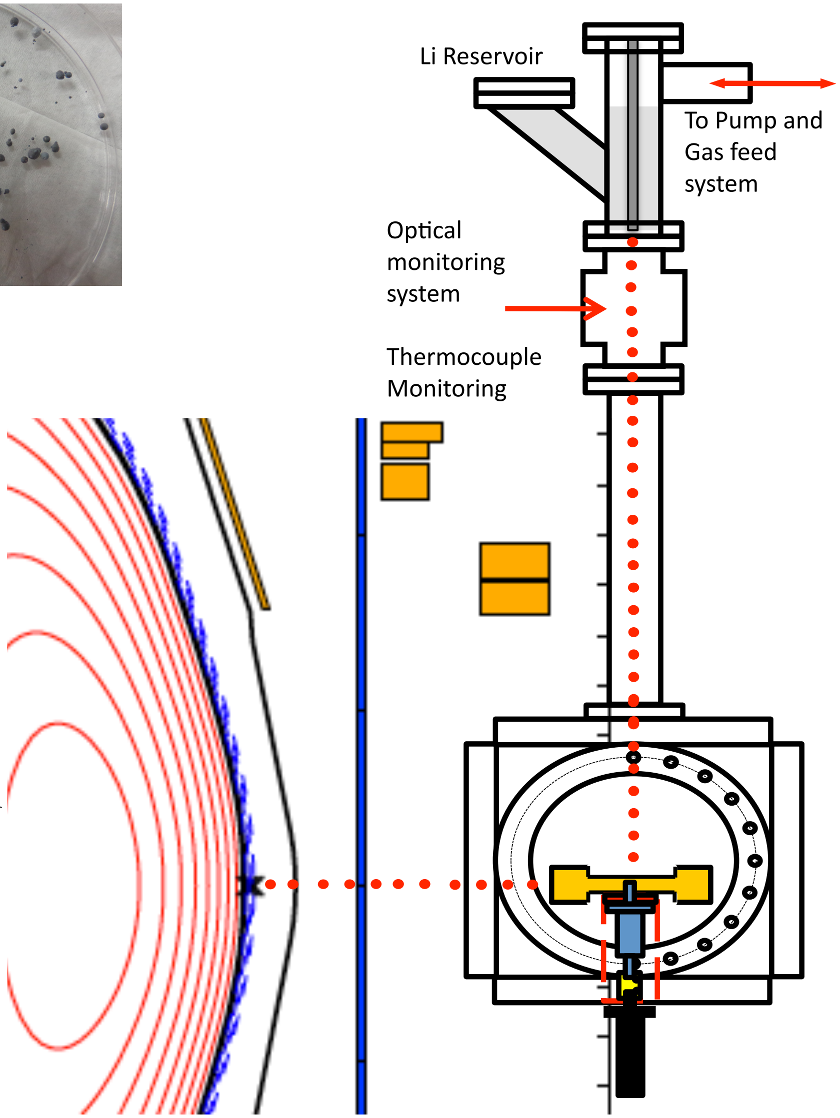


Discussion and Future Work Still Needed

- At stable operation
  - d_{drop} ~ 600 μm
  - 5 s operation at 1 kHz, m ~ 300 mg per pulse
  - Over a run campaign m ~ 0.5 kg



- Turning liquid droplets into solid pellets.
  - Wood's metal does not cool and breaks up on impact.
  - Evidence that Lithium may be solidifying
  - Dominant cooling processes?
- Are solid Li pellets required for NSTX-U.
  - GI definitely needs it
  - Li injected directly, vertically or horizontally?
- These are all questions that still need to be answered.
  - Lithium measurements with vibrating Rod
  - Horizontal injection needs to be characterized with lithium
- Design of LLPI for NSTX-U operation
  - Vertical or Horizontal?
  - SOL or divertor?
  - Safety aspect needs to be considered



Summary

- A new method for delivering pellets of Li into NSTX-U developed.
- Initial considerations for the Granular Injector
- Can be used to directly supply clean Li into plasma edge
- Gas pressure driven,
  - $f_{measured} \rightarrow 2.5$ kHz
  - $v \rightarrow 4.5$ m/s, should be higher with Li
  - $d \rightarrow 0.5$ mm
- 1 run campaign ~ 0.5 kg of lithium.
- Next step: Lithium characterization and design for NSTX-U

Back Up Slides

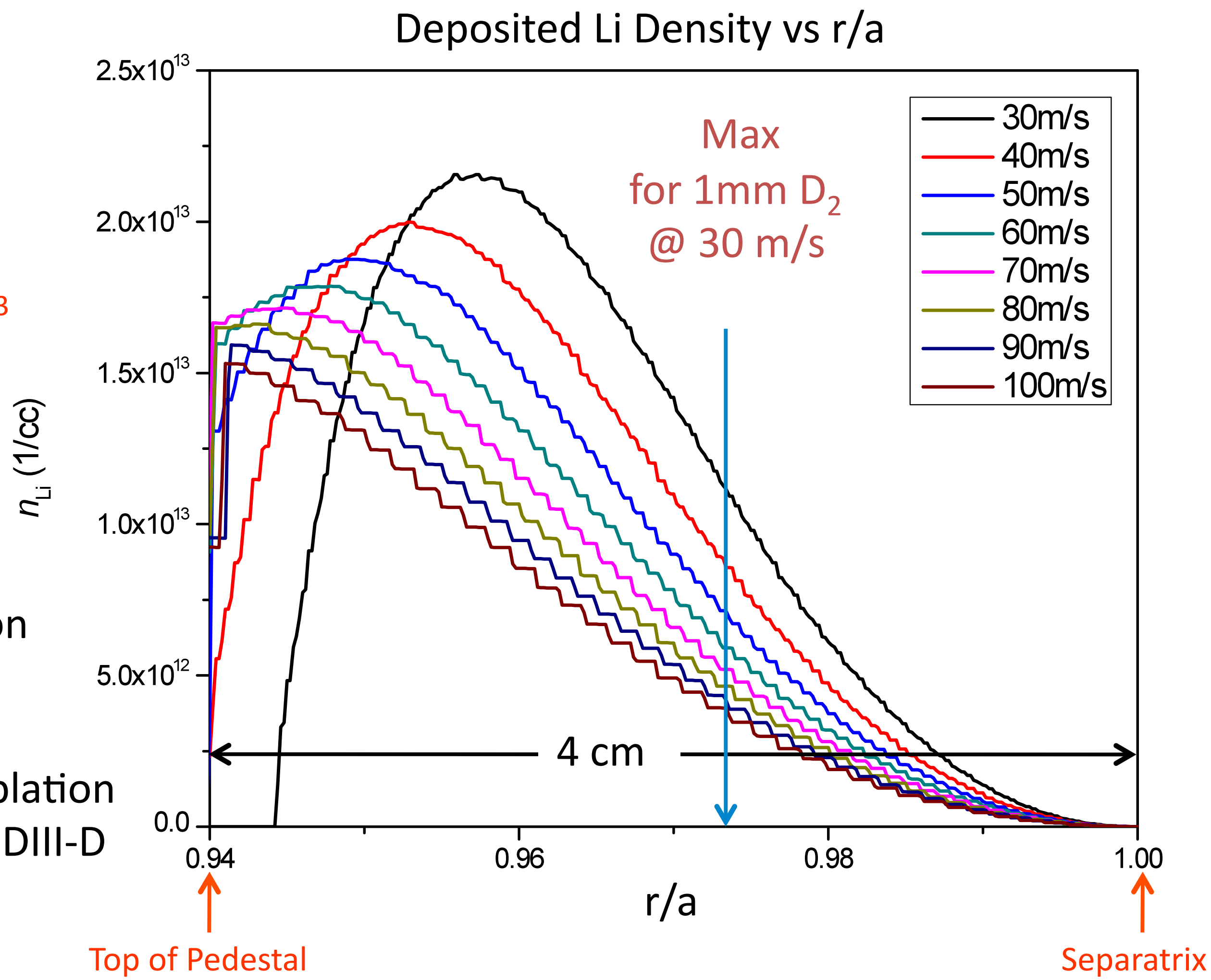
Te (r/a = 1) = 0
Te(r/a = 0.94) = 1 keV

ne(r/a = 1) = 0
ne(r/a = 0.94) = 5 x 10^{13} cm^{-3}

Approx DIII-D Pedestal
R = 1.67 m, a = 0.65 m

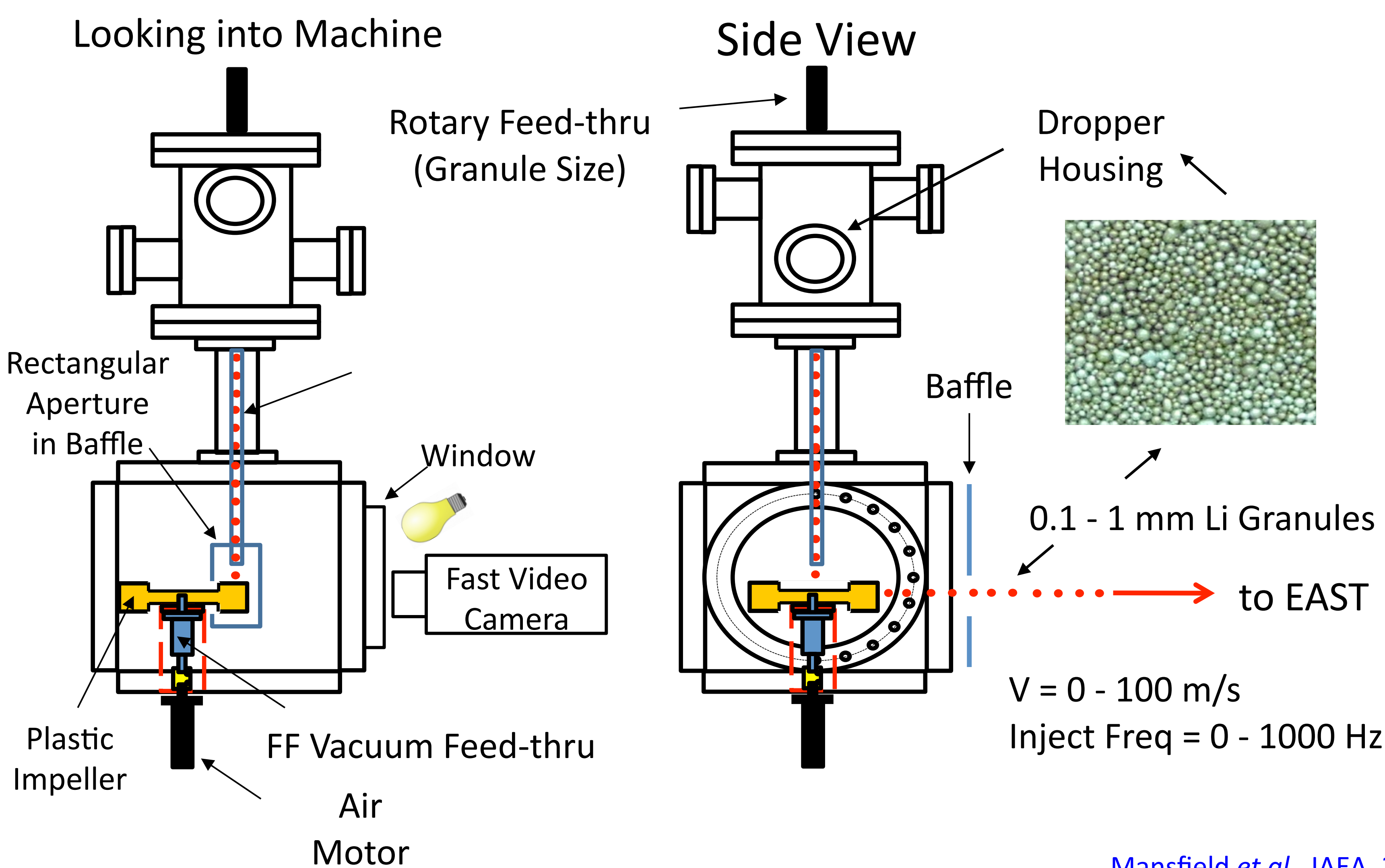
Neutral gas shielding ablation model for Li employed

Results Similar to D pellet ablation which does trigger ELMs on DIII-D



Paul Parks, Wen Wu

Granular Injector



Mansfield *et al.*, IAEA, 2012

EM Pump

- A electromagnetic (EM) pump was built to try and stimulate the droplets into forming a coherent stream
  - Modulating Current
  - I up to 100 A
  - B = 0.3 T
  - Dimensions
    - OD = 12.54 mm
    - ID = 10.72 mm
    - $Wall_{thick}$ = 0.91 mm

- The currents used were not high enough to see any noticeable effect.
  - Losses through the wall of the stainless steel tube are significant, up to 50%

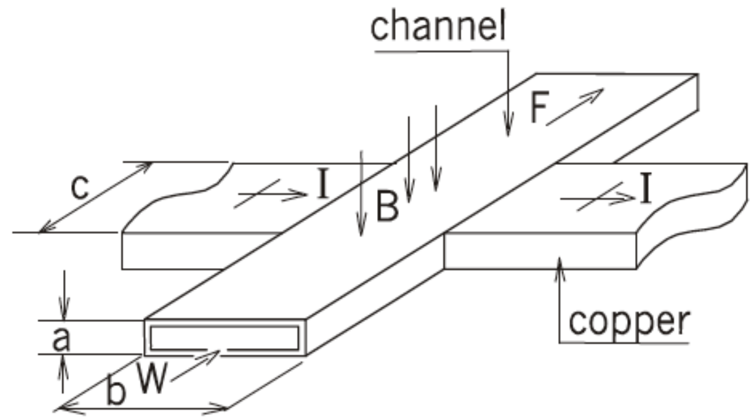
- This still has a future possibility but a higher modulated current source will be required or a larger magnetic field

- One plus side, demonstration that the LLPI works in the horizontal position was shown.

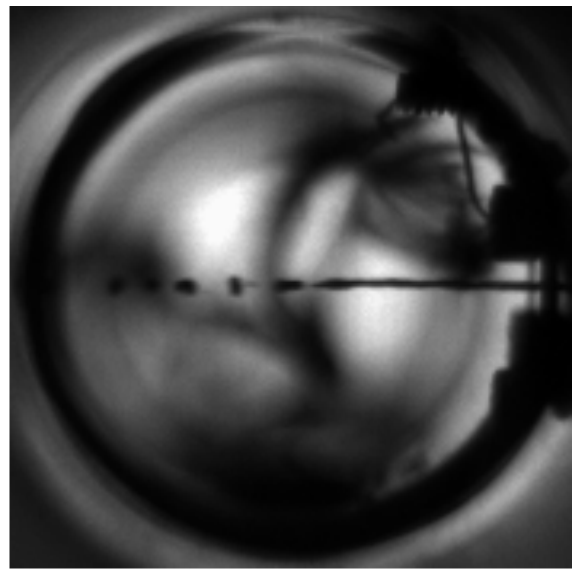
$$F_{J\times B} = BIb$$

$$P_{J\times B} = \frac{F_{J\times B}}{A}$$

$$P_{J\times B} = \frac{BIb}{A}$$



E. M. Borges *et al.*, Thermal Engoneering, Vol. 9, No. 1, 2 December 2010, 47 – 54.
S. Shimasaki and S. Taniguchi, 7th International Conference on CFD in the Materials Process Industries, CSIRO, Melbourne, Australia, 9 – 11 December 2009.



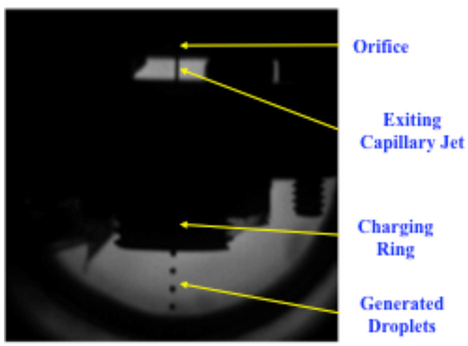
Droplet Charging

- Charging of droplets to keep them separated has been performed.
  - S. Gao et al., J. Mater. Sci. Technol., Vol. 23 No 1, 2007.
- Charging of the droplets works to a certain voltage $V \sim 100$ V
- Higher Voltages cause instabilities in the droplets, seen by Yang where whipping instabilities have been observed.
  - W. Yang *et al.*, PRL **112**, 054501 (2014)

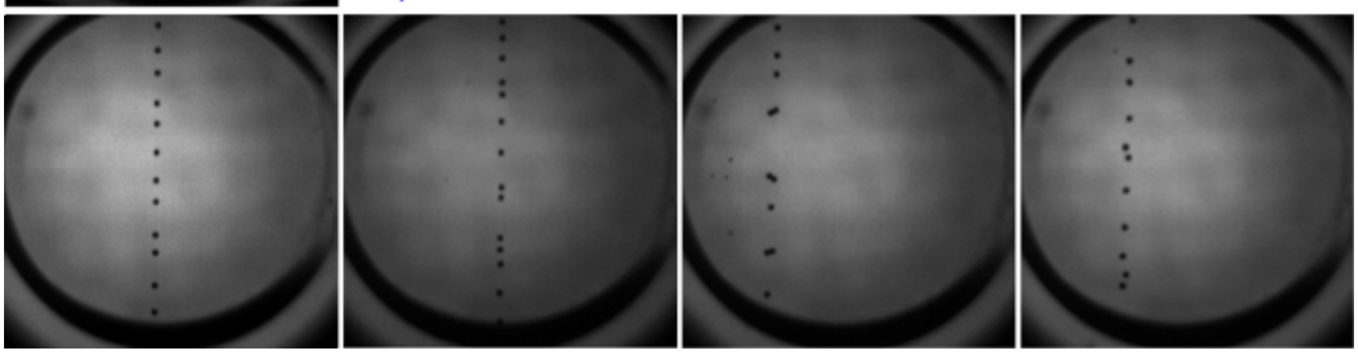
Pressure* = 32 kPa** ***f

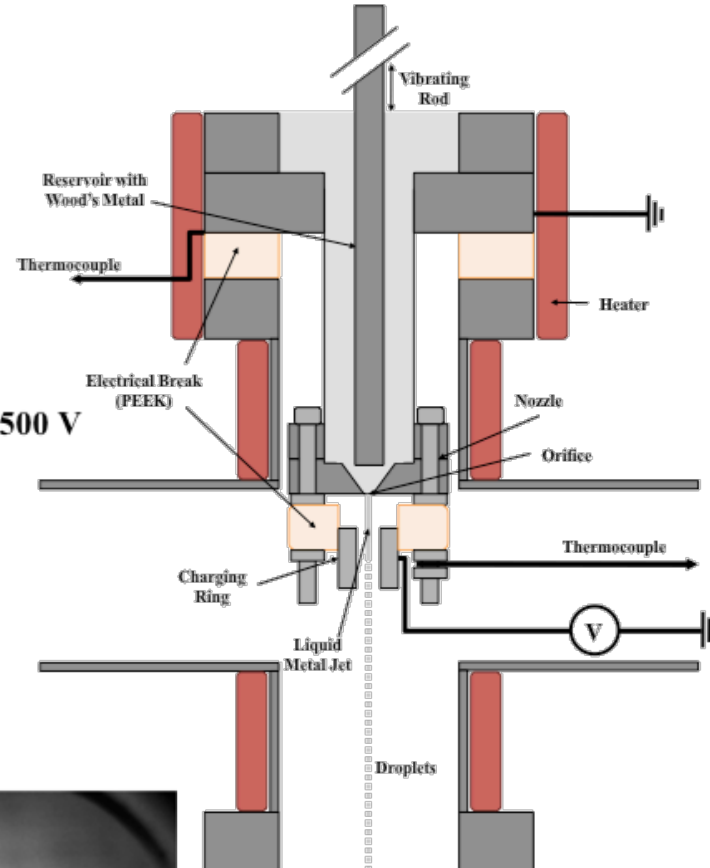
$Pressure = 32$ kPa $\quad f_{induced} = 1.0$ kHz

$V = 100$ V $\quad V = 150$ V $\quad V = 200$ V $\quad V = 500$ V



$$q = \frac{2\pi\varepsilon_0 V_C v_0}{\ln\left(d_C / d_j\right) f}$$





Direct Li Injection into NSTX-U, Vertical and Horizontal