# Quantitative Estimation of Electro-osmosis Force on Charged Particles inside a Borosilicate Resistive-Pulse Sensor

**Yuqian Zhang[1,*], Mostafa Ghobadi[2,*], Ankit Rana[1], Ehsan T. Esfahani[2, ‡], Leyla Esfandiari[1, ‡]**

[1]DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTING SYSTEM, UNIVERSITY OF CINCINNATI, OHIO, USA

[2]DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING, UNIVERSITY AT BUFFALO SUNY, BUFFALO, NY, USA

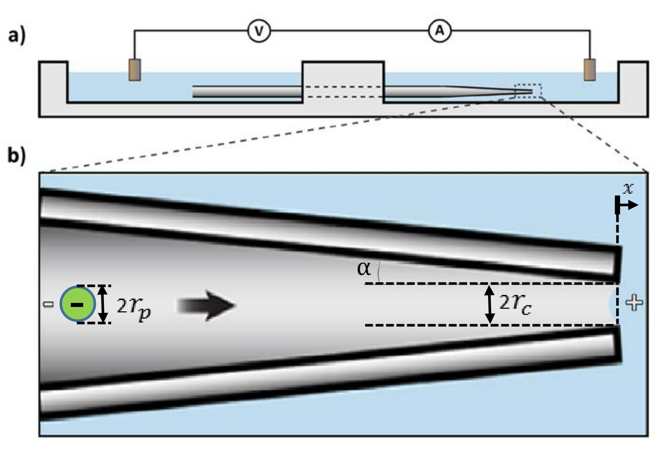
## Introduction

### Motivation

Rapid, sensitive and robust detection of biomolecules is of significant interest in a range of diverse health-related applications such as screening for oncogenes in cancer, drug screening and pathogen microbe identification. Nanopore-based sensor centered on the resistive-pulse technique is a promising tool due to its intrinsic ultra-sensitive, cost-effective and rapid detection criteria.

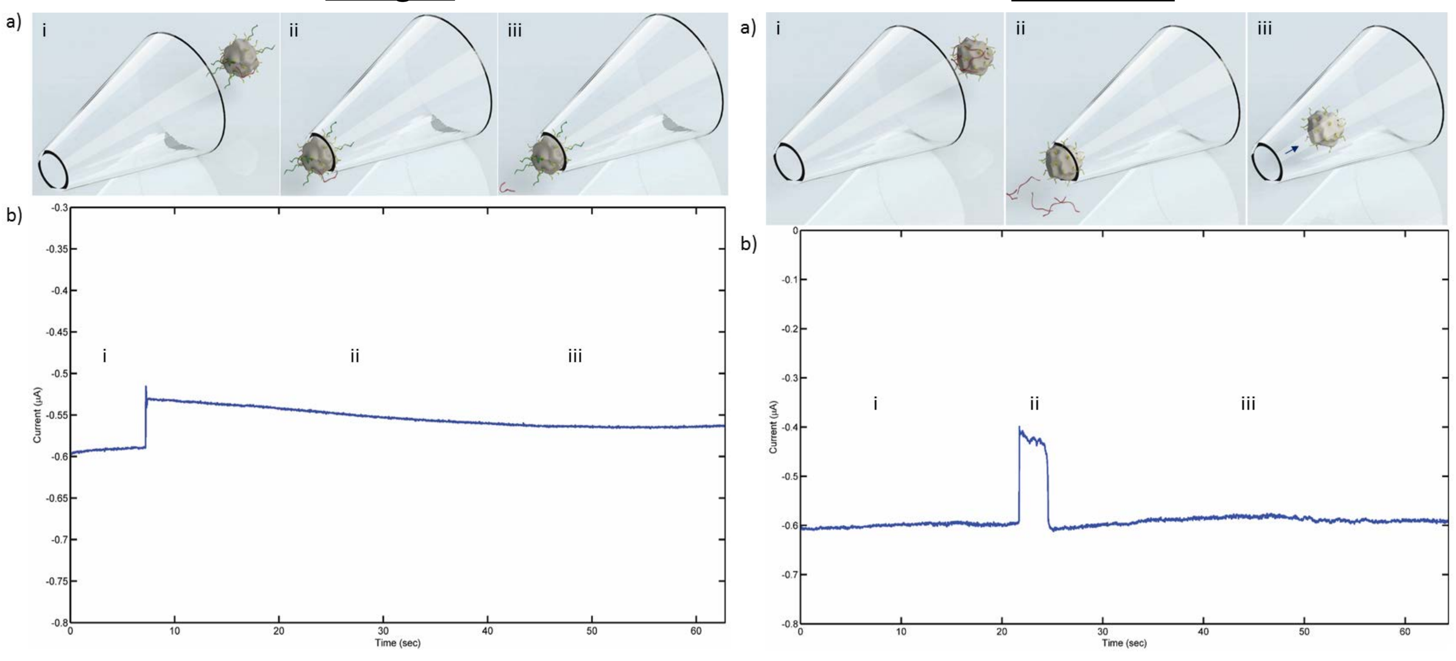
Detection accuracy is one of the essential characteristic of biosensors. This project developed a mathematical model based on the borosilicate resistive-pulse sensor and quantitatively estimated the effective electro-osmosis range to assist the improvement of sensor accuracy.

### Design of target nucleic acid detection




Neutral particles coupled with negatively charged detecting nucleic acid in the capillary experienced two main forces: **electrophoretic force** and **electro-osmosis force** in opposite direction under applied electric field.

Target | Control




**Target:**
- Complementary specific binding with beads;
- Suffered higher electrophoretic force;
- Result in permanent blockage or resistive-pulse.

**Control:**
- Non-specific weakly binding with beads;
- Suffered higher electro-osmosis force;
- Result in transient blockage or no ionic current change.

### Effective electro-osmosis velocity range

$$\mu_{ep\,(non-specific\ bound)} < \mu_{eo} < \mu_{ep\,(target\ specific\ bound\,)}$$

$$\text{Electrophoretic velocity: } \mu_{ep} = \frac{q}{6\pi r_p \eta}$$

$$\text{Electroosmosis velocity: } \mu_{eo} = \frac{\epsilon_0 \epsilon \zeta}{4\eta}$$

## Mathematical Analysis

A method is proposed to estimate the ratio between the electrophoretic force and the portion of drag force affected by electro-osmosis force. The estimation is performed with the expectation of the motion of particle predicted by theory to be similar to the captured motion through experiment.

Three main effects are involved in the problem:

Drag force: $f_D = 6\pi r_p \eta v_p$

Electrophoretic force: $f_{ep}(x) = qE, E(x) = \dfrac{I_b \rho_s}{\pi(r_c - x\tan(\alpha))^2}$

Electroosmosis force: $v_{eo}(x) = \mu_{eo}E(x), \mu_{eo} = \dfrac{\epsilon_0 \epsilon \zeta}{4\eta}$

Based on Newton's Law, relative velocity of particle in the capillary can be written as:

$$m\ddot{x} = f_{ep} - f_D = q\,E(x) - 6\pi r_p \eta(\dot{x} + \mu_{eo}E(x))$$

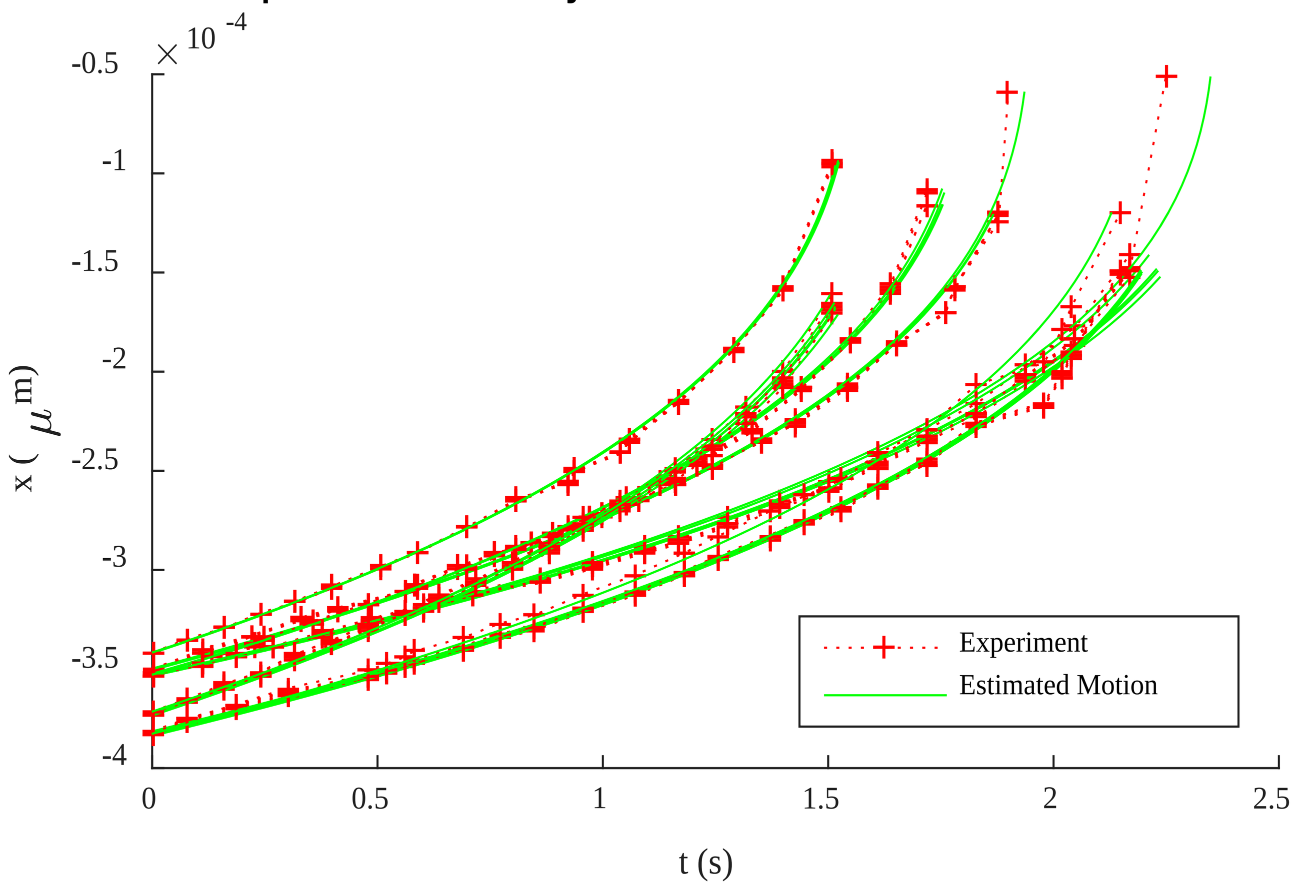
Motion equation of beads can be simplified as:

$$x = k_2 + \sqrt[3]{3k_1 t + (x_0 - k_2)^3}$$

in which, $k_1 = k_{ep} - k_{eo}, k_2 = \dfrac{r_c}{\tan(\alpha)}$

$$k_{ep} = \frac{q I_b \rho_S}{6\pi^2 r_p \eta \tan(\alpha)^2}, \qquad k_{eo} = \frac{\frac{3}{2}\pi r_p \epsilon_0 \epsilon \zeta I_b \rho_S}{6\pi^2 r_p \eta \tan(\alpha)^2}$$

The curve for derived motion equation was quite close to the measured experimental trajectories.



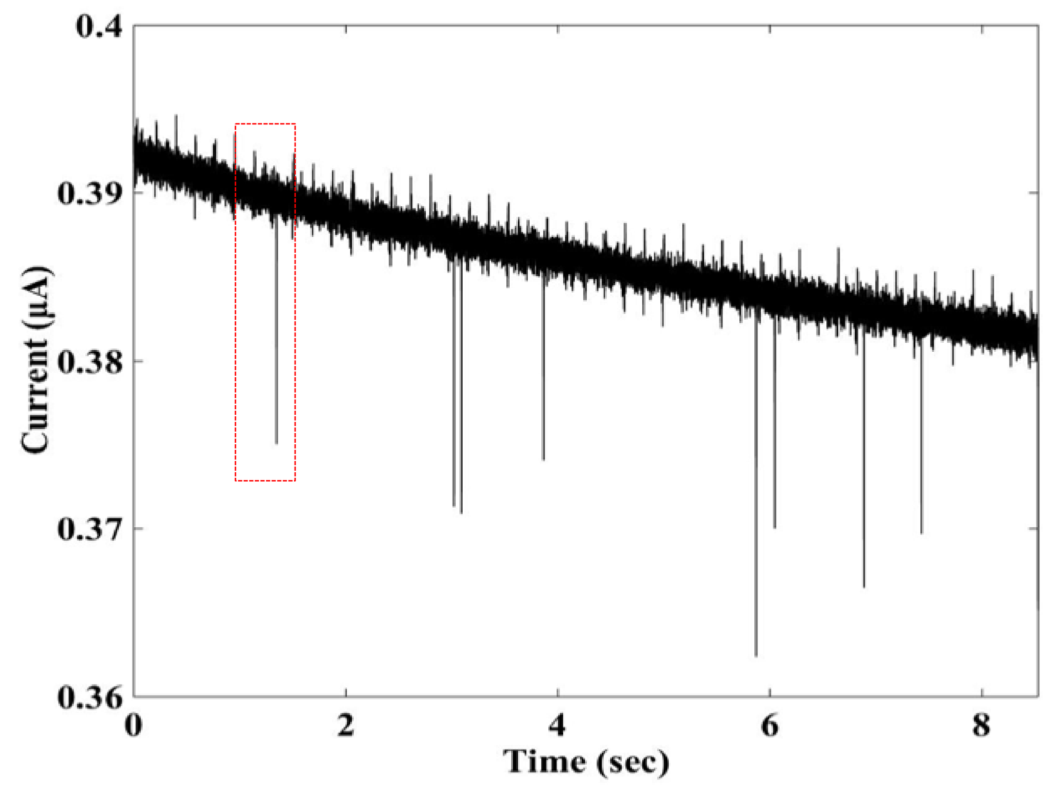

The ratio of electro-osmosis velocity to electrophoretic velocity was derived further.

$$k_v = \frac{k_{eo}}{k_{ep}} = \frac{\frac{3}{2}\pi r_p \epsilon_0 \epsilon \zeta}{q}$$

## Methods

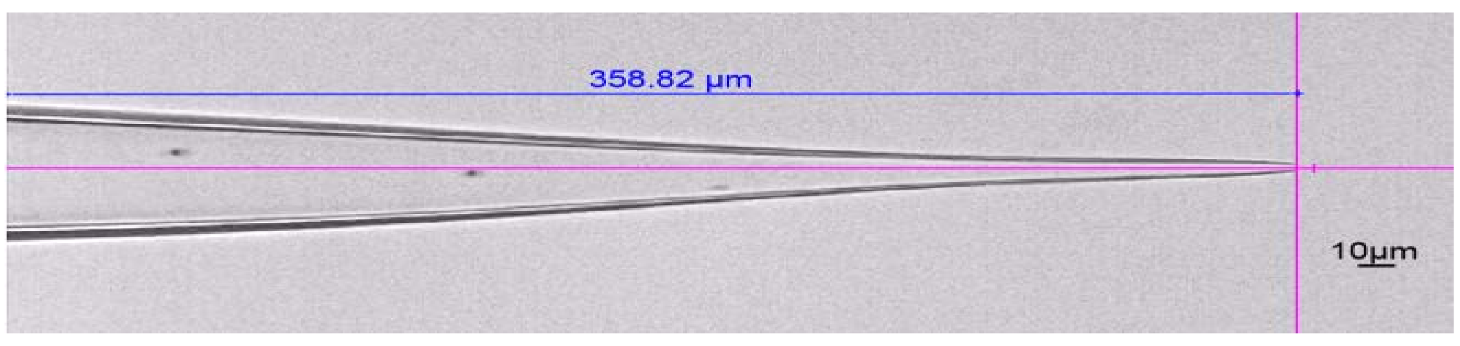
### Resistive-Pulse sensing technique

Carboxylic functionalized polystyrene beads with 2.36 $\mu m$ diameter (zeta potential is -61.63 mV) subjected to constant applied electric field and moved towards the pore driven by electrophoretic force; Translocation events were observed, resulting in conductance changes.




Video was recorded for the particle motion using microscope with a high-resolution camera and analyzed using a motion analysis tool.

### Tracking particles motion trajectories

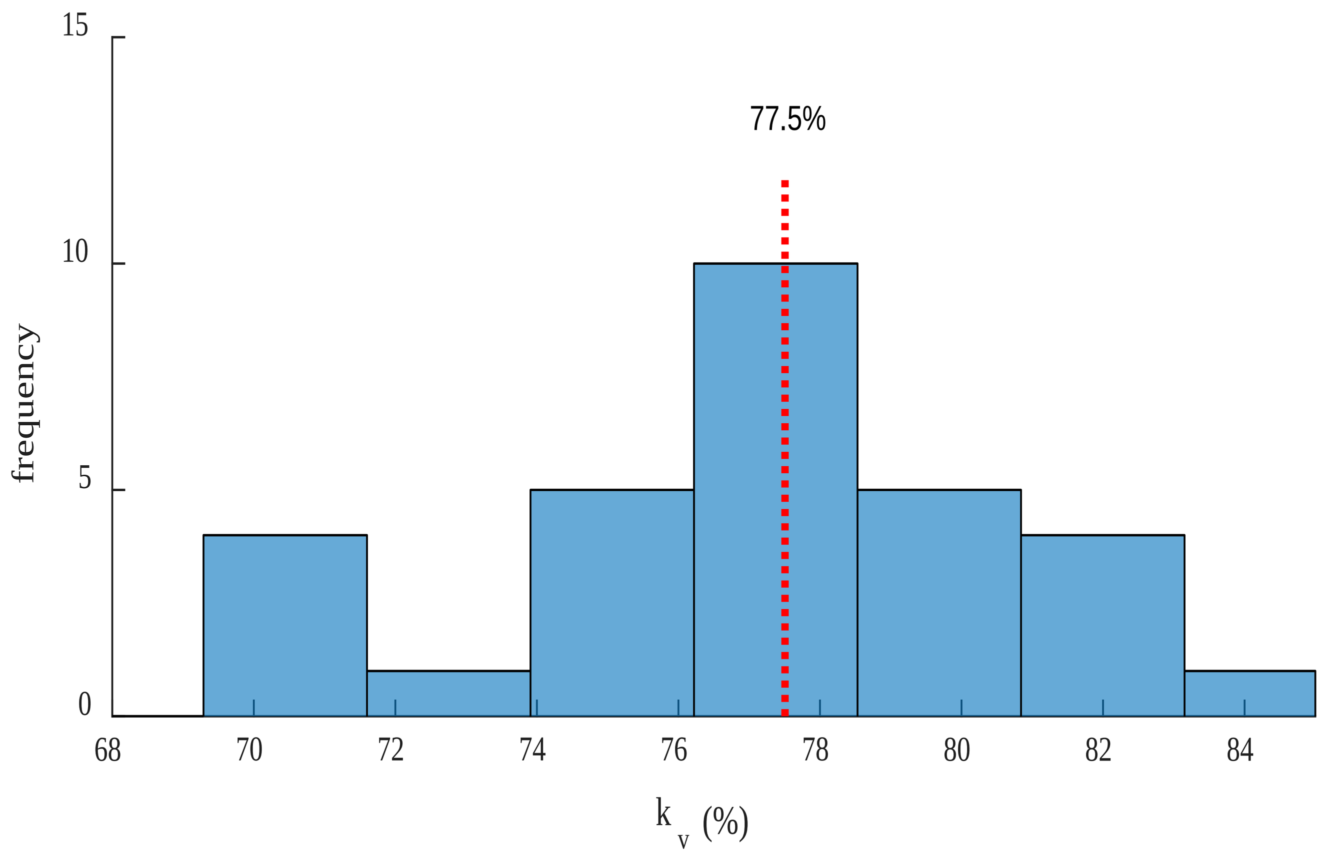



- Axes of reference were set as depicted by magenta lines in the figure. Length of capillary marked as a calibration reference (in blue).
- Video was played frame by frame and position coordinates were marked for each frame for whole trajectory.
- Using the frame rate and the coordinates data and the calibrated reference, the tool computed instantaneous velocities.

## Conclusions

Based on the experimental observation and simulation results, a mathematical model was developed to estimate the motion equation and analyze the electro-osmosis to electrophoretic effect further.

The histogram of $k_v$ (ratio of electro-osmosis velocity to electrophoretic velocity) showed the mean value was around 77.5% for 2 $\mu m$ diameter borosilicate pore.




Results assist the improvement of sensor accuracy and sensitivity by quantitative analysis of electro-osmotic force and its effective range.

### References

1. L. Esfandiari, H.G. Monbouquette, and J.J. Schmidt, "Sequence-specific nucleic acid detection from binary pore conductance measurement.," *J. Am. Chem. Soc.*, 134(38), 15880–6, 2012.
2. L. Esfandiari, M. Lorenzini, G. Kocharyan, H.G. Monbouquette, and J.J. Schmidt, "Sequence-Specific DNA Detection at 10 fM by Electromechanical Signal Transduction," *Anal. Chem.*, 86, 9638–9643, 2014.
3. L. Esfandiari, S. Wang, S. Wang, A. Banda, M. Lorenzini, G. Kocharyan, H.G. Monbouquette and J.J. Schmidt, "PCR-Independent Detection of Bacterial Species-Specific 16S rRNA at 10 fM by a Pore-Blockage Sensor," *Biosensors*, 6(3), 37, 2016.