# An Electrostatic Lithium Injector (ELiI)
## *First Results*

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# 1. Motivation



- Li has shown some excellent properties as a PFC material
  - Hydrogen getter
  - Improved Performance
  - Suppresses ELMs
  - Reduces damage on surfaces that have been coated with lithium
- NSTX and LTX currently active machines that uses lithium as a PFC material
  - Currently deposited using LITER
- However the center stack is one area of NSTX that is not reached by LITER
  - LITER line of sight
  - Center-stack is thin, small target that cannot be uniformly coated
  - Center-stack can be biased up to 2500 V
- Discussions with Dennis Mansfield
  - Can a charged spray of lithium be produced?
  - Biasing of components can target them to be coated with lithium

# 2. Theory – Droplet Formation

- Will a droplet form and what will be its initial velocity?
- Consider a tube which has a liquid with surface tension, $\gamma$
  - The system will be in an equilibrium when the pressure due to $\gamma$, $P(\gamma)$ and the backing pressure, $P_0$, are equal.

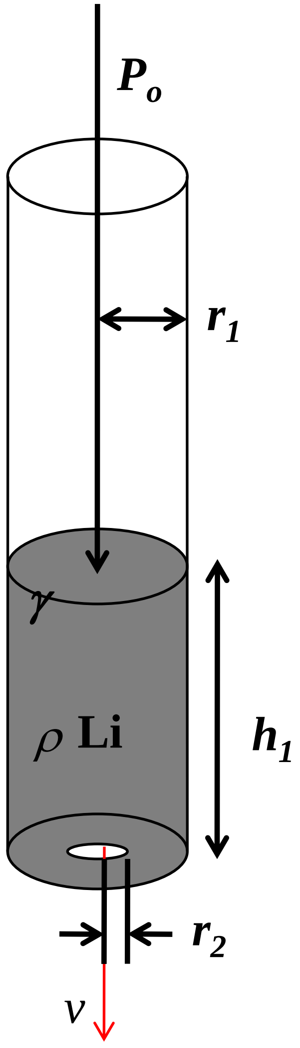
$$\Delta P = P(\gamma) - P_0$$

$$\Delta P = \frac{2\gamma}{r_1} - P_0$$

  - When $\Delta P = 0$, then $P_0 = 2\gamma/r_1$, which for lithium is about 147 Pa in this instance (1/2" tube).
- If $P_0$ exceeds $P(\gamma)$ then the liquid will be forced through the hole at some velocity, $v$, given by [1]

$$v^2 = \frac{2P_0}{\rho\left(\frac{A}{a}-1\right)^2}$$

  - where, $A$, is the larger Surface area and, $a$, is the surface area of the hole the Lithium is being forced through, $\rho$, is the density of liquid Li.



# Droplet Formation and q/m Ratio



- As a droplet is charged, it will charge to the Rayleigh limit.
  - A droplet tends to have a spherical shape because of its surface tension.
  - As it charges up the repulsion between the ions may over come the surface tension.
  - This will lead to a break up of the droplet into smaller ones.
- These two disruptive effects are equal at a characteristic droplet radius, *R* [2]

$$R = \frac{4\gamma}{\left(\varepsilon_0 E^2\right)}$$

  - where, E, is the maximum surface electric field
- The maximum specific charge as a function of radius is given by [3]

$$Q = \frac{6\left(\varepsilon_0 \gamma\right)^{1/2}}{\rho R^{3/2}}$$

  - This is for the parent droplet, where *Q* is the charge on the droplet.
- As this is overcome, the parent droplet will break up into smaller daughter droplets so as to conserve charge and volume.

# Droplet Formation and q/m Ratio



- The number of droplets, *N*, that will break up from the parent drop is

$$N = \left(\frac{R}{r}\right)^3$$

  - where, *r*, is the radius of the daughter droplets.

- Thus for a system where the parent drop has a radius of R = 1 mm and the daughter droplets are 0.2 mm, there would be 125 droplets produced.

- Therefore the charge to mass ratio, *β*, with respect to droplet radius is

$$\beta = \frac{6(\varepsilon_0 \gamma)^{1/2}}{m \rho r^{3/2}}$$

  - Where, *m*, is the mass of a droplet.

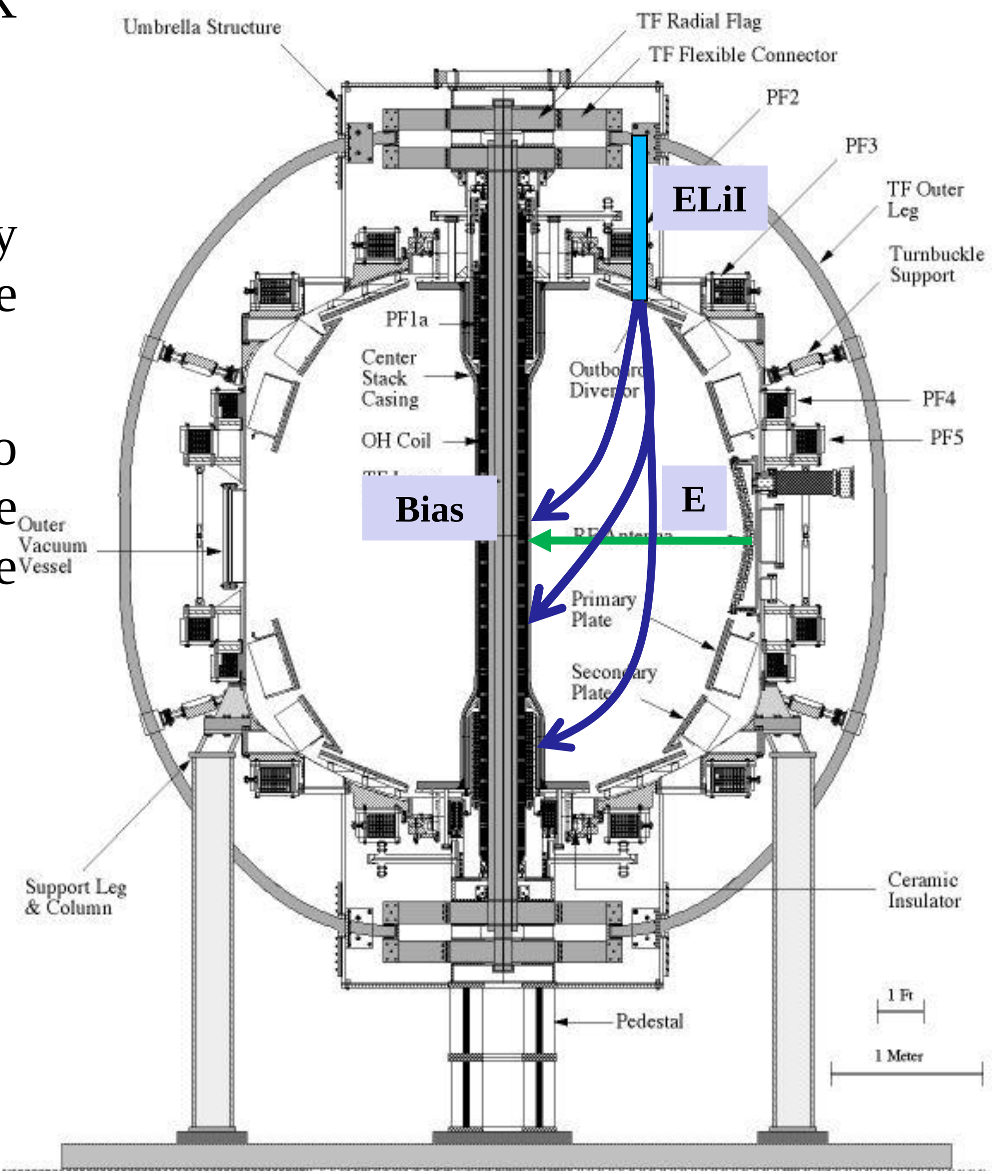
# Trajectory

- By biasing the center-stack on NSTX the particles will be attracted to it.
  - Between shots or before running
- Coat the surface of the center-stack by varying the bias or by changing the pressure in the dropper.
- Basic kinematics should be able to predict the path the particles will take and whether the center stack can be reached.
  - Solving for $F = mg$ and $F = qE = qV/d$

$$x = \frac{1}{2}\frac{qEt^2}{m} - v_o t$$

$$z = z_o - \frac{1}{2}gt^2 - v_o t$$

  - where $z_0 = h$, the height.



# Summary

| Parameter | Symbol | Ranges | Typical Value | Units |
|---|---|---|---|---|
| ELiI cross section | $A$ | $3\times10^{-5} < A < 2\times10^{-3}$ | $6.7\times10^{-5}$ | $m^2$ |
| Orifice cross section | $a$ | $2\times10^{-5} < a < 4\times10^{-6}$ | $3.2\times10^{-6}$ | $m^2$ |
| Radius of parent | $R$ | $500\times10^{-6} < R < 2\times10^{-3}$ | $1\times10^{-3}$ | m |
| Radius of daughter | $r$ | $1\times10^{-6} < r < 200\times10^{-6}$ | $100\times10^{-6}$ | m |
| Surface Tension | $\gamma$ | $0.2 < \gamma < 0.4$ [5] | 0.32 (@250 $^oC$) [4] | N/m |
| Pressure | $P_0$ | $150 < P_0 < 350\times10^3$ | $40\times10^3$ | Pa |
| Density | $\rho$ | - | 512 (liquid) | $Kg/m^3$ |
| Initial velocity | $v$ | $0 < v < 2$ | 0.6 | m/s |

$$v^2 = \frac{2P_0}{\rho\left(\frac{A}{a}-1\right)^2}$$

$$Q = \frac{6(\varepsilon_0\gamma)^{1/2}}{\rho R^{3/2}}$$

$$x = \frac{1}{2}\frac{qEt^2}{m} - v_0 t$$

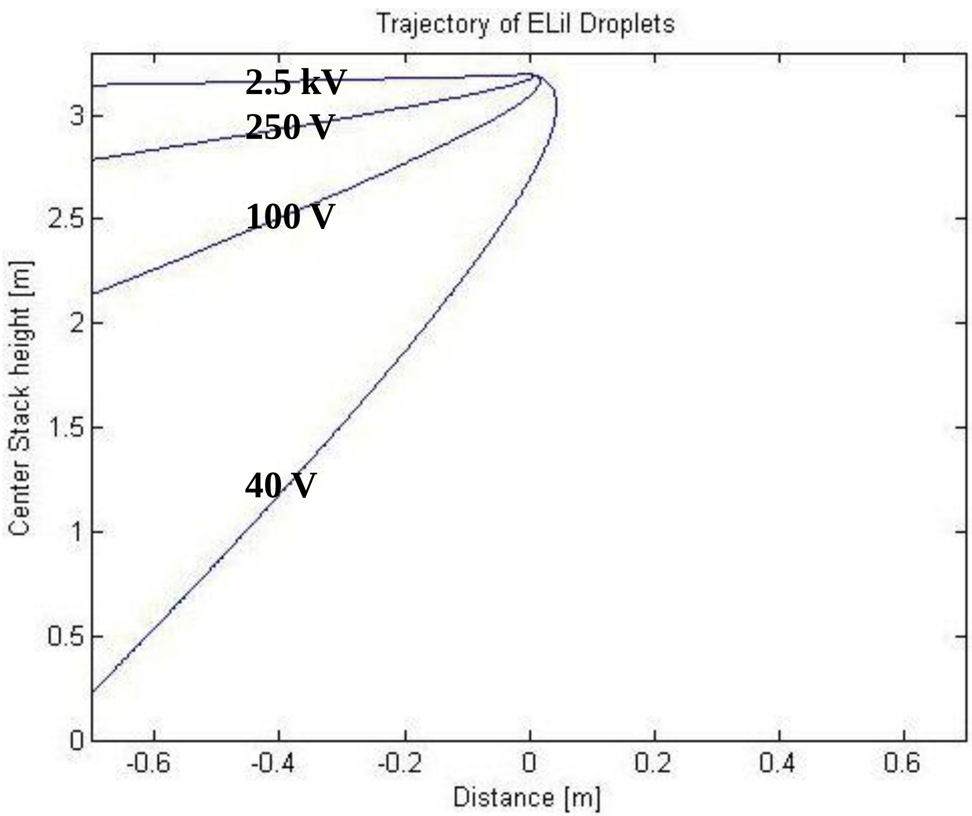
$$R = \frac{4\gamma}{(\varepsilon_0 E^2)}$$

$$\beta = \frac{6(\varepsilon_0\gamma)^{1/2}}{m\rho r^{3/2}}$$

$$z = z_0 - \frac{1}{2}gt^2 - v_0 t$$

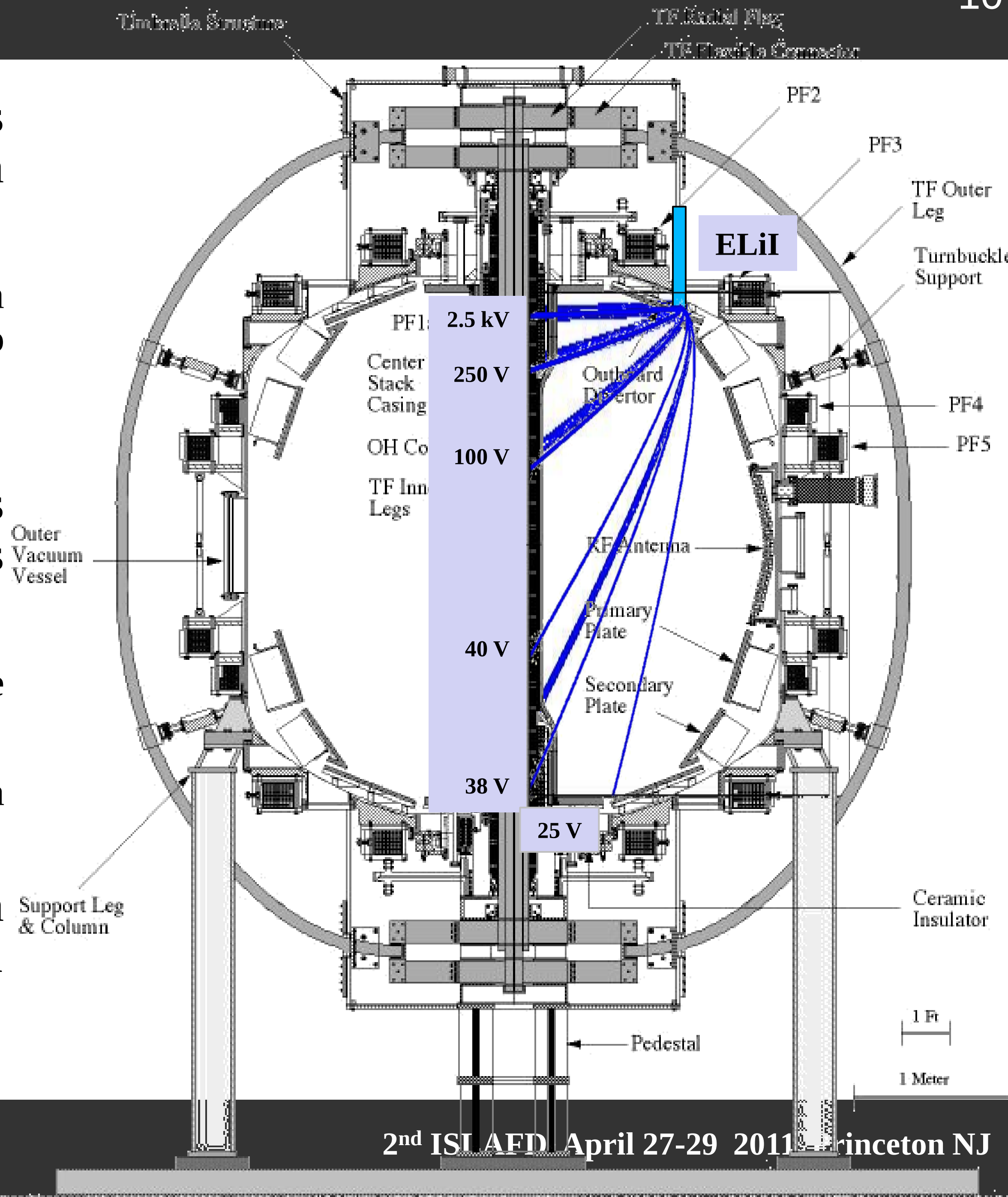
# 3. Results – Modeling Trajectory

- Using the typical values in the previous slide an estimate of the path a droplet will take can be made.
- For a 1/2" tube with a 0.08" orifice
  - $v = 0.6$ m/s
  - A parent droplet with a diameter of 2 mm will charge up to 311.96 μC
  - If the daughter droplets are 200 μm in diameter then there will be $N = 1000$ droplets
- Bias voltage on the center-stack:
  - $V = 40$ V
  - E-field → $E_{bias} = 38.6$ V/m
- Results show that this will be the lower limit of where the droplets will go.
  - By sweeping the bias voltage on the center-stack, it can be ***"Painted"*** by ELiI



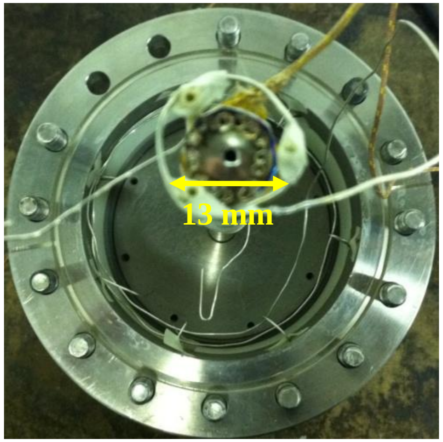
# Modeling Trajectory

- If the results from the previous slide are superimposed onto a cross section of NSTX
  - See that the voltage sweep from 40 V - 2500 V is enough to **"Paint"** the center-stack.
    - *v* = 60 cm/s in this example
- The minimum voltage bias needed on the center-stack is only $V_{min}$ = 38 V
  - Lower voltages will cover the divertor.
  - Potential to be able to cover a large array of surfaces.
- ELiI shows great potential as a complimentary tool for LITER



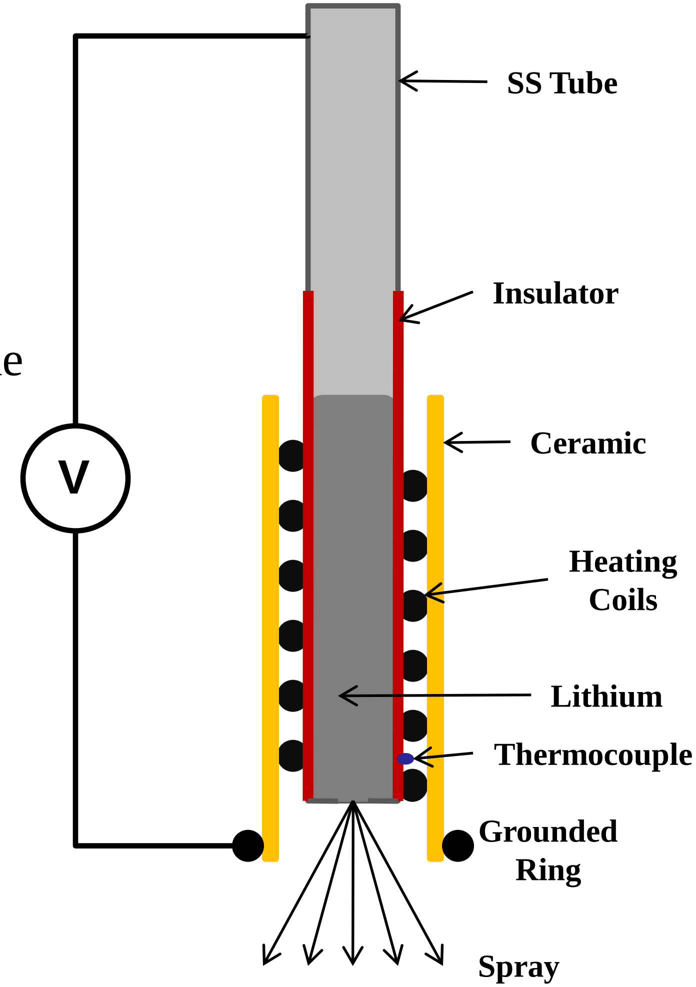
# ELiI Prototype

- ELiI Prototype specifications
  - 0.5 inch tube used
  - Heating wire wrapped around tube
    - Isolated with kapton tape
  - Thermocouple is used to measure the temperatures
  - An orifice made from SS shim is spot welded onto the end of the tube
- Ceramic rods
  - Used to keep away from heating coils
  - Provide a spacer for the distance from the biased tube
- Voltage of up to $V$ = 2000 V can be provided



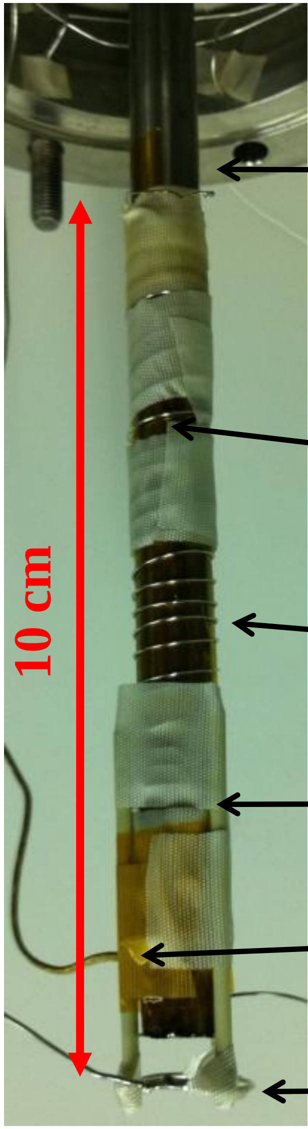

**Top: View of ELiI from the top**

**Left: side on view of ELiI**



# ELiI Prototype






SS Tube

Insulator

Heating Coils

Ceramic

Thermocouple

Grounded Ring

**ELiI Tube**

**ELiI Chamber**

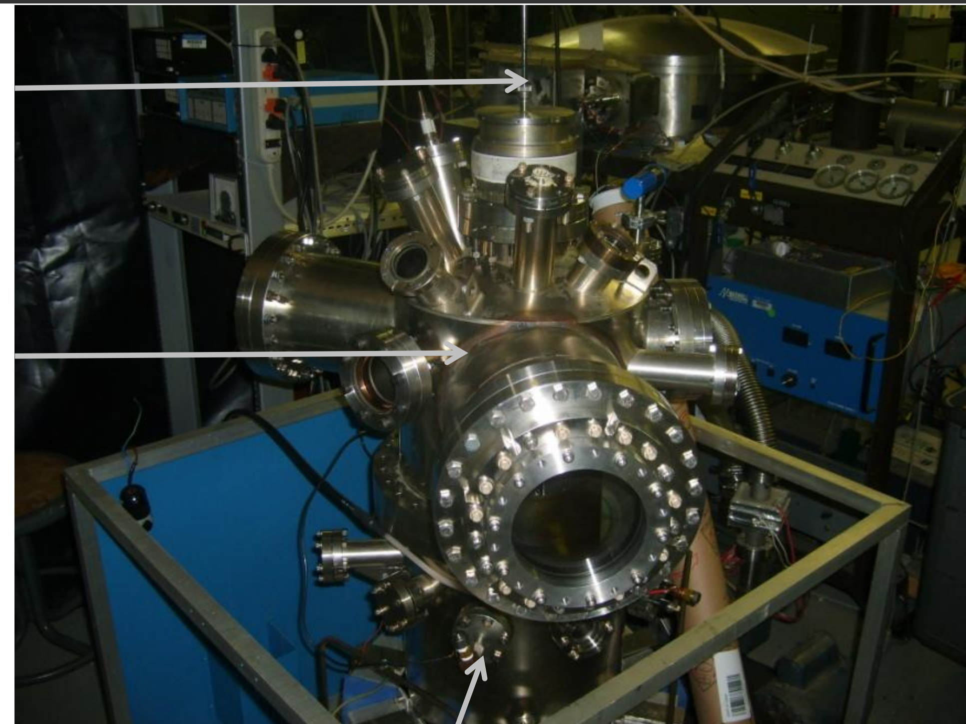
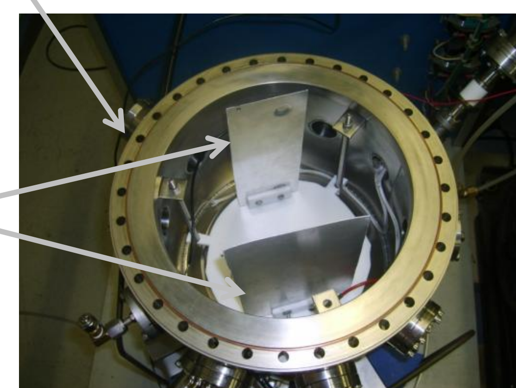


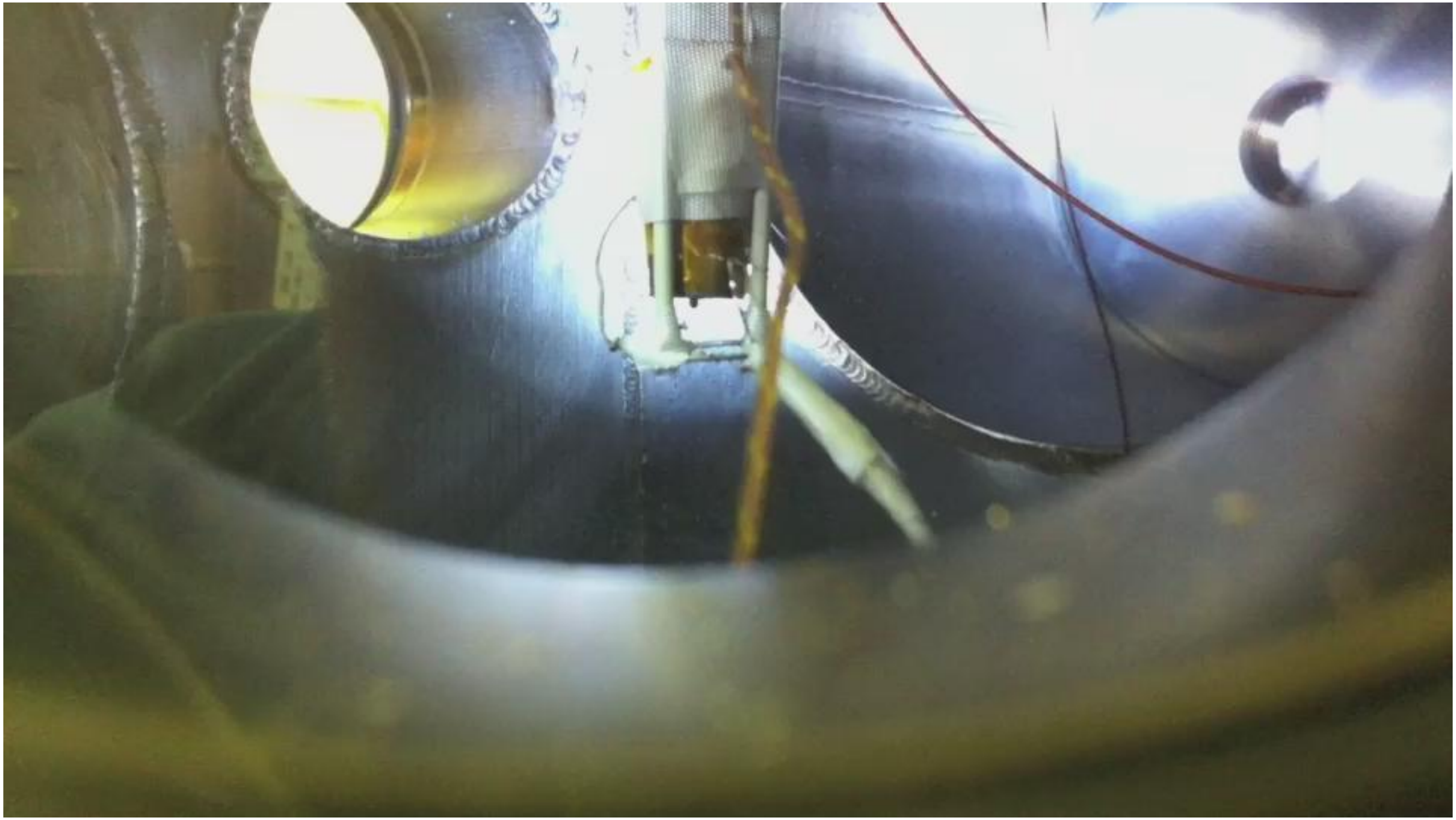
**Plate Chamber**

**Bias Plates**



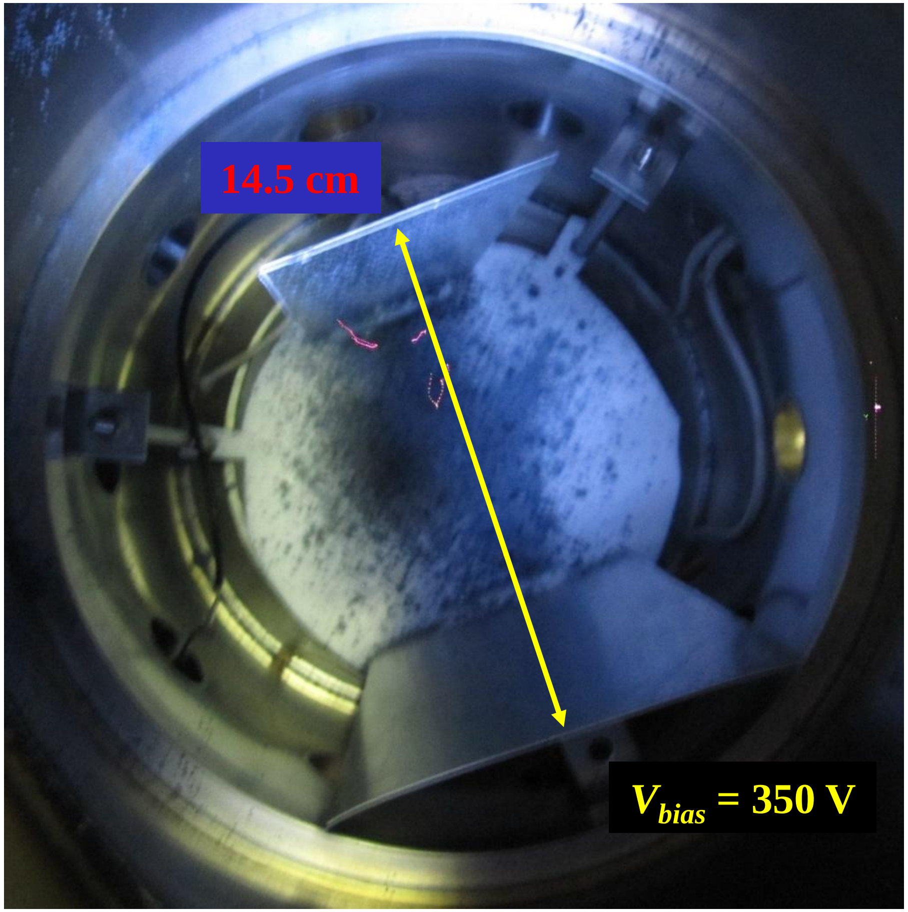
# Video of ELiI

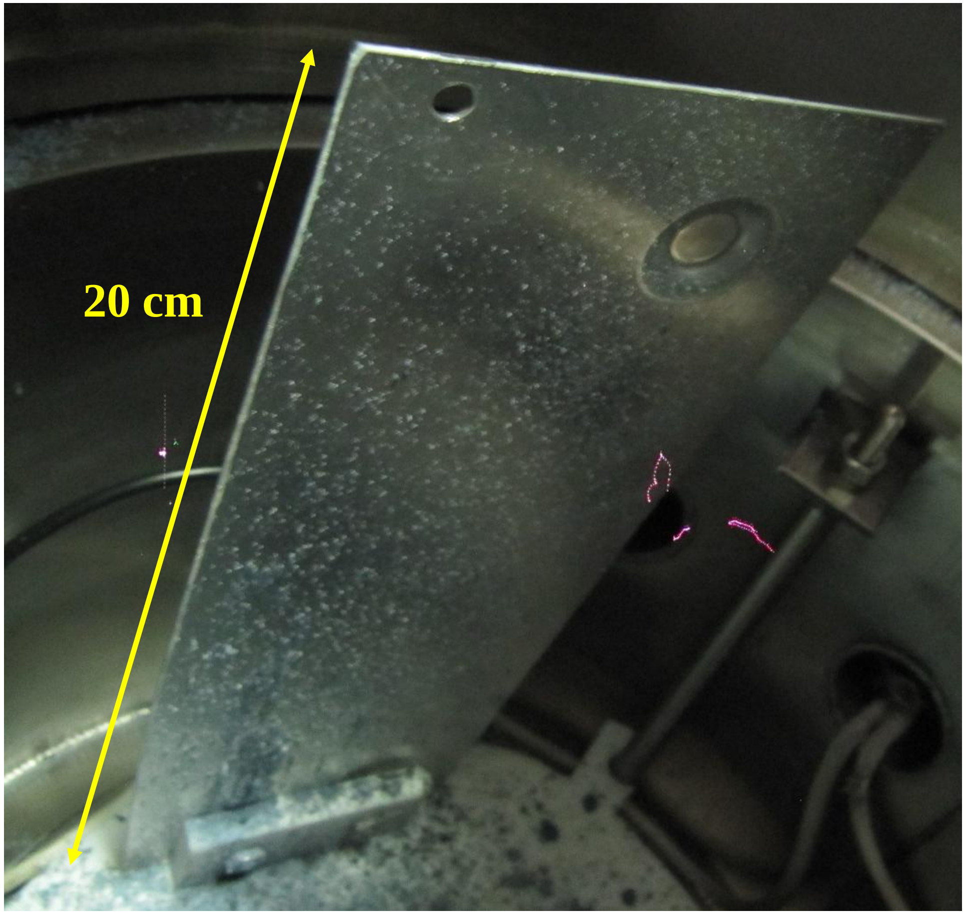




# Spray

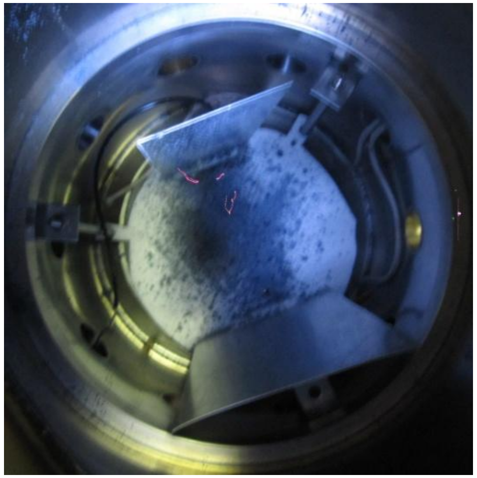
# Biasing of the plates

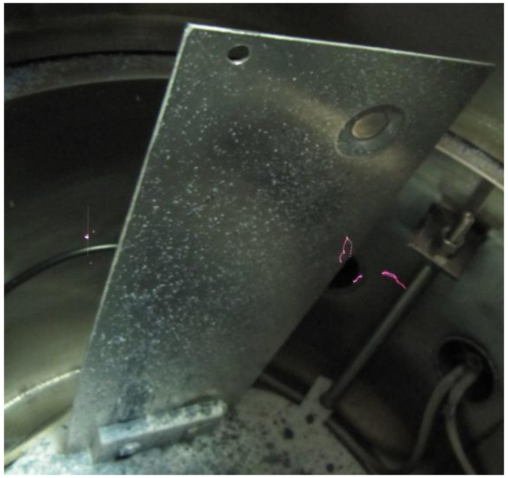


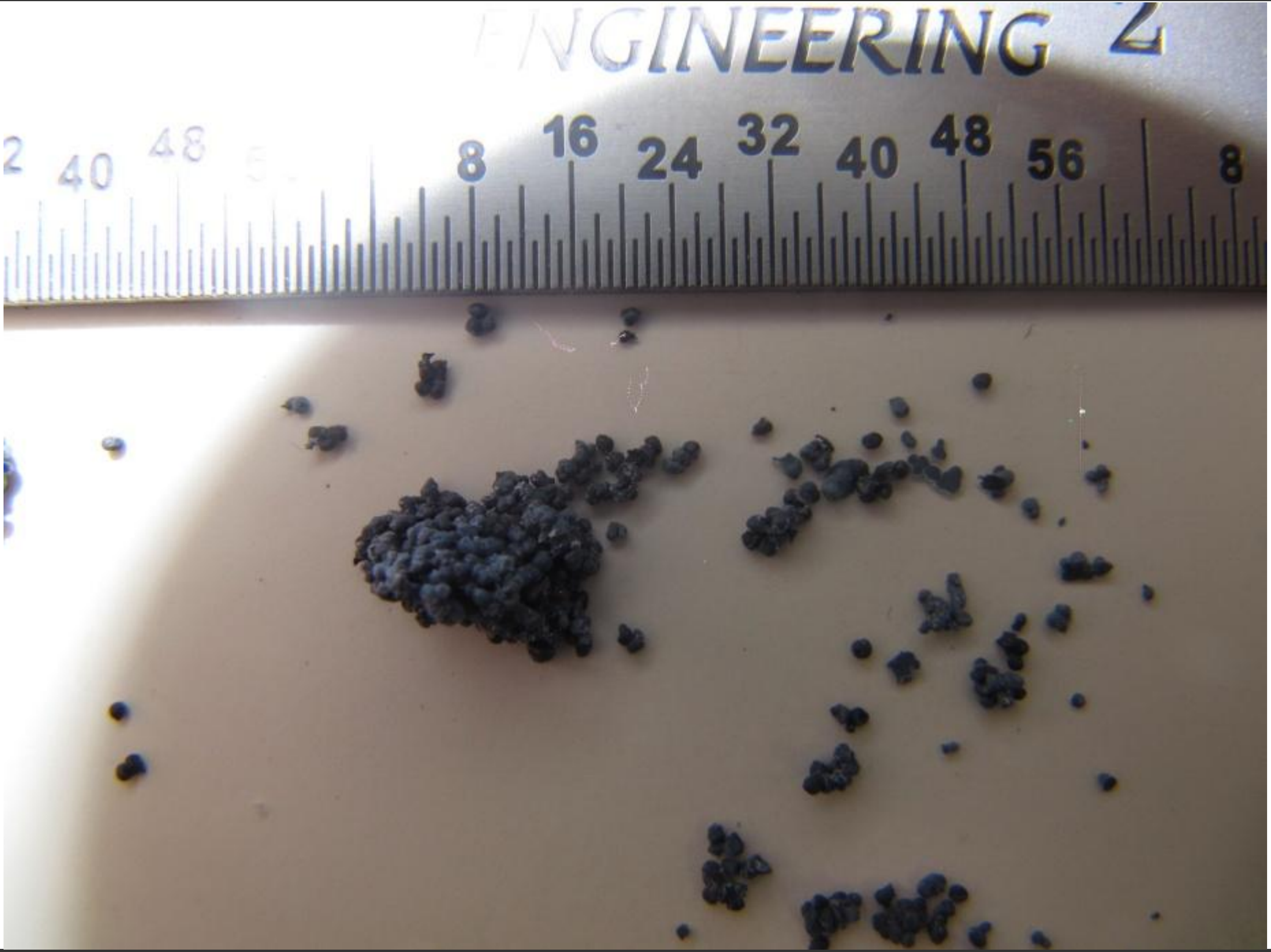
# Summary – EliI & Spray

- Proof of concept experiments:
  - As the voltage is increased
    - droplets seem to decrease.
    - As droplet charges up, breaks up and a spray develops.
  - Voltage switched off:
    - Droplet size grew and no spray observed.
  - Biasing of the plates shows that the droplets are attracted to the –ve side
    - More evidence for charging
- Modeling:
  - Biasing of target PFC can effectively "Paint" them.
    - NSTX center-stack biased up to *V*=2.5 kV, can easily be covered by ELiI
- Conclusions of initial results:
  - Electrostatic Lithium Injector **is a very real possibility** as a way to cover a fusion machines PFC with lithium.



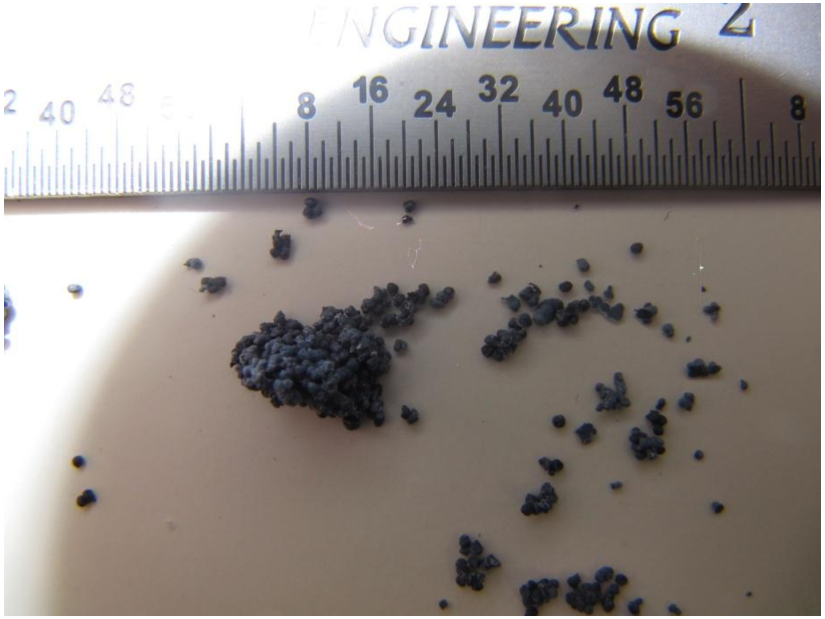


# Droplets



# Droplets

- Parameters:
  - Li temperature $T_{Li} \approx 220$ °C
  - Backing pressure $P_o = 3.5$ atm
  - Initial velocity measured $v \approx 60$ cm/s
- The particles that sprayed out collected on the wall and plates.
- The particles were quite small:
  - D ≈ 50 μm -1000 μm




**Above:** Lithium particles that have deposited on the wall of vacuum vessel.

**Left:** Some examples of the sprayed particles from ELiI.

# 4. Conclusion and Future Work



- An Electrostatic Lithium Injector has started to be developed
  - Based on the Electro-Spray Concept
  - Envisaged to be used to cover the center-stack of NSTX
- Initial modeling shows that the concept can indeed work within the parameters of NSTX biasing and design of ELiI
  - Sweeping Voltage can **“Paint”** the center Stack
- Initial results show that a droplet and spray can be produced.
  - A spray is initiated as it passes through a ring that is grounded w.r.t. the tube
    - Droplet formation could also produce a powder of lithium
- **Future work**
  - Produce a more robust design
  - Base the orifice on an optimized Taylor Cone
  - Biasing of components to show the spray is being deflected by an E-field

**References**

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**3. R. Pfeifer & C. Hendricks, *Phys. Of Fluids*, Vol. 10, No 10, 2149-2154, 1967.**

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**5. K. A. Yakimovich & A. G. Mozgovoi, *High Temperature*, Vol. 38, No. 4, pp 657-659, 2000**