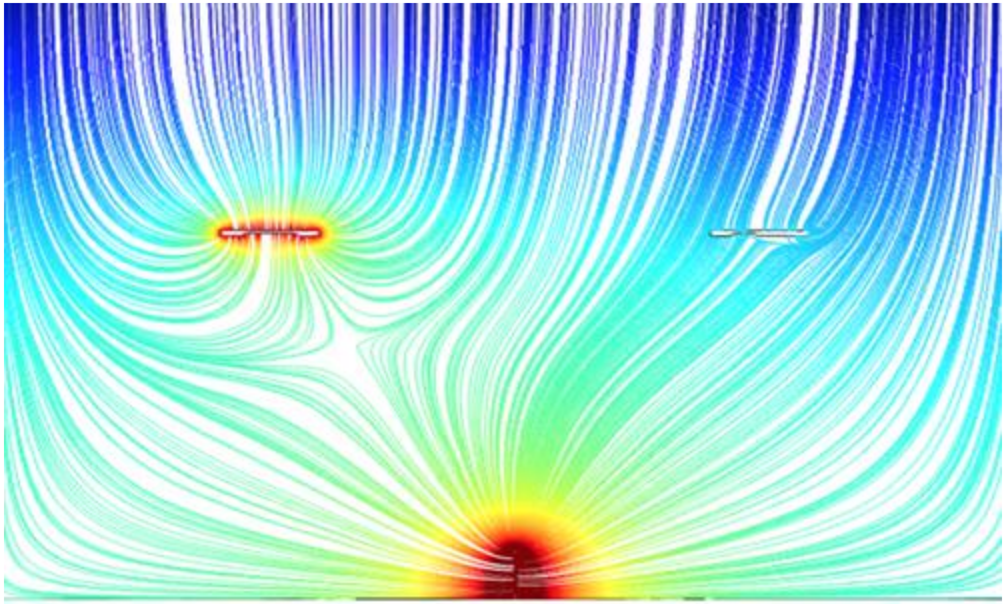
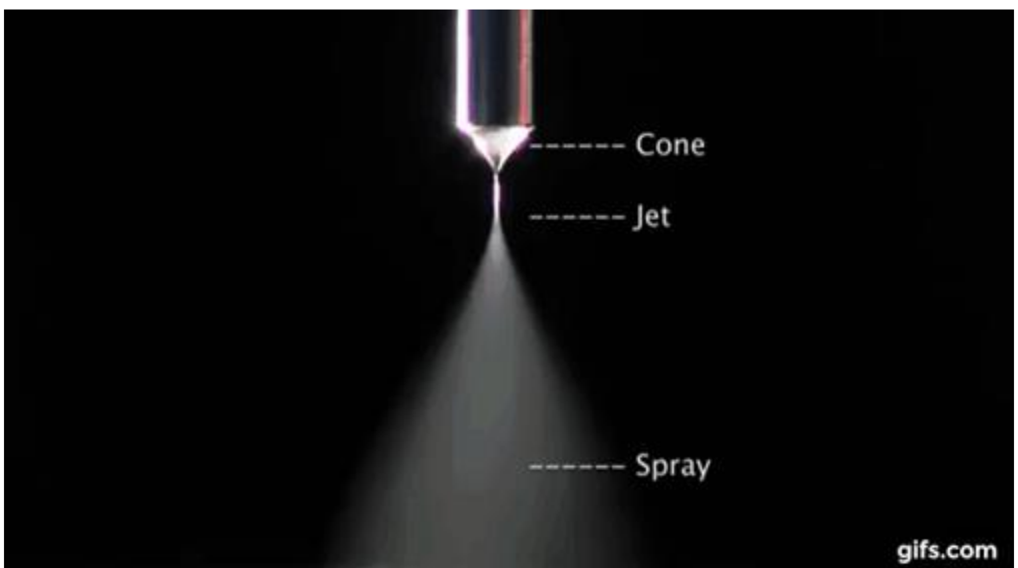
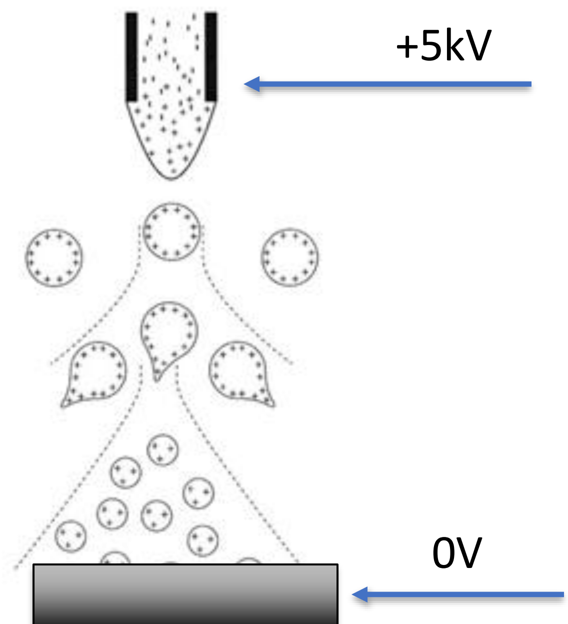
Electrohydrodynamic Control Systems for Nanomanufacturing



Electrospray Ionization

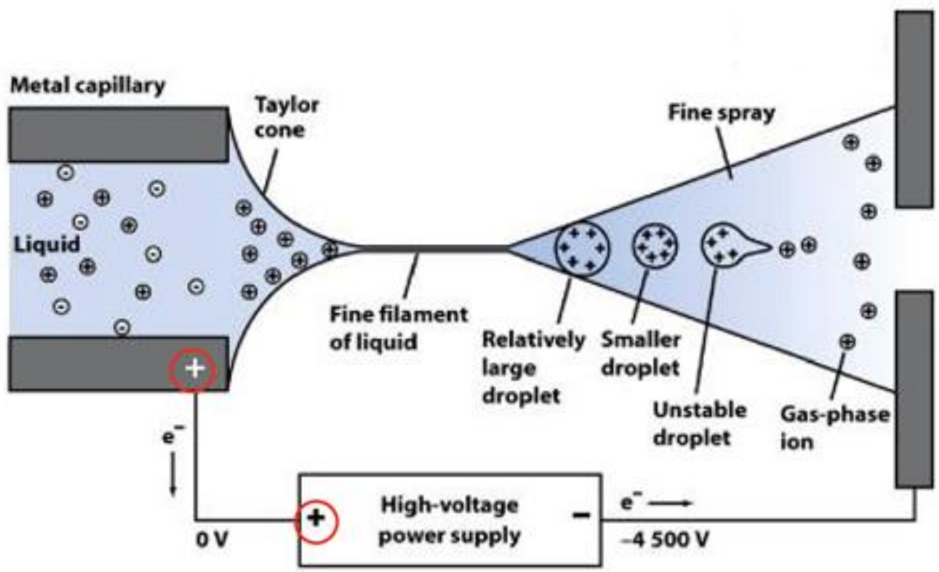
- **Electrospray ionization occurs when:**
  - a strong electric field is applied in the vicinity of a liquid
  - enough charge accumulates on the surface of a liquid to overcome the surface tension





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

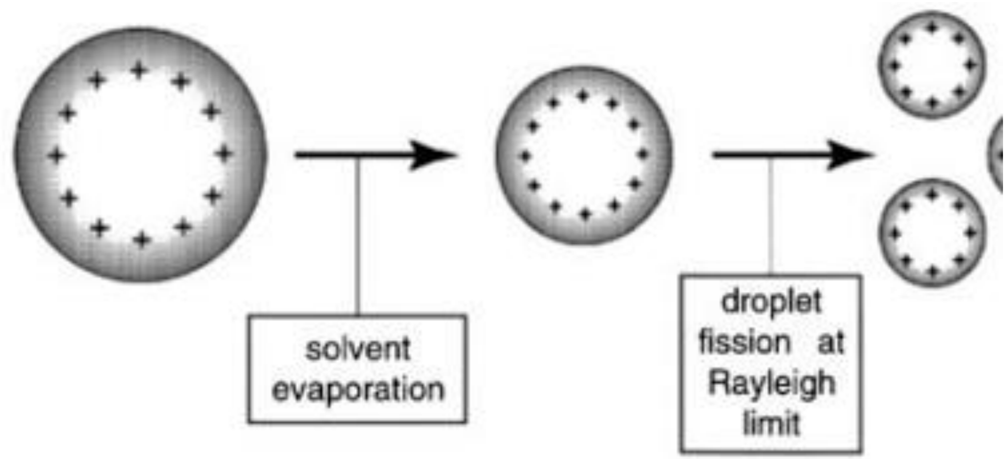


Rayleigh Limit of a Charged Droplet

- 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



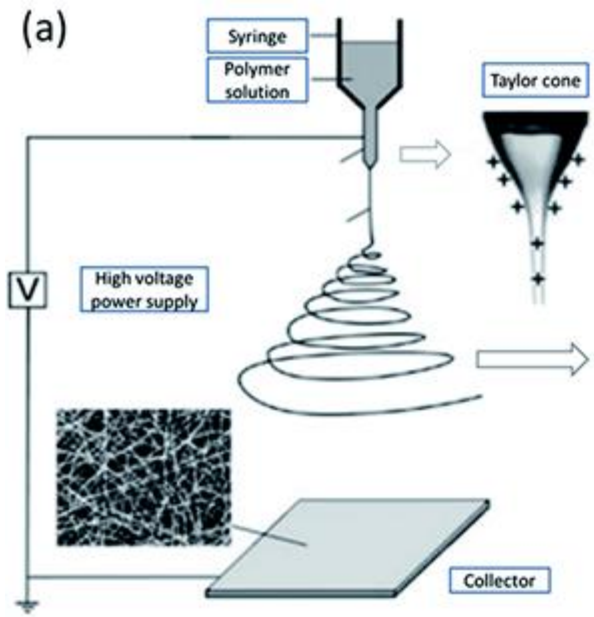
Coulomb Fission

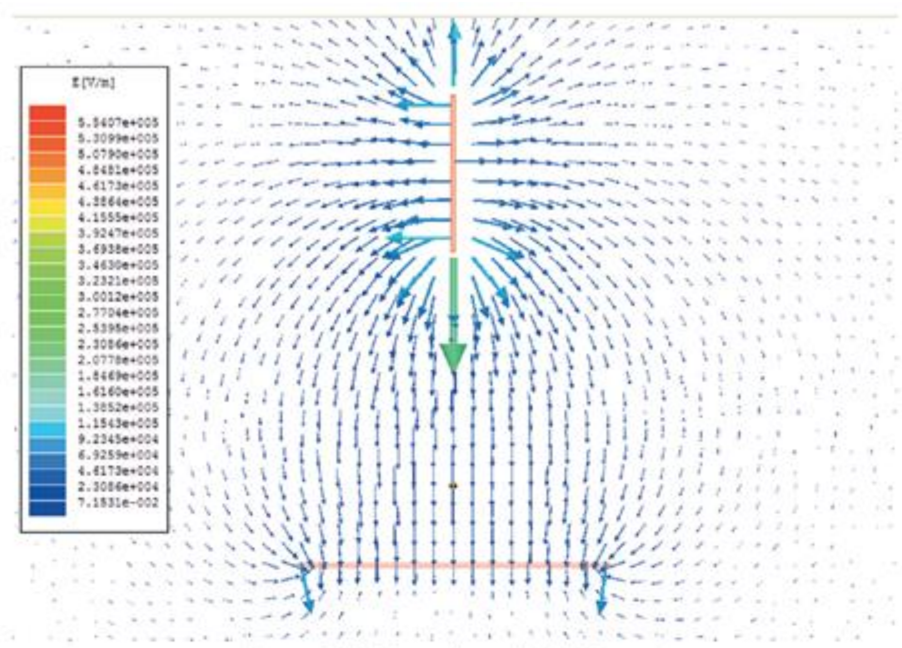
- Coulomb fission: droplet explosions due to evaporation and pressure (droplet radius decreases) while surface charges get closer (electrostatic repulsion breaks the surface tension)
- During fission, the droplet loses a small percentage of its mass (1.0–2.3%) along with a relatively large percentage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

What is Electrospinning?

Decrease the electric field or increase the viscosity …

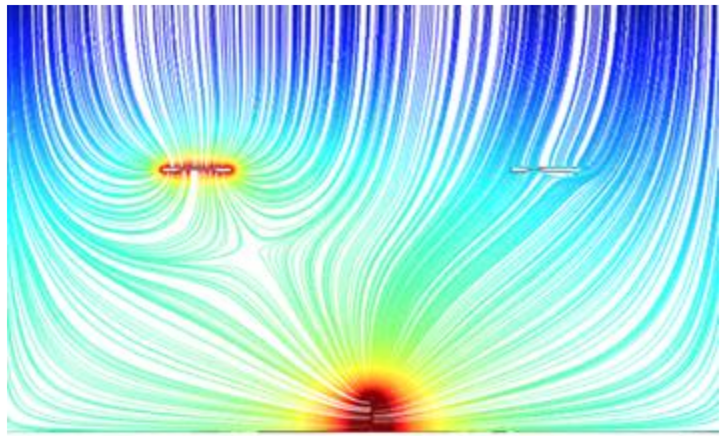
- Electrohydrodynamic & viscoelastic process
  Easy to produce nanofibers
- Jet solidifies during trajectory
- Variable rheological properties
- <u>**Random deposition**</u>





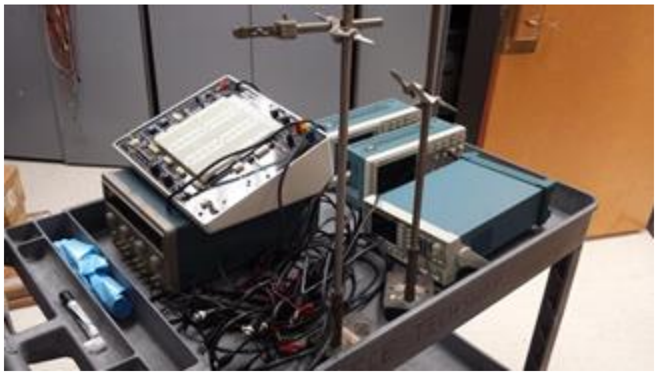
Idea: Deflect the Charged Jet

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



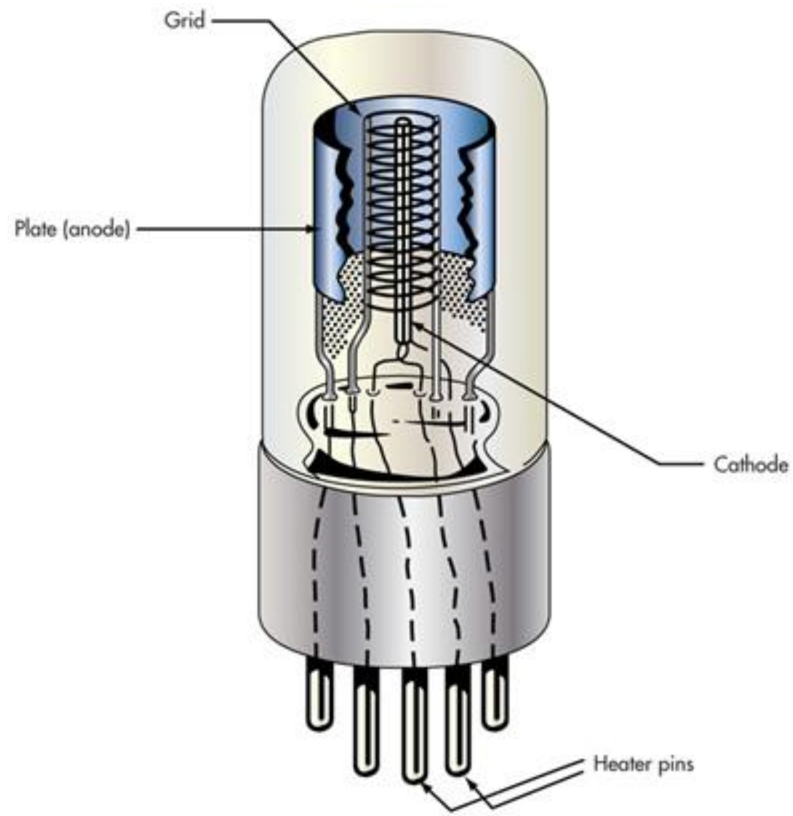
- Several intermediate electrodes
- Electric lensing decreases spot size

Is this Possible with Current Resources?



Not sure how to build a tube circuit?

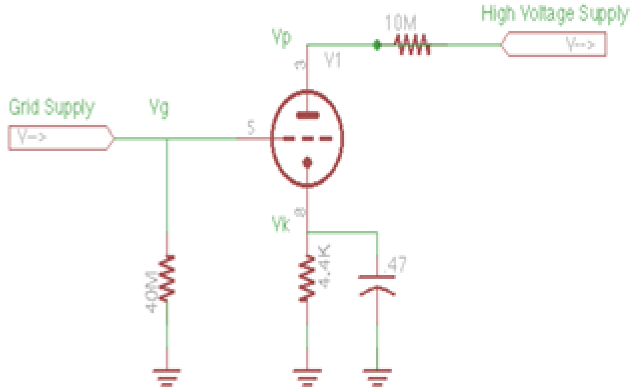
- Go to the library annex
- Read books from the 1940s



Will need:

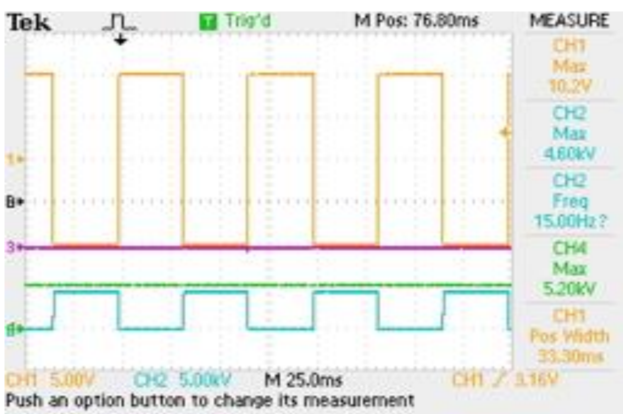
- Vacuum tubes
- Function generators
- Oscilloscope
- High voltage probes
- High voltage power supplies
- Copper
- Miscellaneous electronics/wiring
- Syringe pump
- Teflon/HDPE/Nylon stock

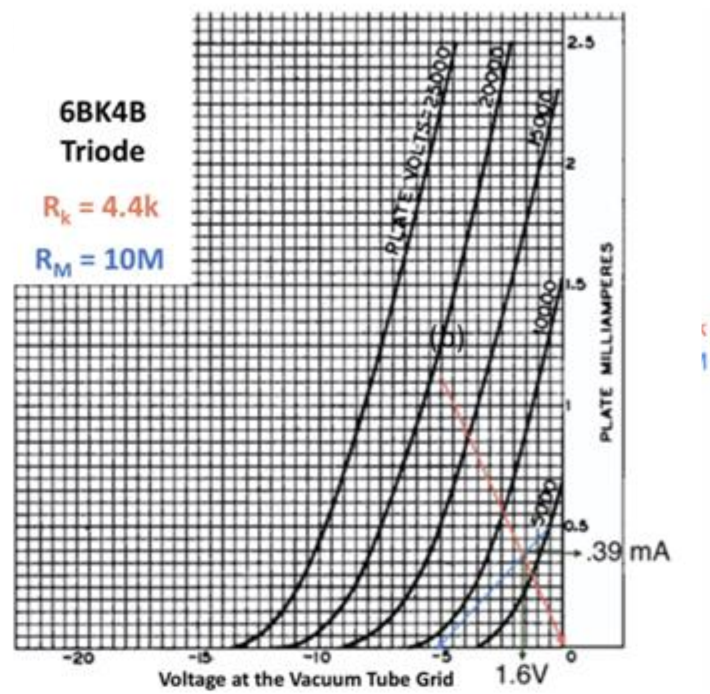
Switching High Voltage



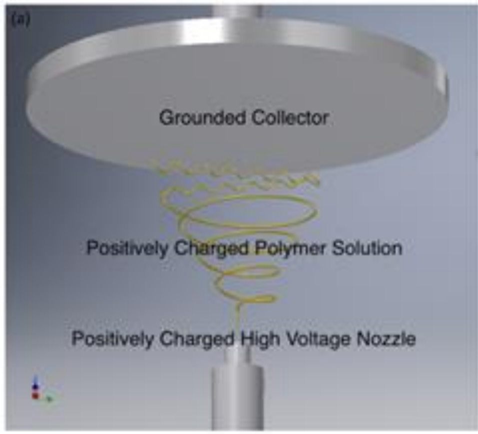
- Drawing the load lines for quiescent conditions using the transfer characteristic curves
- *Common-cathode configuration: high input impedance, medium-to-low output impedance, relatively high gain, good frequency response*

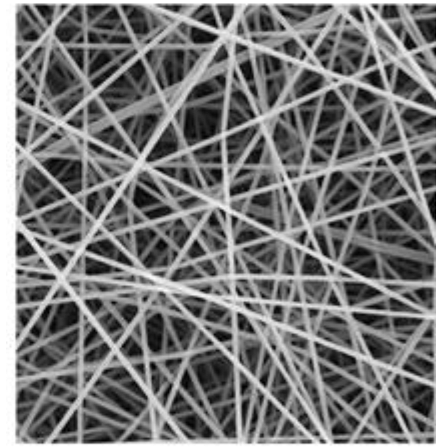
- Choose circuit components based on amplifier requirements and power supply ratings

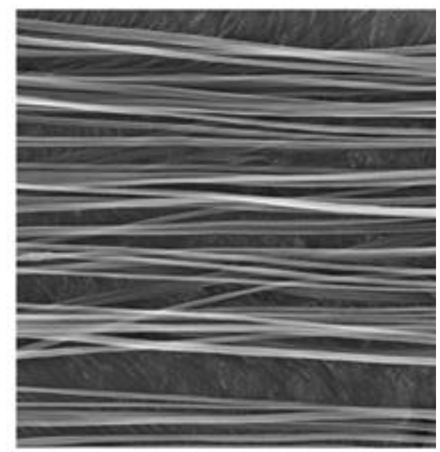




CAD + Simulations to Understand & Automate the Electrohydrodynamic Deflection Process







Goals:

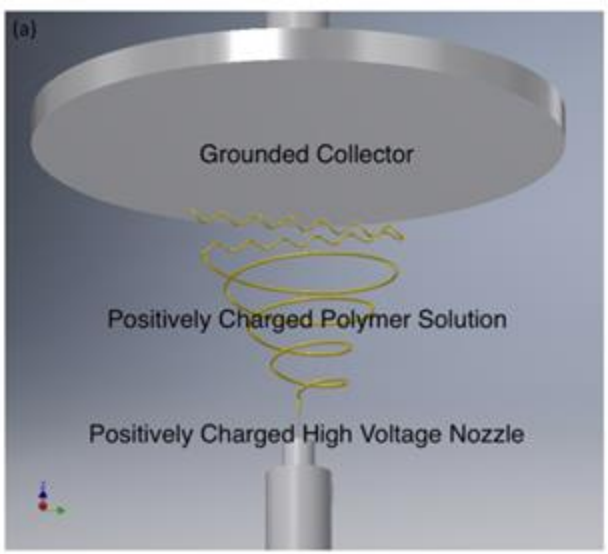
- Test current mathematical models
- Control deposition
- Develop feedback control
- data

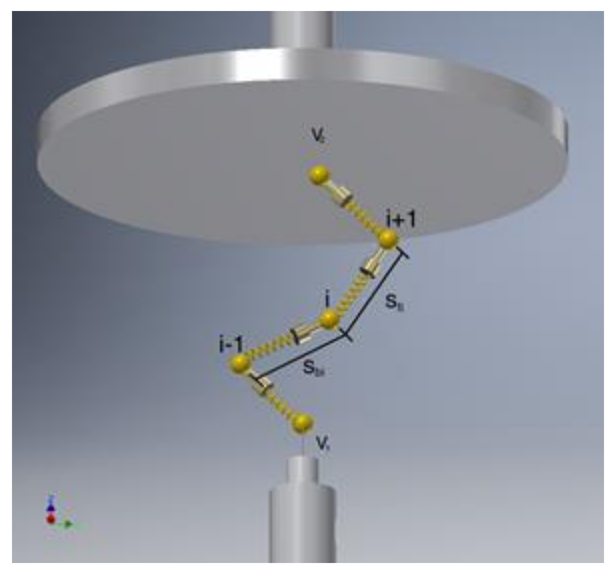
Space Charge Effects: Mass-Spring-Damper Model

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

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 $i \neq j$):

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



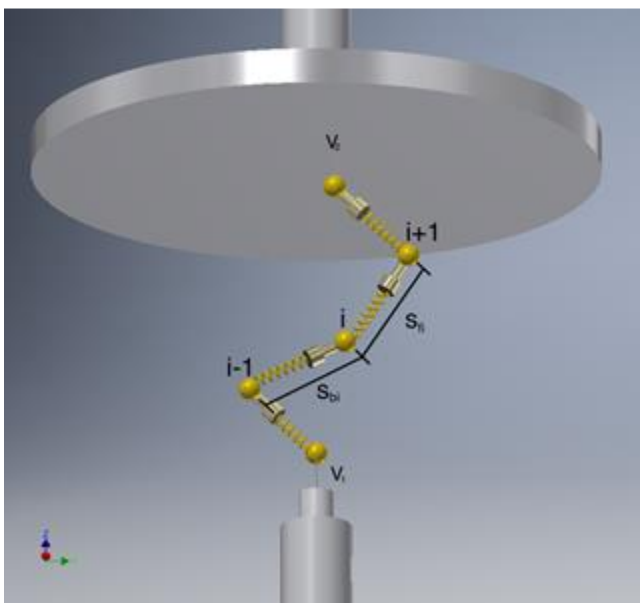


Viscous & Elastic Effects

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

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

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



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

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

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

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

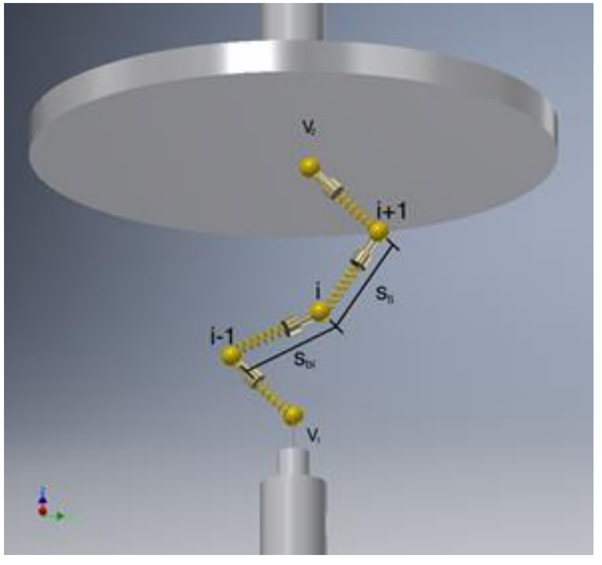
- L = Initial filament Length
- a_0 = Initial filament cross sectional radius

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 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

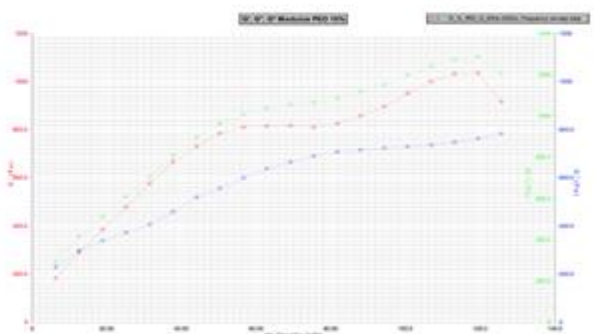


Figure 14: This image shows measurements of the elastic modulus (G’) of PEO 10% using a frequency sweep from 1 to 10Hz, with 20 sample points, at $25^{\circ}C$ with a strain percentage of .6% using an Advanced Rheometer AR 2000.

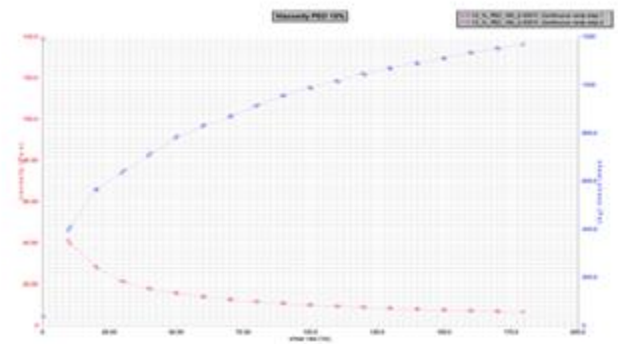


Figure 13: This image shows viscosity measurements of a 10% (w/w) mixture of deionized (DI) water and Polyethylene Oxide (PEO), with a molecular weight of $M_w = 600,000$, at 20°C over 4 minute intervals at shear rates ranging between $(0-180)\frac{1}{s}$ using an Advanced Rheometer AR 2000.

Measured Parameters for PEO 10%

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

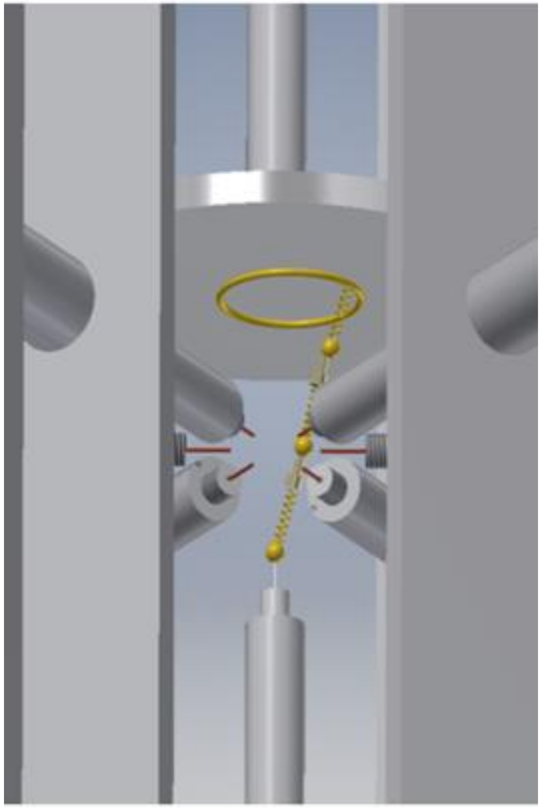
New Algorithm

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

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

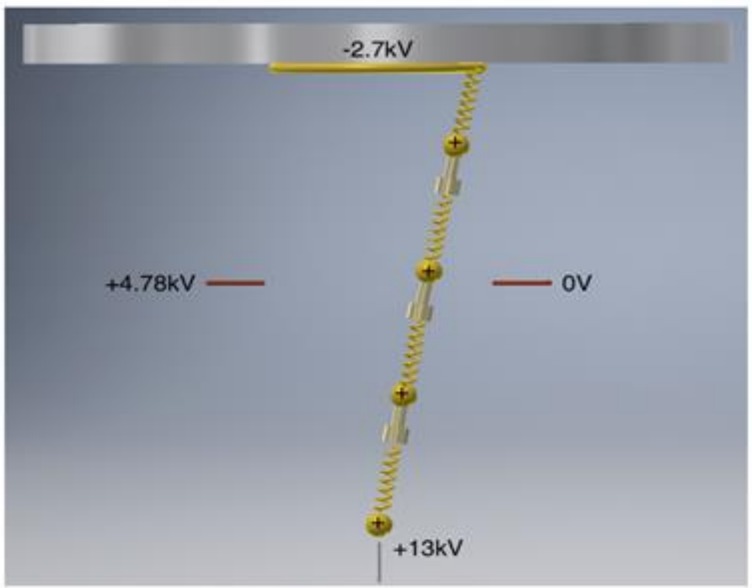
$$\vec{F}_{external_i} = q_i \vec{E}_i,$$

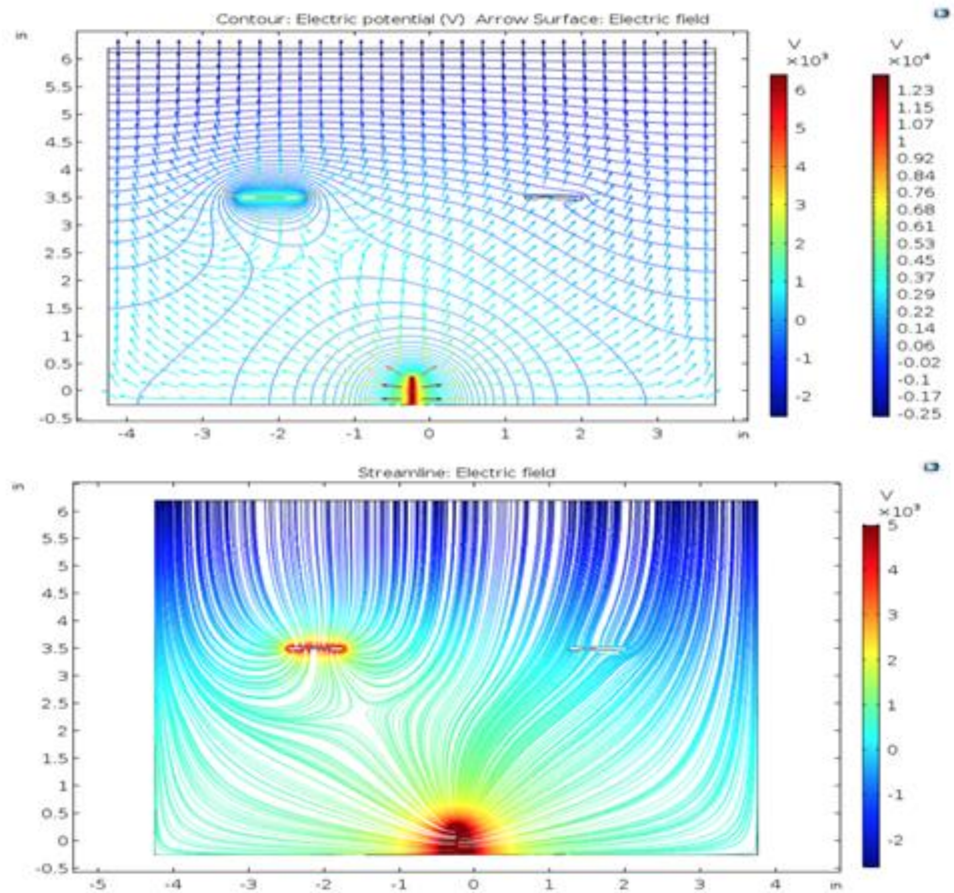
Must be more specific to electrode architecture and relative distances



Importing CAD models into Comsol

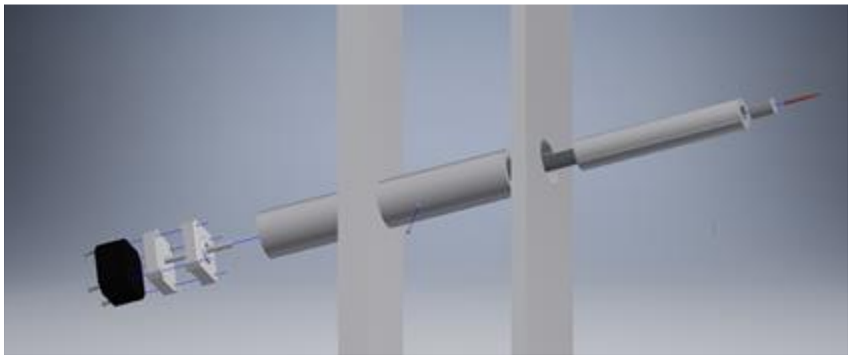
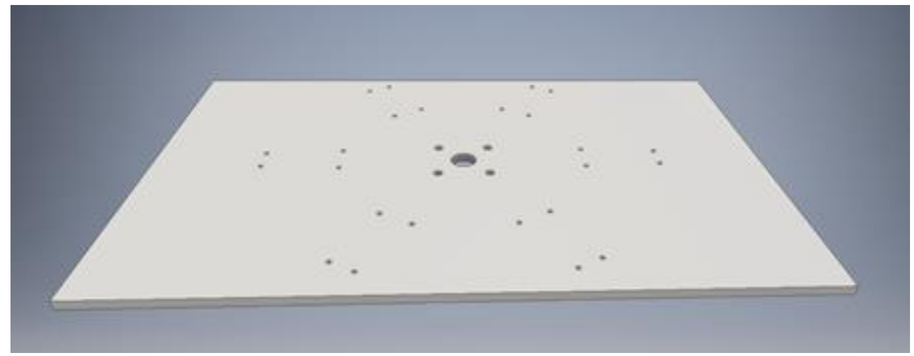
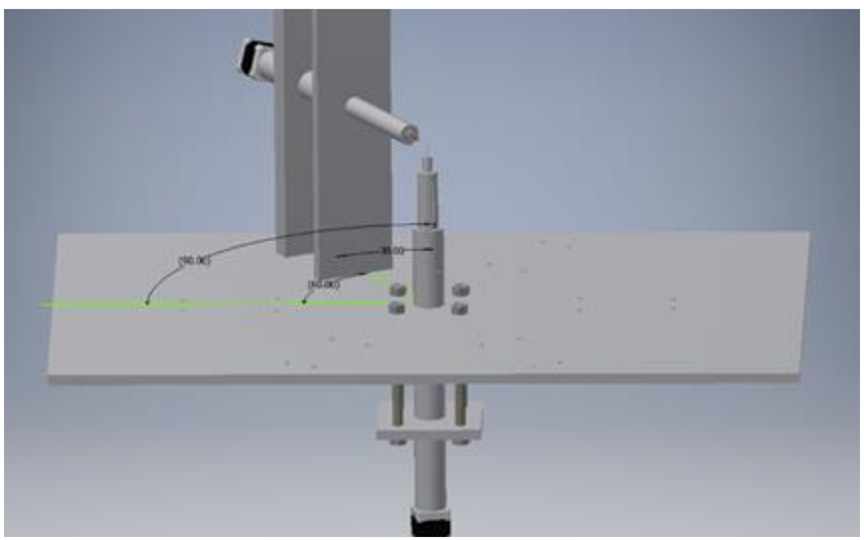
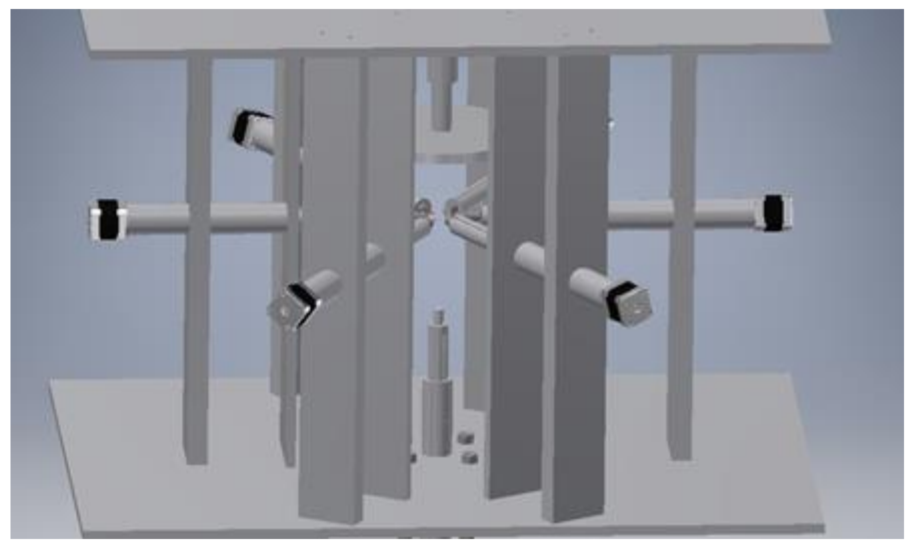
- Cross sectional analysis of 3D electrode architecture

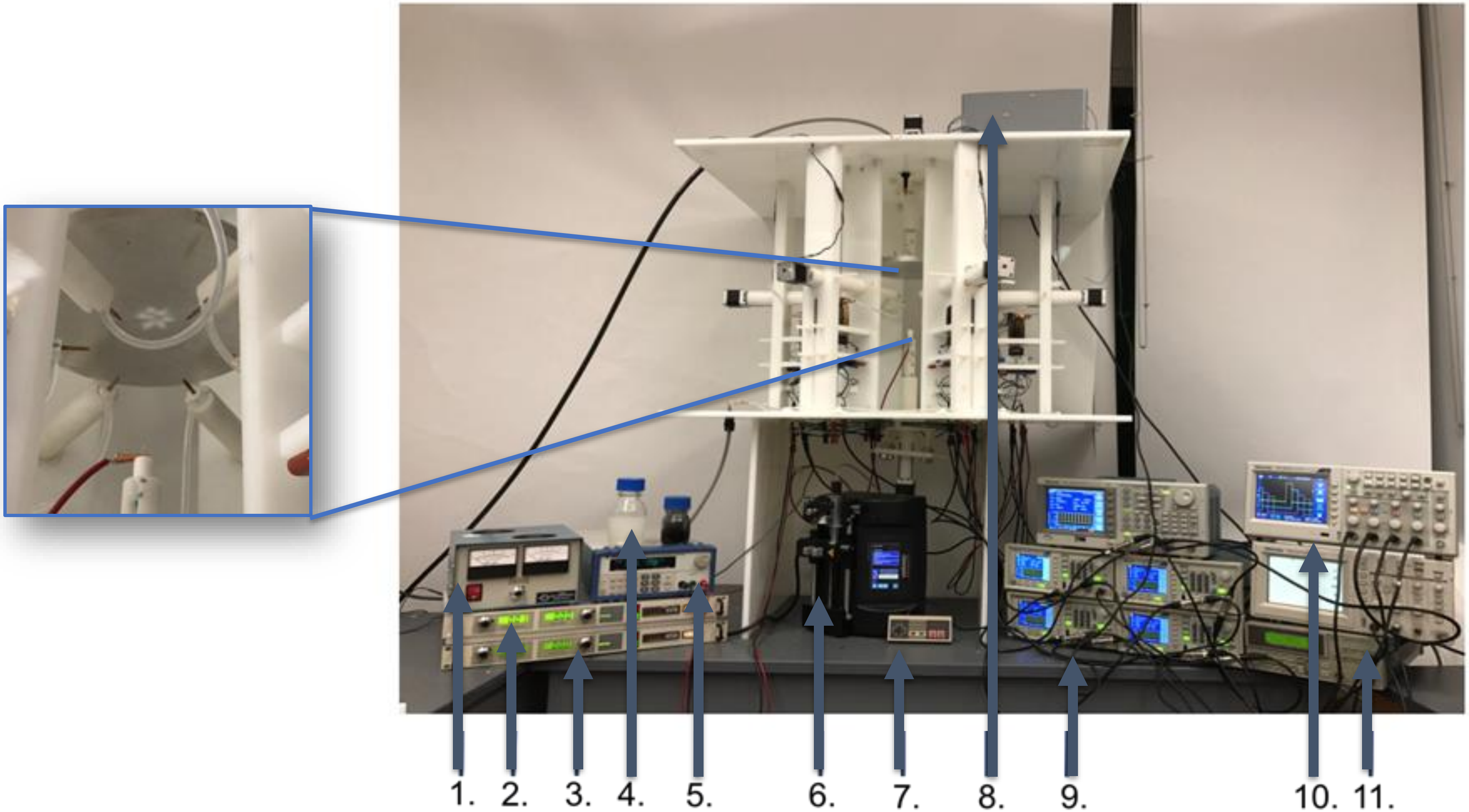




More CAD -> Machine Shop

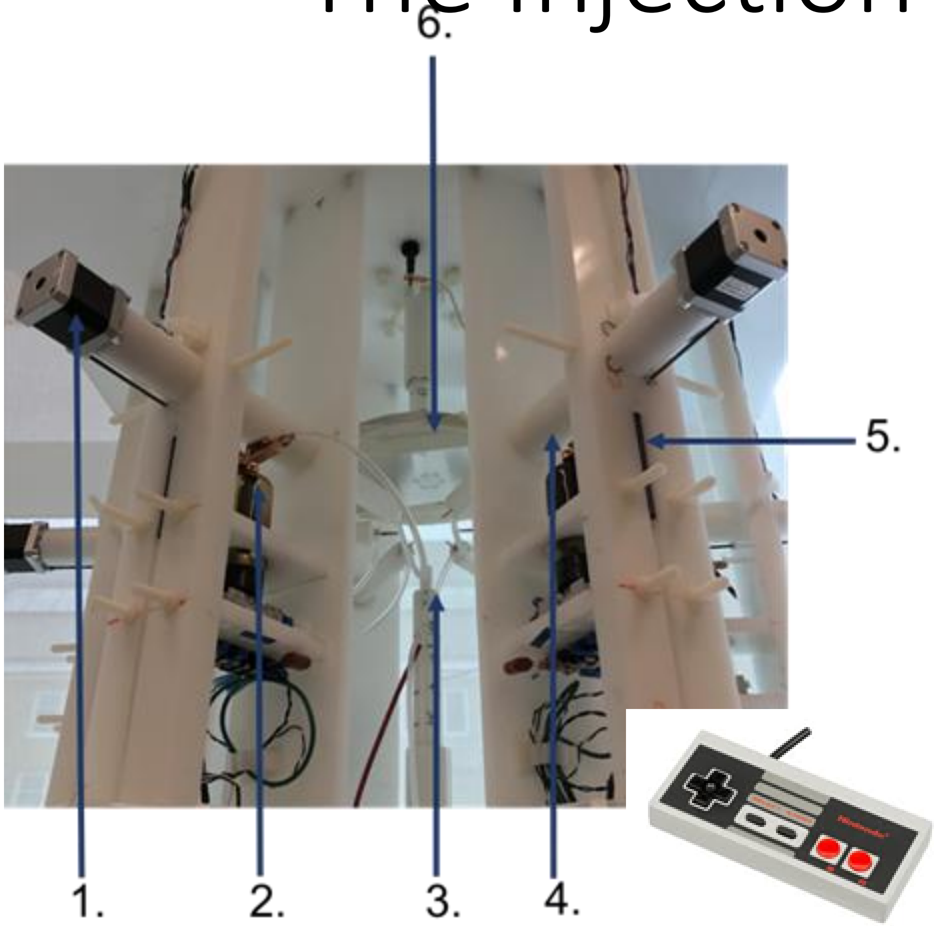
- HDPE, Nylon, Delrin, & Teflon to insulate v_{cc} from high voltage

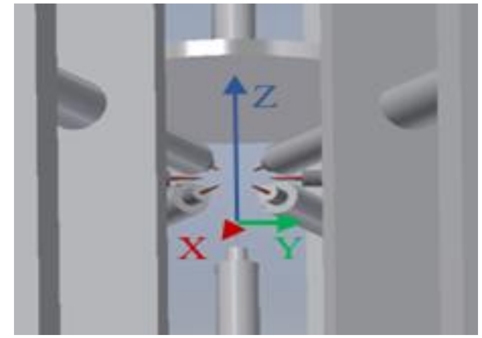





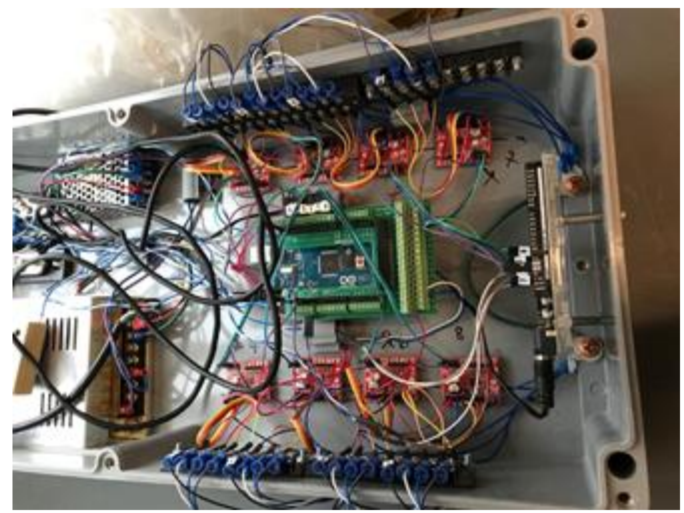


1. High voltage power supply (0-30kV, 0-200μA); **2.** High Voltage DC power supply (0V-15kV, 0-10mA); **3.** Negative High Voltage DC power supply (0 to -40kV, 0-7.5mA); **4.** Polymer solution (PEO & PEO + Carbon Black. **5.** Precision DC power supply (0-60V, 2.5A); **6.** Syringe pump 70-3005 with ±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

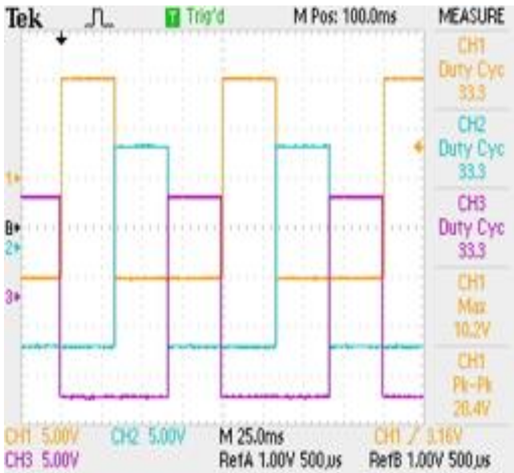






(**Left**) The injection chamber, which includes: **1.** Stepper motor; **2.** Vacuum tube amplifier; **3.** Syringe needle/driving mechanism; **4.** Electrode driving mechanism; **5.** 10M resistor**; 6.** Collector (½’’ thick, 6061 8’’ diameter Aluminum plate)

Guiding the Nanofiber in 2-D



Drawing a Triangle:

- f = 10Hz pulses, D_N=33.3% duty cycle. The 2nd and 3rd pulses are ϕ_2 =33.3ms and ϕ_3=66.6 ms, out of phase from ϕ_1, respectively.

Determining Phases:

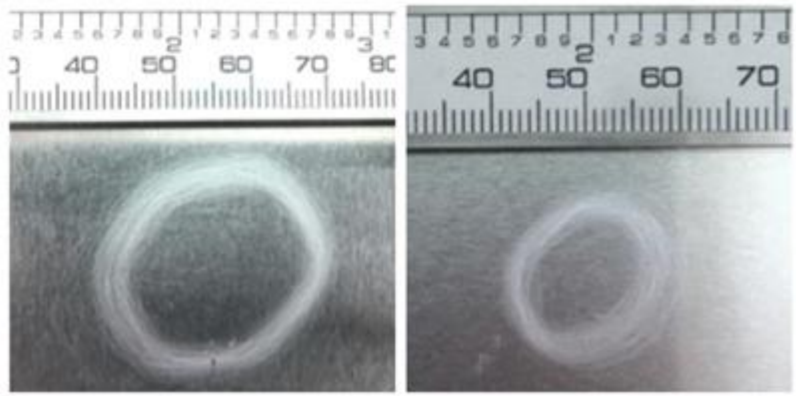
$$\phi_n = \frac{D_N}{f}\frac{(n-1)}{100}$$

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

Printing a Star

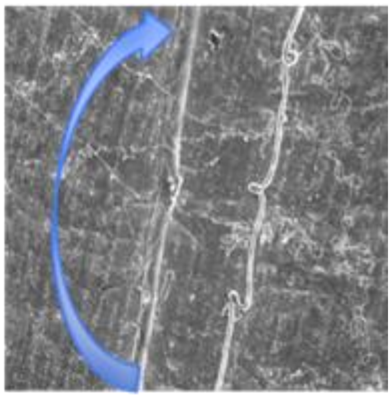
Printing a Hexagon

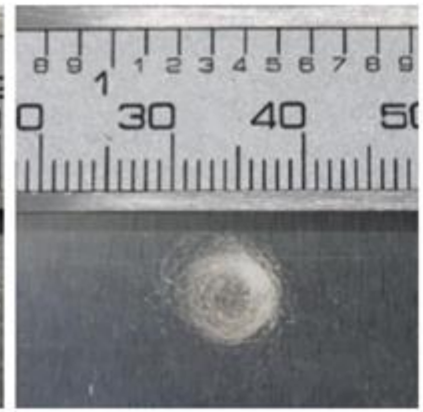
Voltage and Distance Dependence

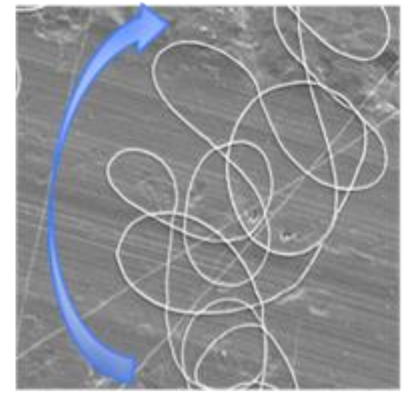


PEO 10%	$\frac{\Delta V}{\Delta Z}$ Dependency	
Frequency (f)	15Hz	15Hz
Nozzle Position from Origin (Z_N)	-76.2mm	-114.3mm
Collector Position from Origin (Z_C)	76.2mm	114.3mm
Nozzle Voltage (V_N)	13kV	13kV
Collector Voltage (V_C)	-2.6kV	-9.2kV
Intermediary-electrode Position from Z-axis	19.1mm	19.1mm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

Frequency Dependence

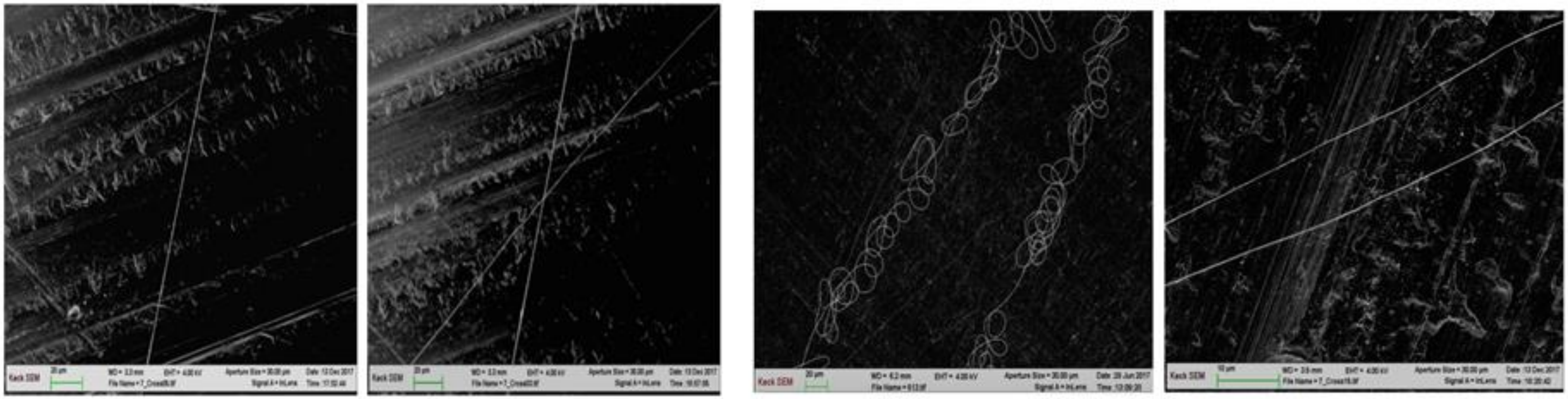






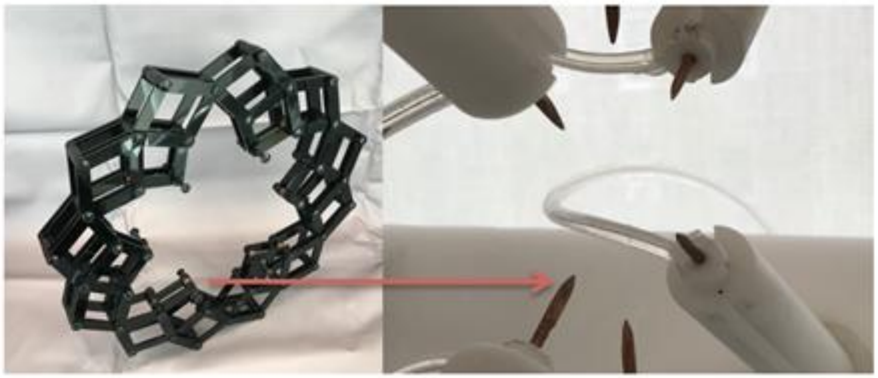
PEO 10%	*f* Dependency	
Electrode Pulsing Frequency (f)	30Hz	45Hz
Nozzle Position from origin(Z_N)	-114.3mm	-114.3mm
Collector Position from origin (Z_C)	57.2mm	57.2mm
Nozzle Voltage (V_N)	13kV	13kV
Collector Voltage (V_C)	-7kV	-7kV
Intermediary-electrode Position from z-axis	12.7mm	12.7mm
Deposition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

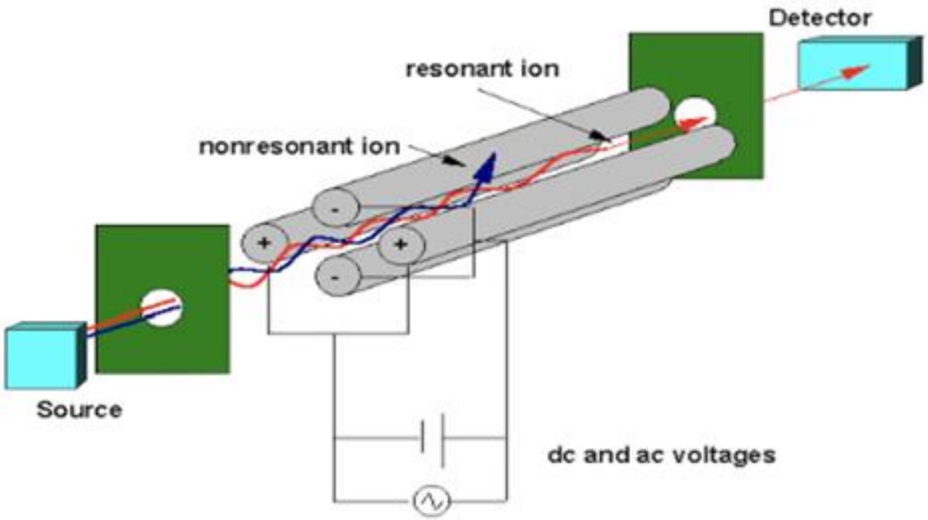
Goal: 2D and 3D Print Aligned Nanofibrous Structures



Future Work: Actuated Quadrupole Mass Spectrometer

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





- Decrease spot size

Thank you!