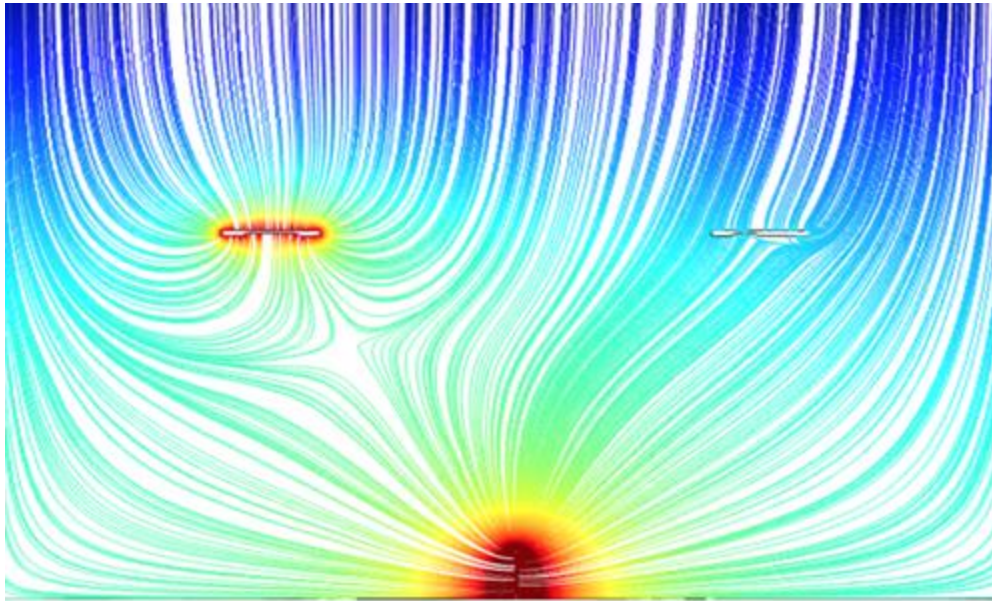
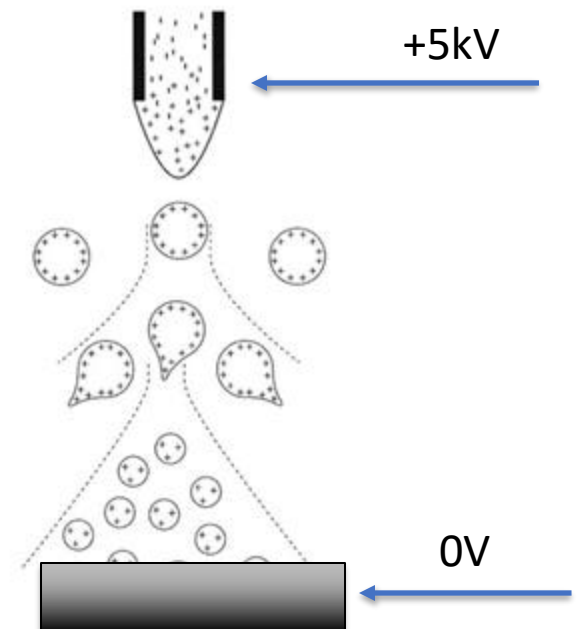
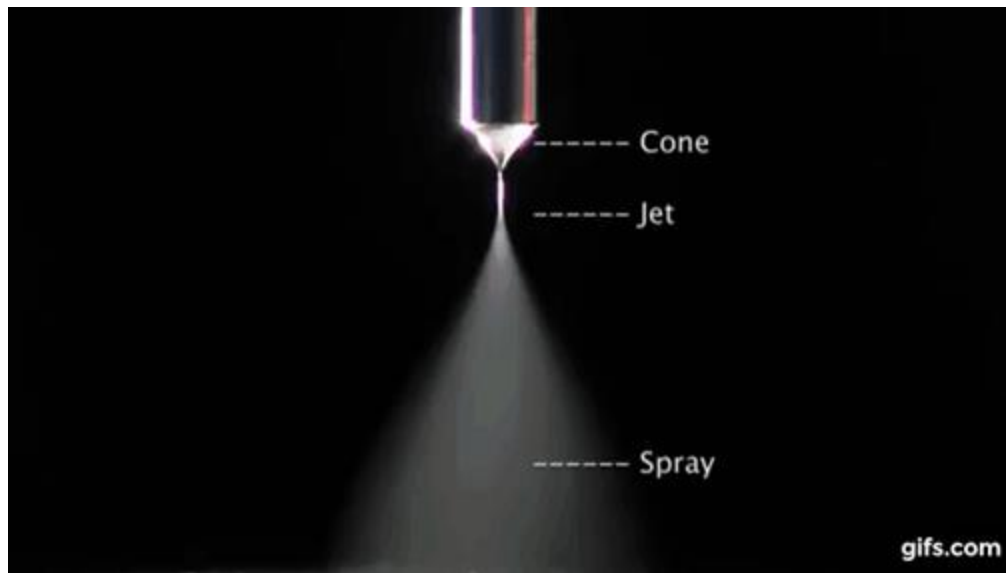


Electrohydrodynamic Control Systems for Nanomanufacturing



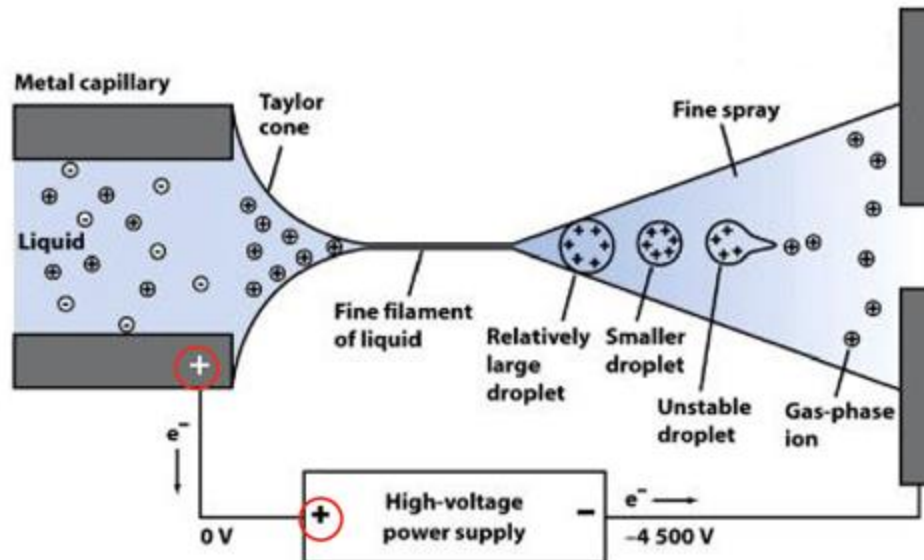
Electrospray Ionization

- **Electrospray ionization occurs when:**
 - a strong electric field is applied in the vicinity of a liquid
 - enough charge accumulates on the surface of a liquid to overcome the surface tension



Destabilization at the surface

- **Destabilization at the surface occurs when:**
 - enough *charge accumulates in a small region of the liquid to overcome the surface tension*
 - the solvent evaporates (volume abruptly decreasing)
- The liquid elongates into a “Taylor cone” and an aerosol spray of positively charged droplets is formed



Rayleigh Limit of a Charged Droplet

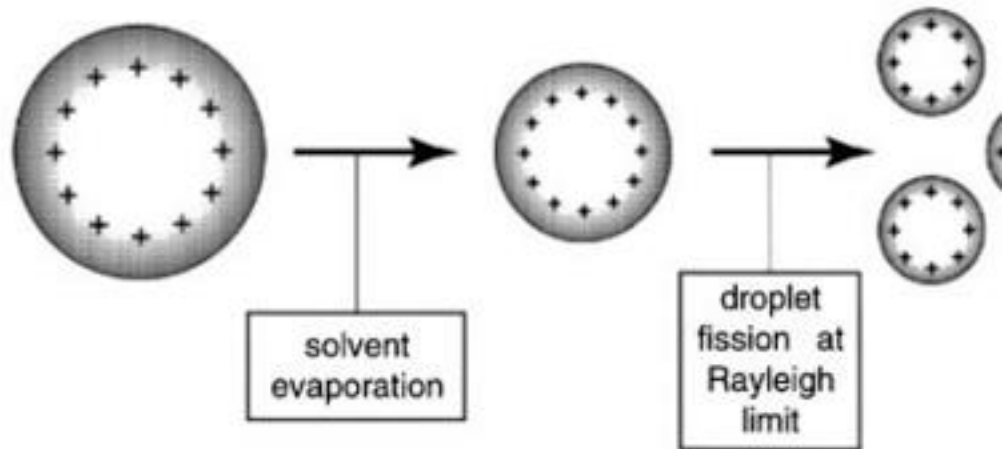
- In 1882, Lord **Rayleigh** published on stability **limits** of electrically **charged liquid** droplets
- Maximum amount of charge a droplet may hold before Coulomb Fission occurs ([Rayleigh limit](#) (Q_{ray}):

$$Q_{ray} = 8\pi\sqrt{\alpha\epsilon_0}r_d^3$$

α = surface tension

ϵ_0 permittivity of free space

r_d = radius of droplet



Coulomb Fission

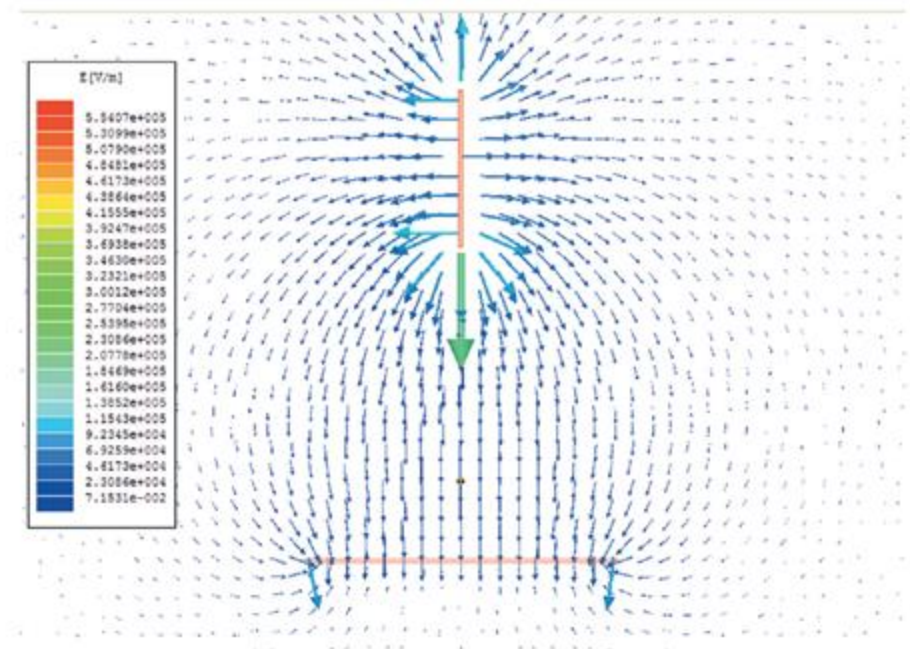
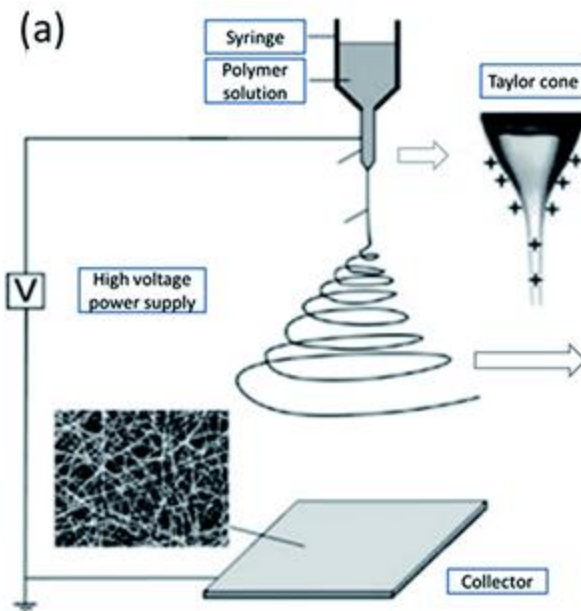
- Coulomb fission: droplet explosions due to evaporation and pressure (droplet radius decreases) while surface charges get closer (electrostatic repulsion breaks the surface tension)
- During fission, the droplet loses a small percentage of its mass (1.0–2.3%) along with a relatively large percentage of its charge (10–18%)
- Bernoulli's principle due to increasing velocities



What is Electrospinning?

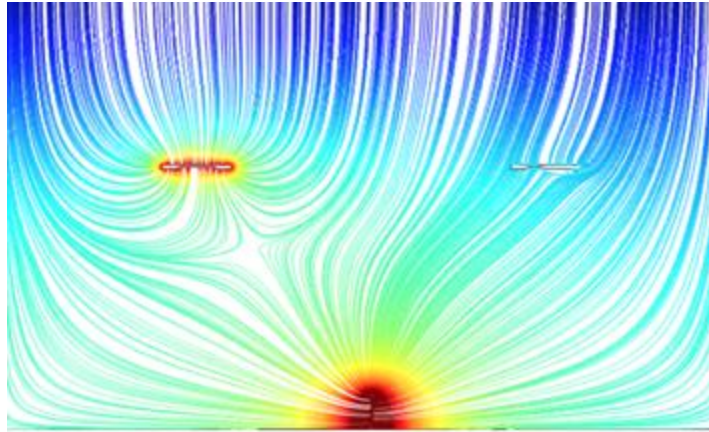
Decrease the electric field or increase the viscosity ...

- Electrohydrodynamic & viscoelastic process
Easy to produce nanofibers
- Jet solidifies during trajectory
- Variable rheological properties
- **Random deposition**



Idea: Deflect the Charged Jet

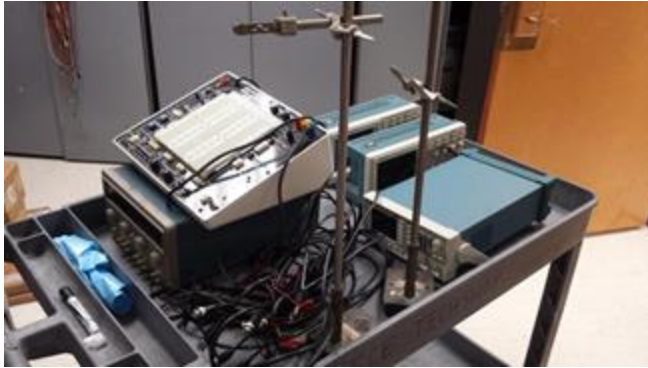
- Grounded intermediate electrode attracts jet
- Positive intermediate electrodes deflect jet



- Several intermediate electrodes
- Electric lensing decreases spot size



Is this Possible with Current Resources?

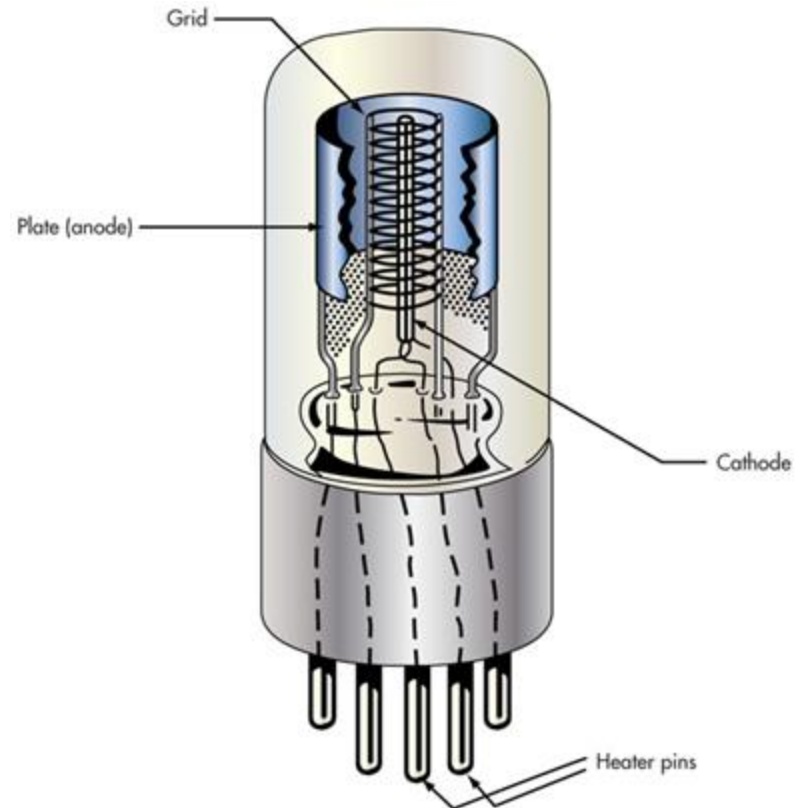


Not sure how to build a tube circuit?

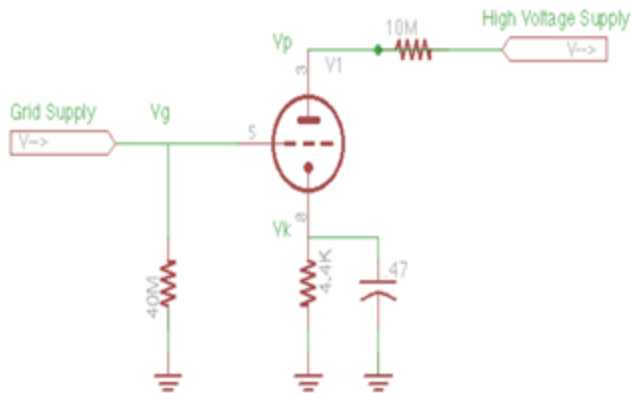
- Go to the library annex
- Read books from the 1940s

Will need:

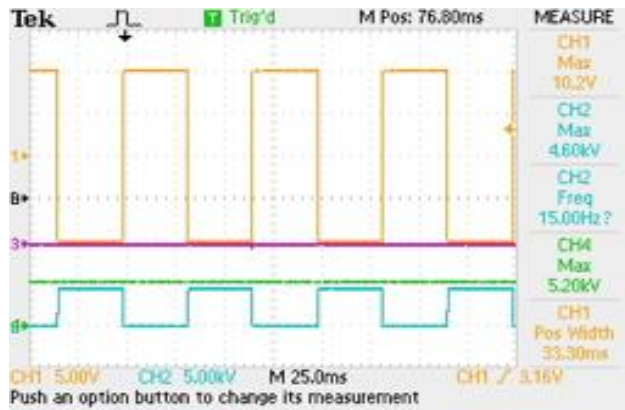
- Vacuum tubes
- Function generators
- Oscilloscope
- High voltage probes
- High voltage power supplies
- Copper
- Miscellaneous electronics/wiring
- Syringe pump
- Teflon/HDPE/Nylon stock



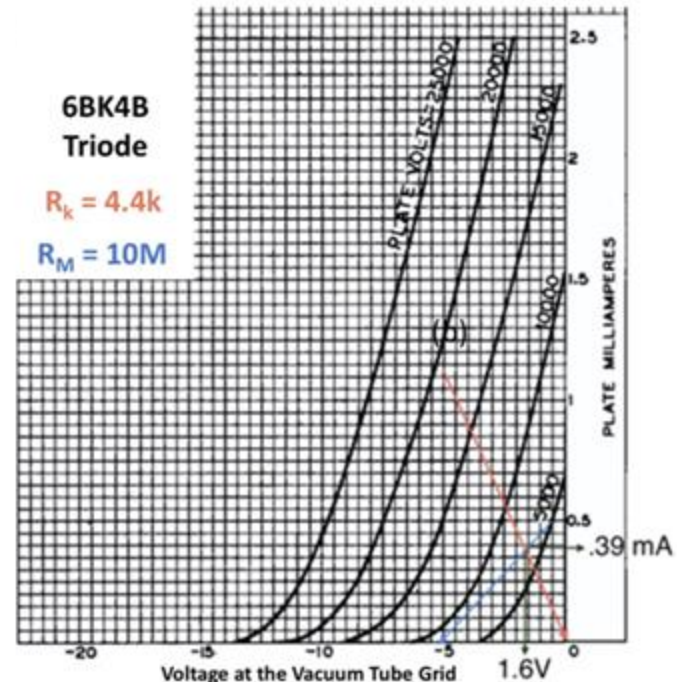
Switching High Voltage



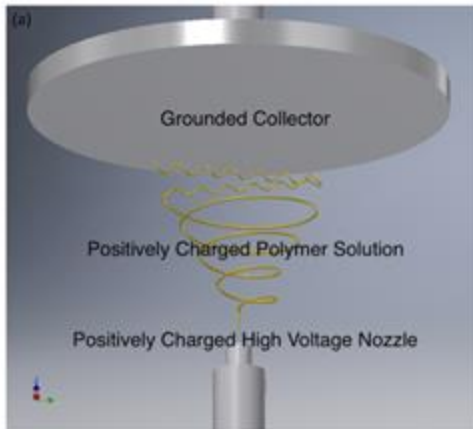
- Choose circuit components based on amplifier requirements and power supply ratings



- Drawing the load lines for quiescent conditions using the transfer characteristic curves
- Common-cathode configuration: high input impedance, medium-to-low output impedance, relatively high gain, good frequency response*

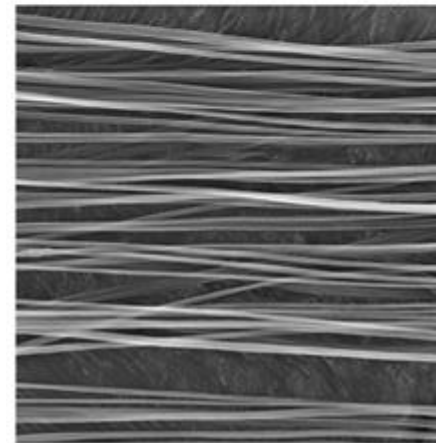
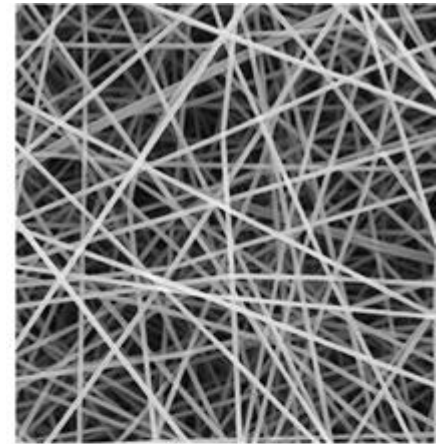


CAD + Simulations to Understand & Automate the Electrohydrodynamic Deflection Process



Goals:

- Test current mathematical models
- Control deposition
- Develop feedback control data

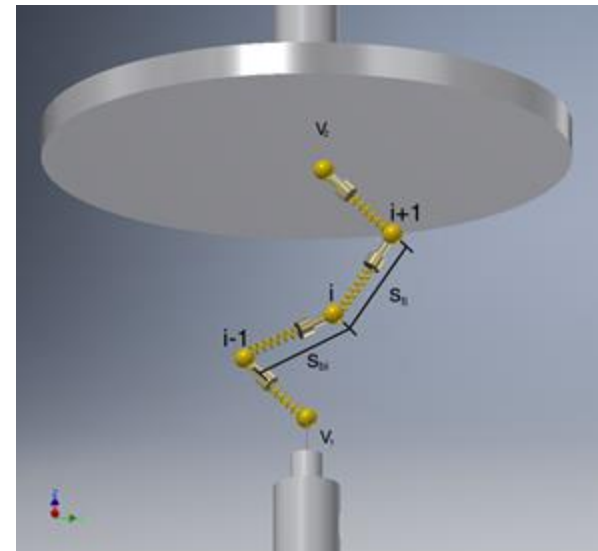
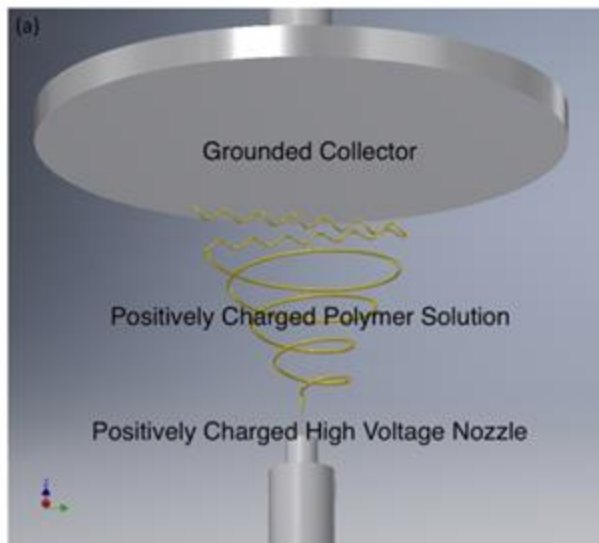


Space Charge Effects

- $$\vec{F}_{coulomb_i} = k_e \sum_{j=1, j \neq i}^N \frac{q_i q_j}{R_{ij}^2} \left[\frac{(x_i - x_j)}{R_{ij}} \hat{e}_x + \frac{(y_i - y_j)}{R_{ij}} \hat{e}_y + \frac{(z_i - z_z)}{R_{ij}} \hat{e}_z \right],$$

where N is the number of beads in the system, x_i, y_i, z_i and x_j, y_j, z_j , are the current positions of each corresponding element, which promotes each j^{th} effect on the i^{th} charge, and R_{ij} is the distance between them (note that $i \neq j$):

- $$R_{ij} = [(x_i - x_j)^2 + (y_i - y_j)^2 + (z_i - z_j)^2]^{\frac{1}{2}}.$$



Viscous & Elastic Effects

$$\bullet \vec{F}_{viscoelastic_i} = \vec{F}_{fi} - \vec{F}_{bi},$$

$$\vec{F}_{bi} = \pi a_{bi}^2 \sigma_{bi} \left[\frac{(x_i - x_j)}{s_{bi}} \hat{e}_x + \frac{(y_i - y_j)}{s_{bi}} \hat{e}_y + \frac{(z_i - z_j)}{s_{bi}} \hat{e}_z \right].$$

- a_{bi} = cross sectional radius between i & $i-1$
- σ_{bi} = longitudinal stress pulling m_i backward

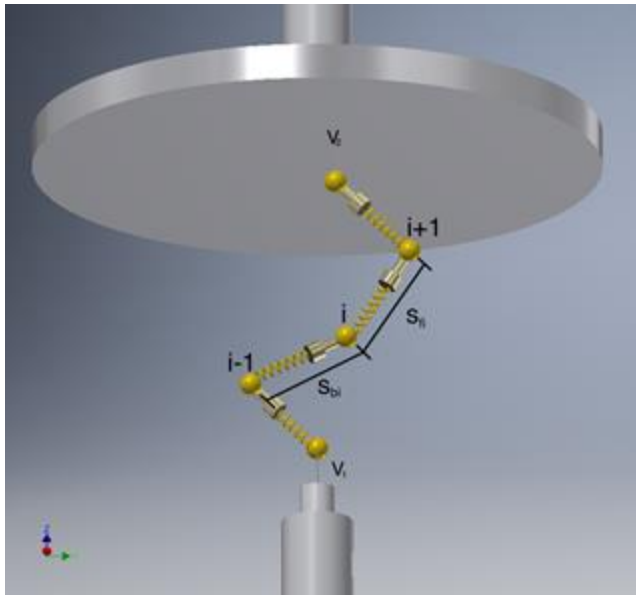
$$s_{bi} = [(x_{i-1} - x_i)^2 + (y_{i-1} - y_i)^2 + (z_{i-1} - z_i)^2]^{\frac{1}{2}}.$$

$$\frac{d\sigma_{bi}}{dt} = G \frac{1}{s_{bi}} \frac{ds_{bi}}{dt} - \frac{G}{\mu} \sigma_{bi},$$

- G = Elastic modulus (vary in time)
- μ = viscosity (vary in time)

$$\pi a_{bi}^2 s_{bi} = \pi a_0^2 L.$$

- L = Initial filament Length
- a_0 = Initial filament cross sectional radius

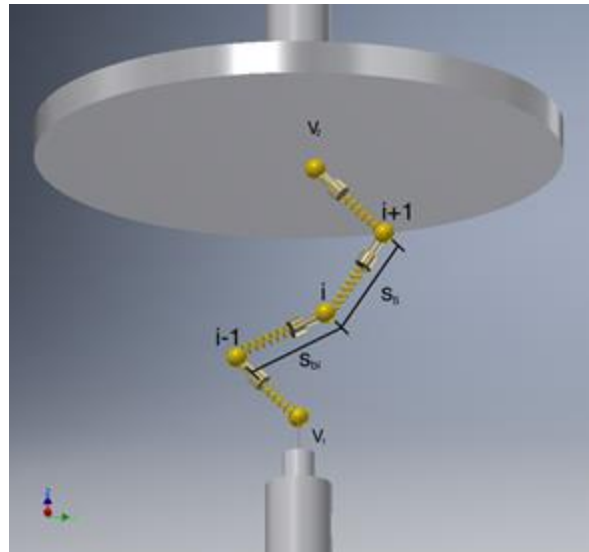


Surface Tension

$$\vec{F}_{tension_i} = -\alpha \pi a_{average}^2 k_i \hat{p}_i,$$

where α is the surface tension coefficient, k_i is the curvature of the jet with respect to the coordinates of m_{i-1} , m_i , and m_{i+1} , \hat{p}_i is a unit vector from the i^{th} element toward the center of curvature (with respect to $i+1$ and $i-1$), and the average radius, $a_{average}$, at the i^{th} element is given by,

$$a_{average} = \frac{a_{fi} + a_{bi}}{2}$$



Simulations Require Rheological Measurements

- Using FSAD's Advanced Rheometer 200 & KSV Sigma 701 Instruments

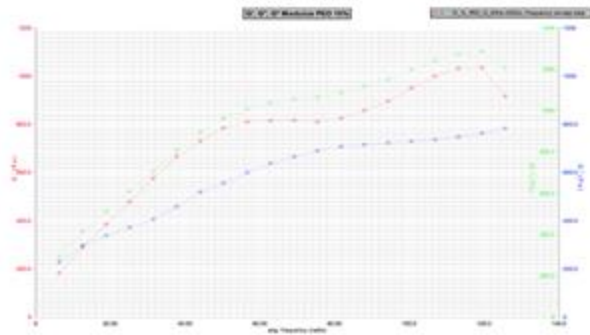


Figure 14: This image shows measurements of the elastic modulus (G') of PEO 10% using a frequency sweep from 1 to 10Hz, with 20 sample points, at 25°C with a strain percentage of .6% using an Advanced Rheometer AR 2000.

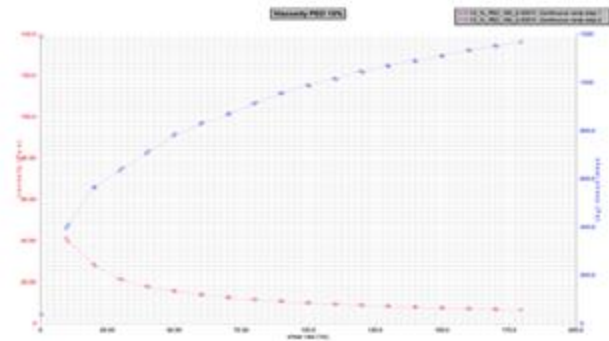


Figure 13: This image shows viscosity measurements of a 10% (w/w) mixture of deionized (DI) water and Polyethylene Oxide (PEO), with a molecular weight of $M_w = 600,000$, at 20°C over 4 minute intervals at shear rates ranging between $(0 - 180) \frac{1}{s}$ using an Advanced Rheometer AR 2000.

Measured Parameters for PEO 10%		
Variable	Definition	Value
μ	Viscosity	$4 - 42 \text{ Pa} \cdot \text{s}$
α	Surface Tension	$30.95 \frac{\text{m} \cdot \text{N}}{\text{m}}$
G	Elastic Modulus	$190 - 1020 \text{ Pa}$
ρ	Mass Density	$1.02 \frac{\text{g}}{\text{cm}^3}$

New Algorithm

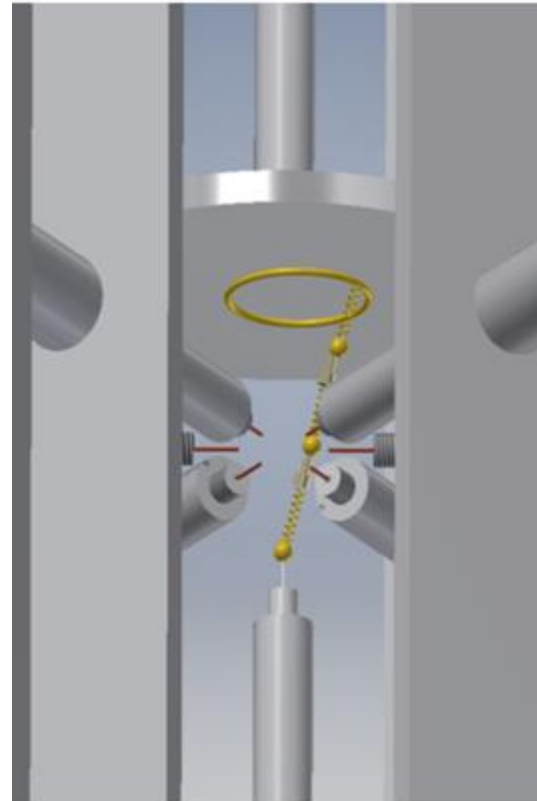
$$\bullet m_i \frac{d^2 \vec{r}_i}{dt^2} = \vec{F}_{external_i} + \vec{F}_{coulomb_i} + \vec{F}_{viscoelastic_i} + \vec{F}_{tension_i}$$

$$\hat{r}_i = x_i \hat{e}_x + y_i \hat{e}_y + z_i \hat{e}_z.$$

$$\vec{F}_{external_i} = q_i \vec{E}_i,$$

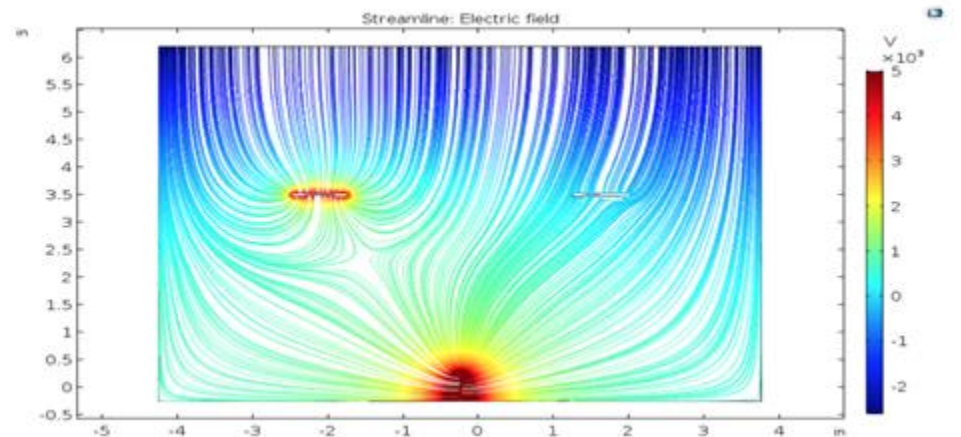
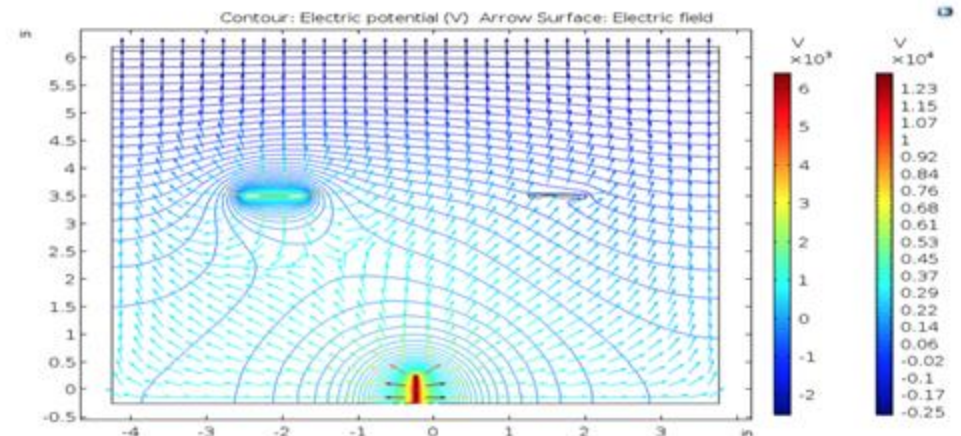
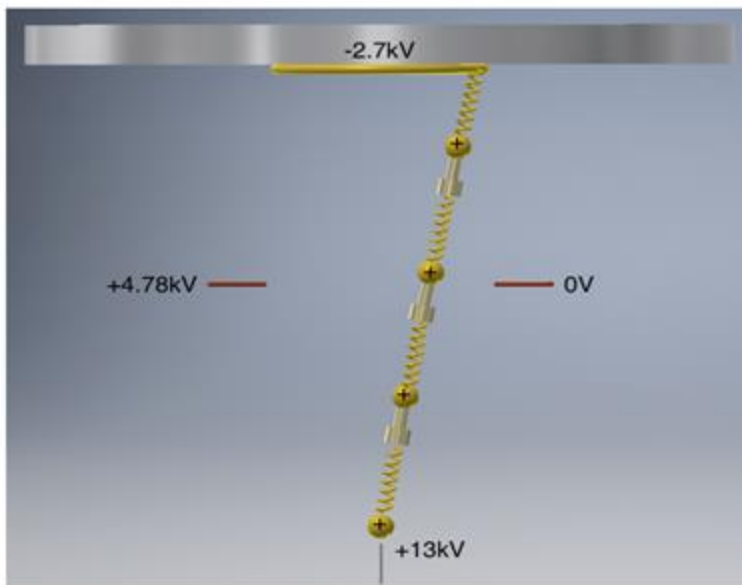


Must be more specific to
electrode architecture
and relative distances



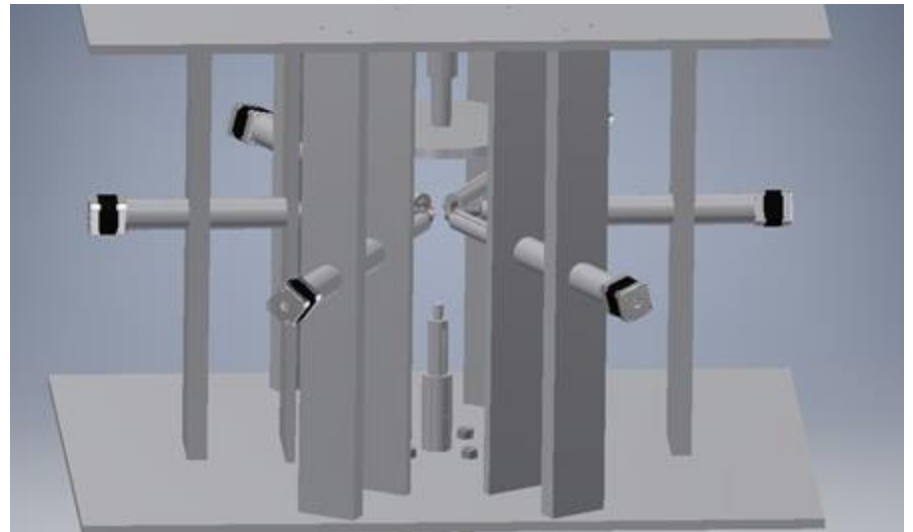
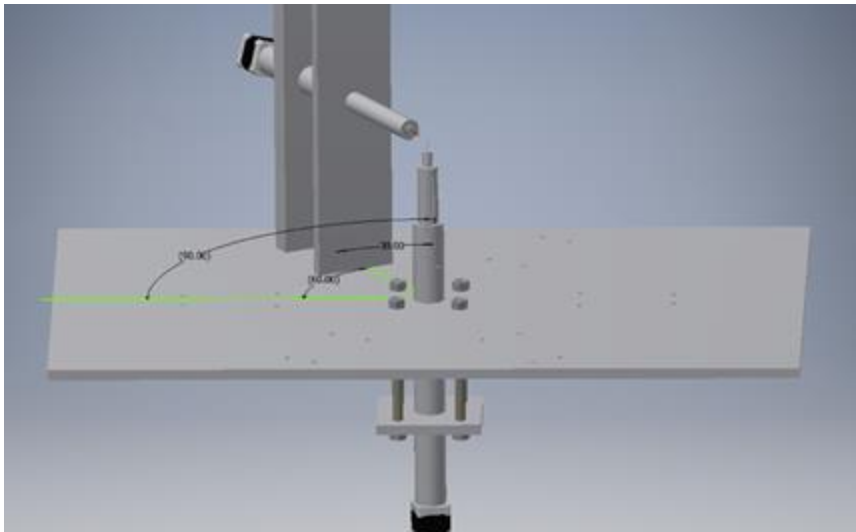
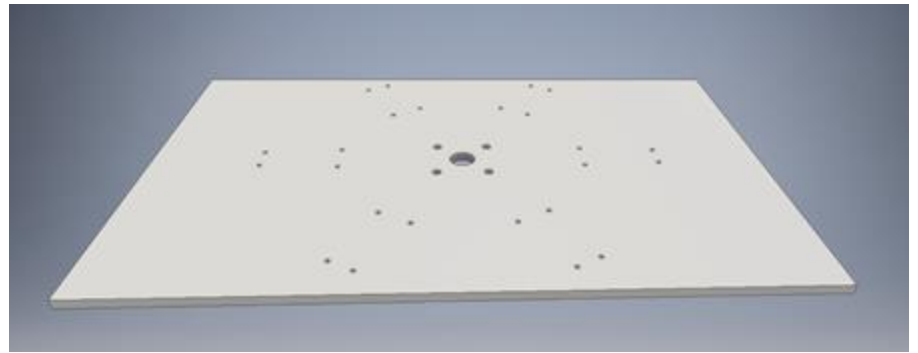
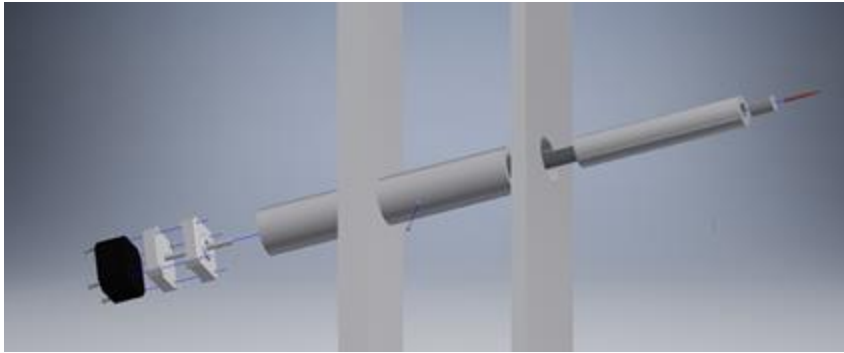
Importing CAD models into Comsol

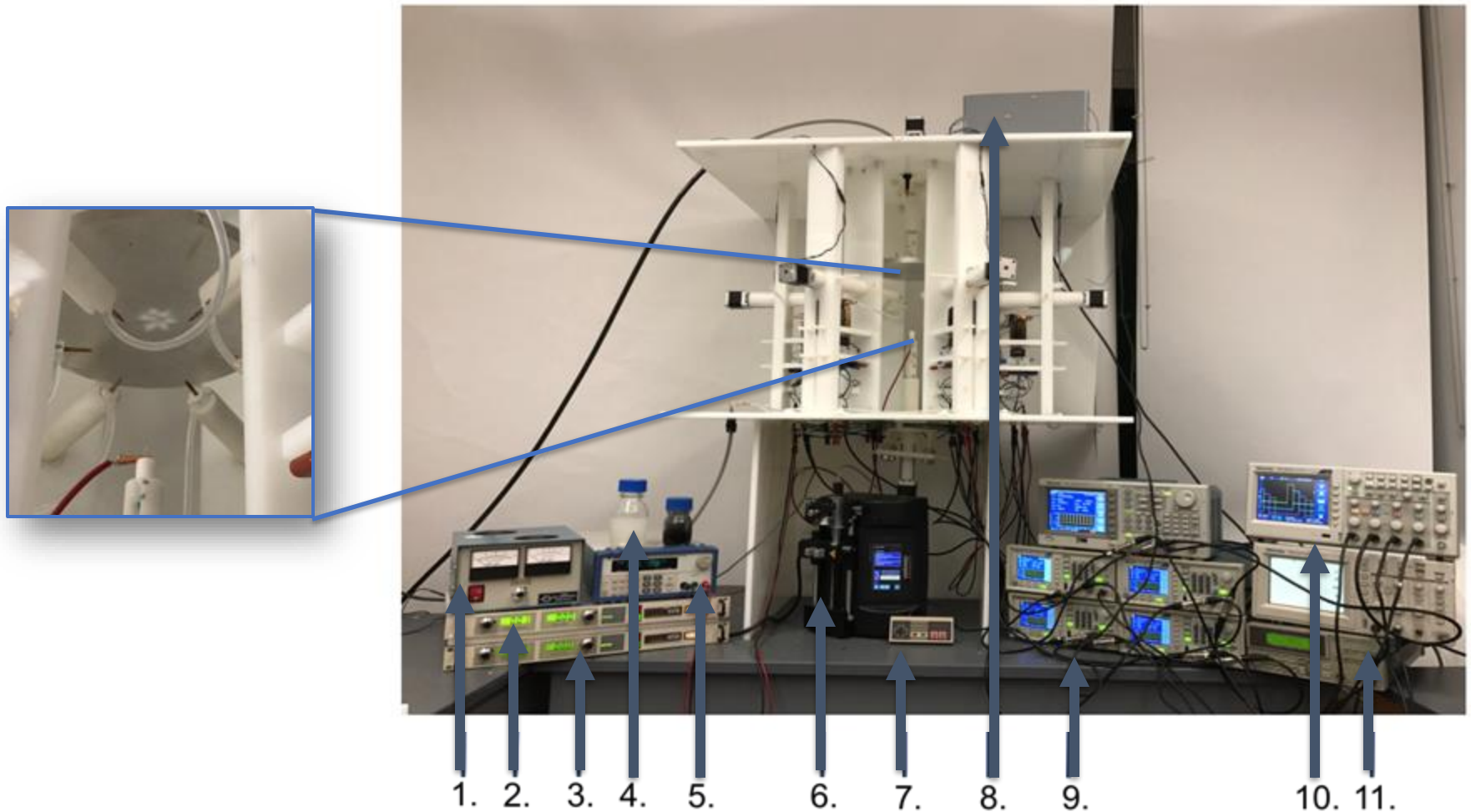
- Cross sectional analysis of 3D electrode architecture



More CAD -> Machine Shop

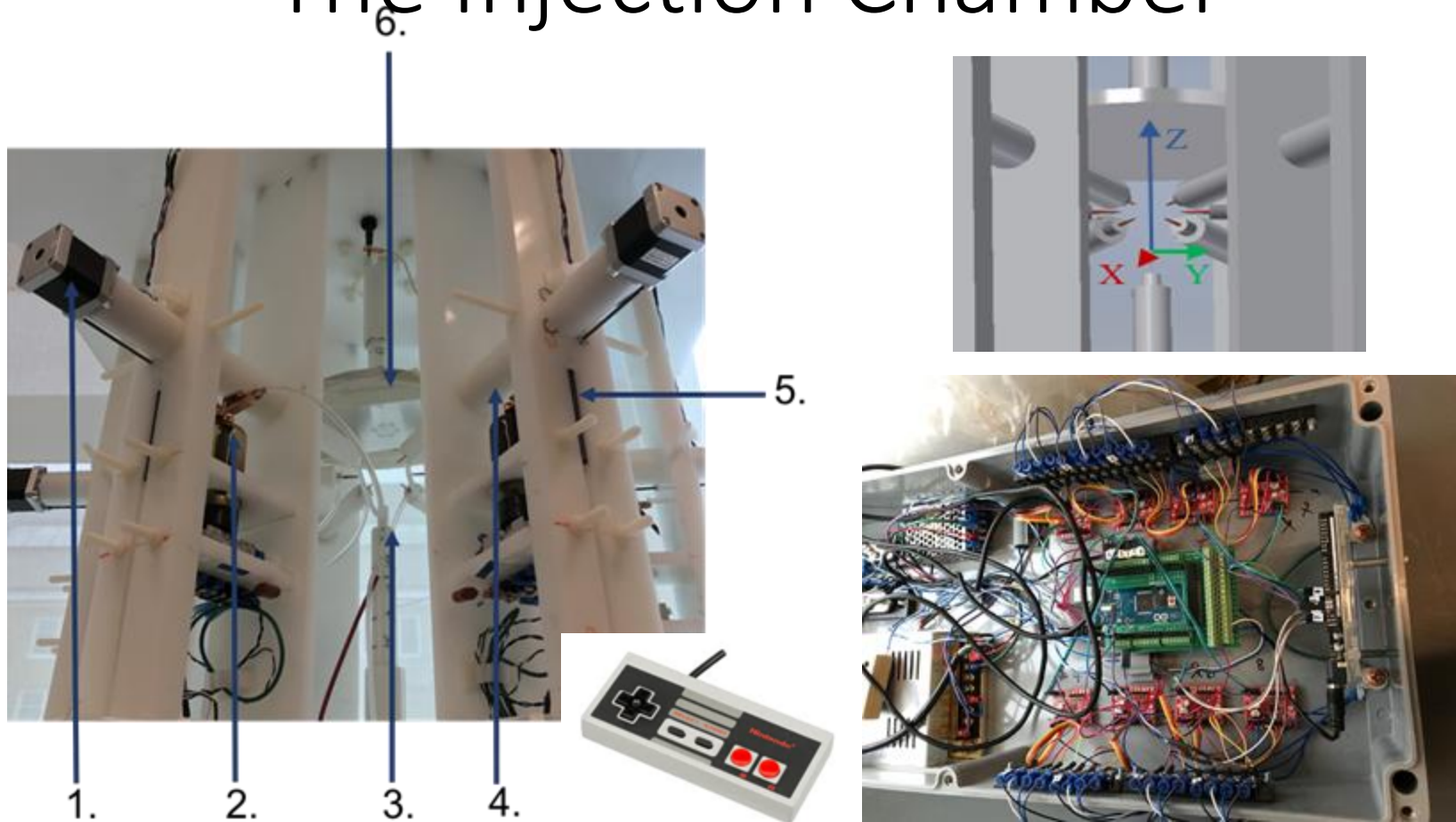
- HDPE, Nylon, Delrin, & Teflon to insulate v_{cc} from high voltage





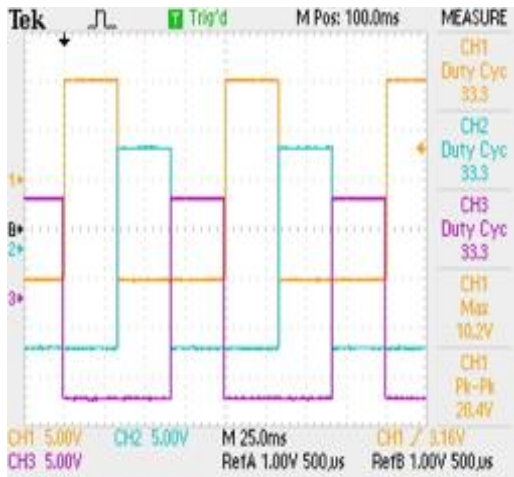
1. High voltage power supply (0-30kV, 0-200 μ A); **2.** High Voltage DC power supply (0V-15kV, 0-10mA); **3.** Negative High Voltage DC power supply (0 to -40kV, 0-7.5mA); **4.** Polymer solution (PEO & PEO + Carbon Black. **5.** Precision DC power supply (0-60V, 2.5A); **6.** Syringe pump 70-3005 with $\pm 0.25\%$ accuracy; **7.** Nintendo controller; **8.** Electronic controls for stepper motors; **9.** Function generators; **10.** Oscilloscopes; **11.** 10MHz reference clock sign

The Injection Chamber



(Left) The injection chamber, which includes: **1.** Stepper motor; **2.** Vacuum tube amplifier; **3.** Syringe needle/driving mechanism; **4.** Electrode driving mechanism; **5.** 10M resistor; **6.** Collector ($\frac{1}{2}$ " thick, 6061 8" diameter Aluminum plate)

Guiding the Nanofiber in 2-D



Drawing a Triangle:

- $f = 10\text{Hz}$ pulses, $D_N = 33.3\%$ duty cycle. The 2nd and 3rd pulses are $\phi_2 = 33.3\text{ms}$ and $\phi_3 = 66.6\text{ms}$, out of phase from ϕ_1 , respectively.



Determining Phases:

$$\phi_n = \frac{D_N (n - 1)}{f \cdot 100}$$

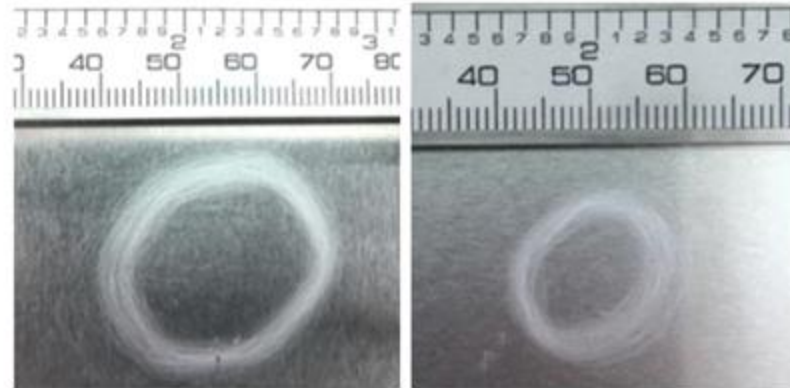
$$D_N = \frac{1}{N} (100)$$

Printing a Star

Printing a Hexagon

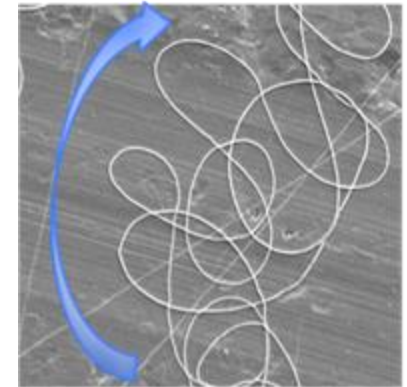
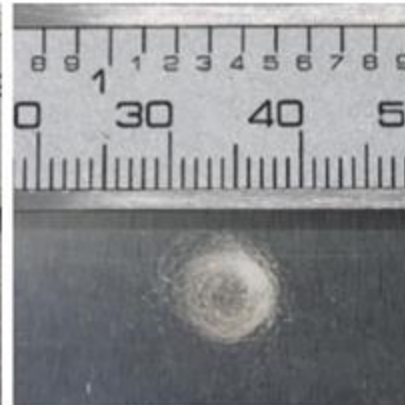
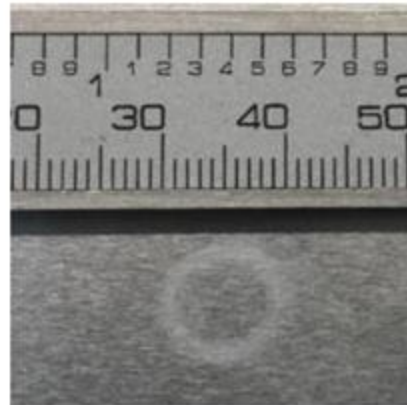
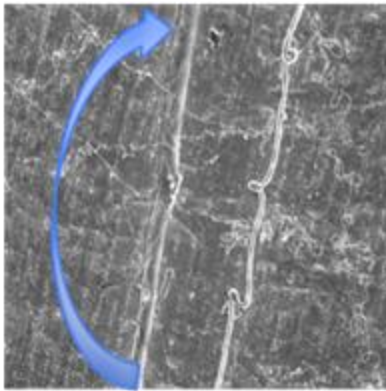


Voltage and Distance Dependence



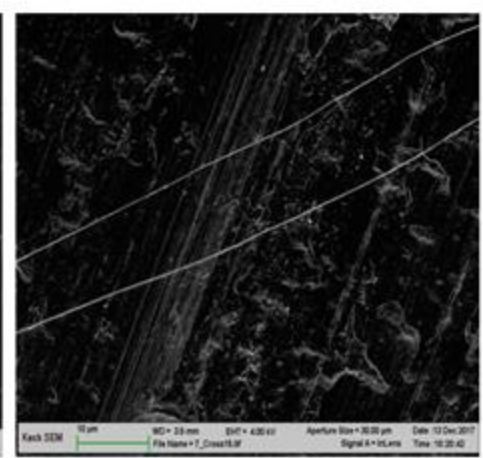
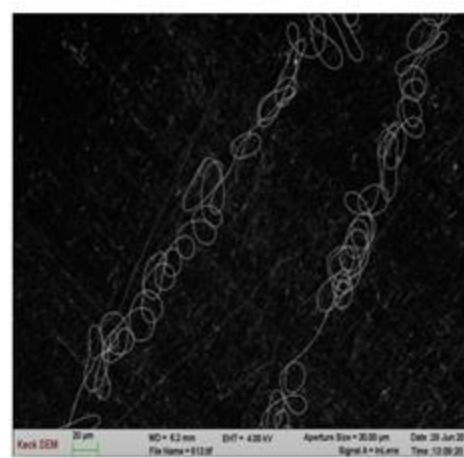
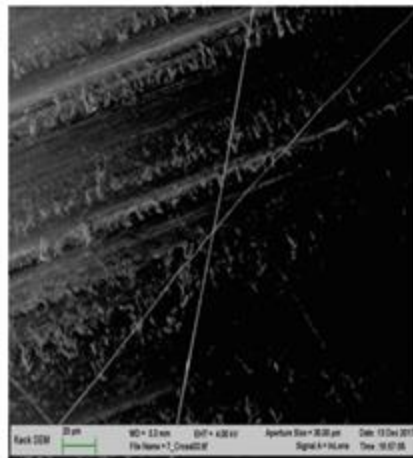
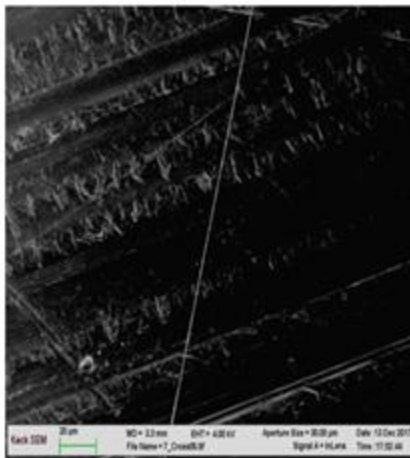
PEO 10%	$\frac{\Delta V}{\Delta Z}$ Dependency	
Frequency (f)	15Hz	15Hz
Nozzle Position from Origin (Z_N)	-76.2mm	-114.3mm
Collector Position from Origin (Z_C)	76.2mm	114.3mm
Nozzle Voltage (V_N)	13kV	13kV
Collector Voltage (V_C)	-2.6kV	-9.2kV
Intermediary-electrode Position from Z-axis	19.1mm	19.1mm
Deposition Diameter (D_{Dep})	$\sim 30mm$	$\sim 20mm$

Frequency Dependence



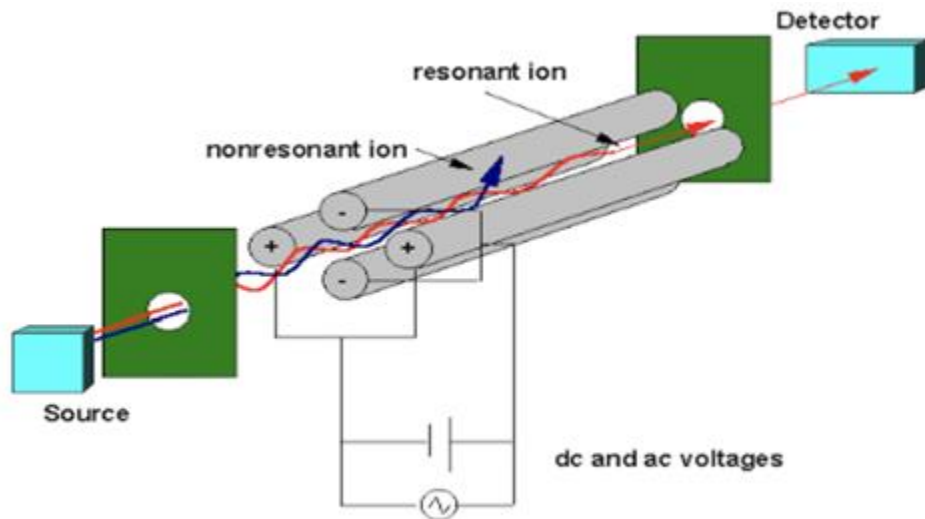
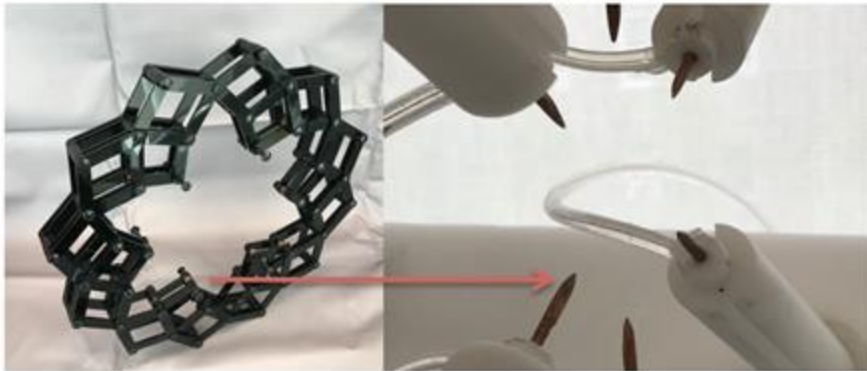
PEO 10%	f Dependency	
Electrode Pulsing Frequency (f)	30Hz	45Hz
Nozzle Position from origin (Z_N)	-114.3mm	-114.3mm
Collector Position from origin (Z_C)	57.2mm	57.2mm
Nozzle Voltage (V_N)	13kV	13kV
Collector Voltage (V_C)	-7kV	-7kV
Intermediary-electrode Position from z-axis	12.7mm	12.7mm
Deposition Diameter (D_{Dep})	$\sim 10mm$	$\sim 7.5mm$

Goal: 2D and 3D Print Aligned Nanofibrous Structures



Future Work: Actuated Quadrupole Mass Spectrometer

- Single point of actuation
- No need for calibration or motors



- Decrease spot size

