Simulation of a Novel Induced-Charge Electrokinetic Actuation Mechanism for Diaphragm Micropumps

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Introduction

Bipolar electrodes (BPEs) have proven to be useful tools for a wide range of applications [1-3]. Here, we propose to leverage pressure forces associated with induced-charge electroosmotic flow (ICEOF) to actuate a diaphragm-based micropumping mechanism.

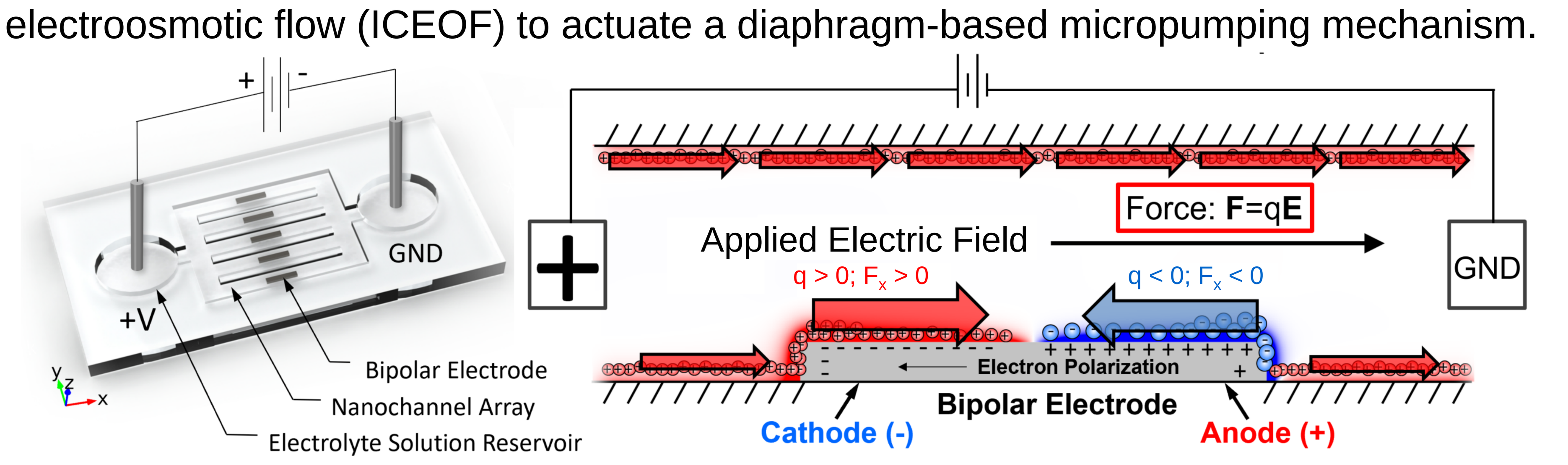
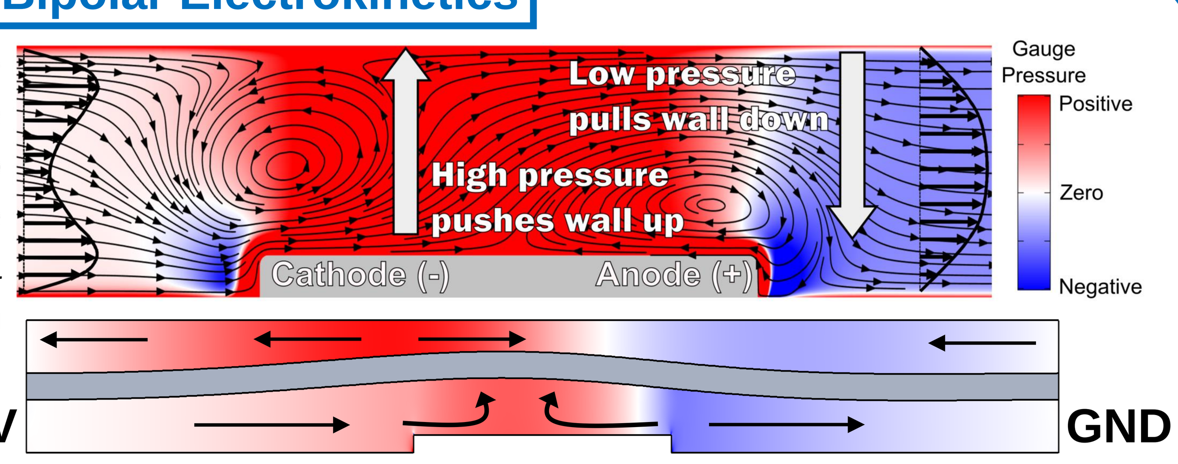


Fig. 1: Example fluidic device containing floating BPEs (left), and associated electrokinetics (right).

Bipolar Electrokinetics

Fig. 2: Recirculating induced-charge flow at the BPE generates pressure forces that simultaneously push up and down on the top wall of the channel; if this wall is replaced with a flexible diaphragm, periodic actuation can displace fluid in a top channel.



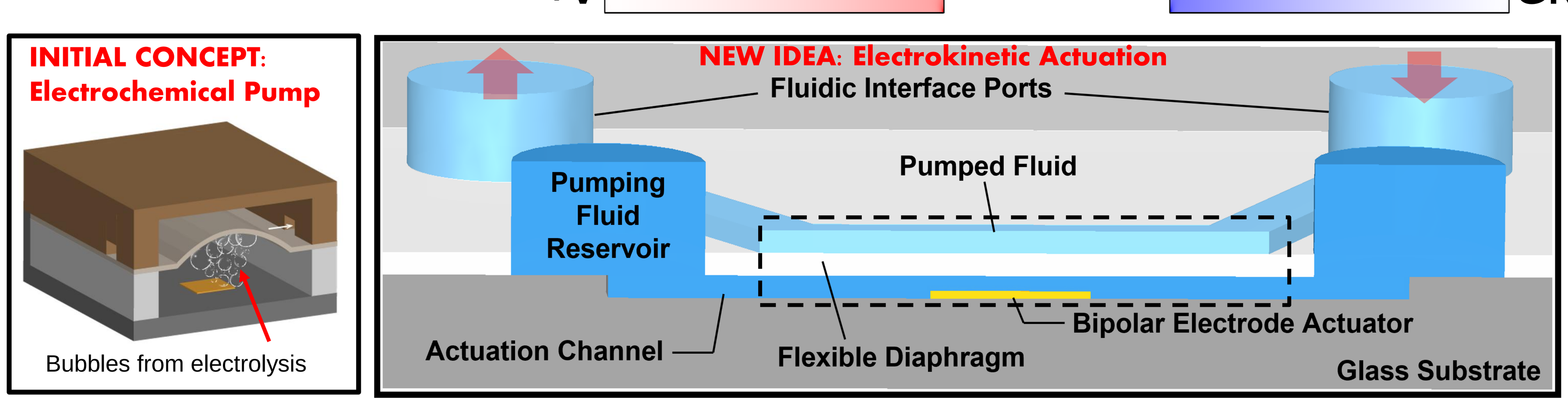


Fig. 3: Our initial concept involved a bipolar electrochemical actuator (left), but we are investigating whether electrokinetic ICEOF alone might be sufficient for actuation within a new scheme (right).

Fully Coupled Numerical Model

- Full model includes surface polarization and nanoscale charge screening dynamics
- Model assumptions:
  - *Dilute electrolyte solution*
  - *Fixed channel wall surface charge*
  - *No specific adsorption of charged species on BPE*
  - *No Faradaic reactions (ideally polarizable)*
  - *Neglect homogeneous buffer reactions*
  - *No hydrostatic pressure difference across channels*

Governing Equations

Navier-Stokes & Continuity: (velocity field)

$$\rho_f\left(\frac{\partial \mathbf{u_f}}{\partial t}+\mathbf{u_f}\cdot\nabla\mathbf{u_f}\right)=\eta\nabla^2\mathbf{u_f}-\nabla p-\sum_{i=1}^{n}Fz_ic_i\nabla\psi;\qquad \nabla\cdot\mathbf{u_f}=0$$

Solid Mechanics: (displacement field)

$$\rho_s\frac{\partial^2\mathbf{u_s}}{\partial t^2}=\nabla\cdot\sigma_s$$

Poisson's Equation: (electric field)

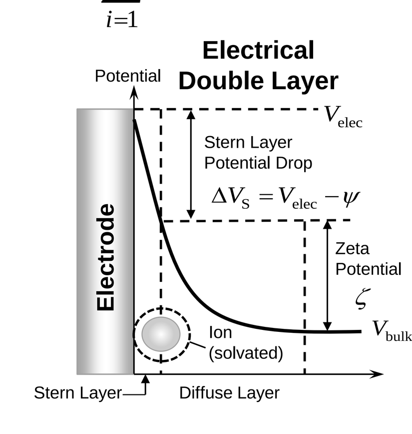
$$-\varepsilon\nabla^2\psi=\sum_{i=1}^{n}Fz_ic_i;$$

Floating Electrode: (BPE Potential)

$$\int_{\partial\Omega}C_S\left(V_{elec}-\psi\right)dS=0$$

Species Conservation: (ionic transport)

$$\frac{\partial c_i}{\partial t}=-\nabla\cdot\left(\mathbf{u_f}c_i-D_i\nabla c_i-\frac{D_i}{RT}z_iFc_i\nabla\psi\right)$$



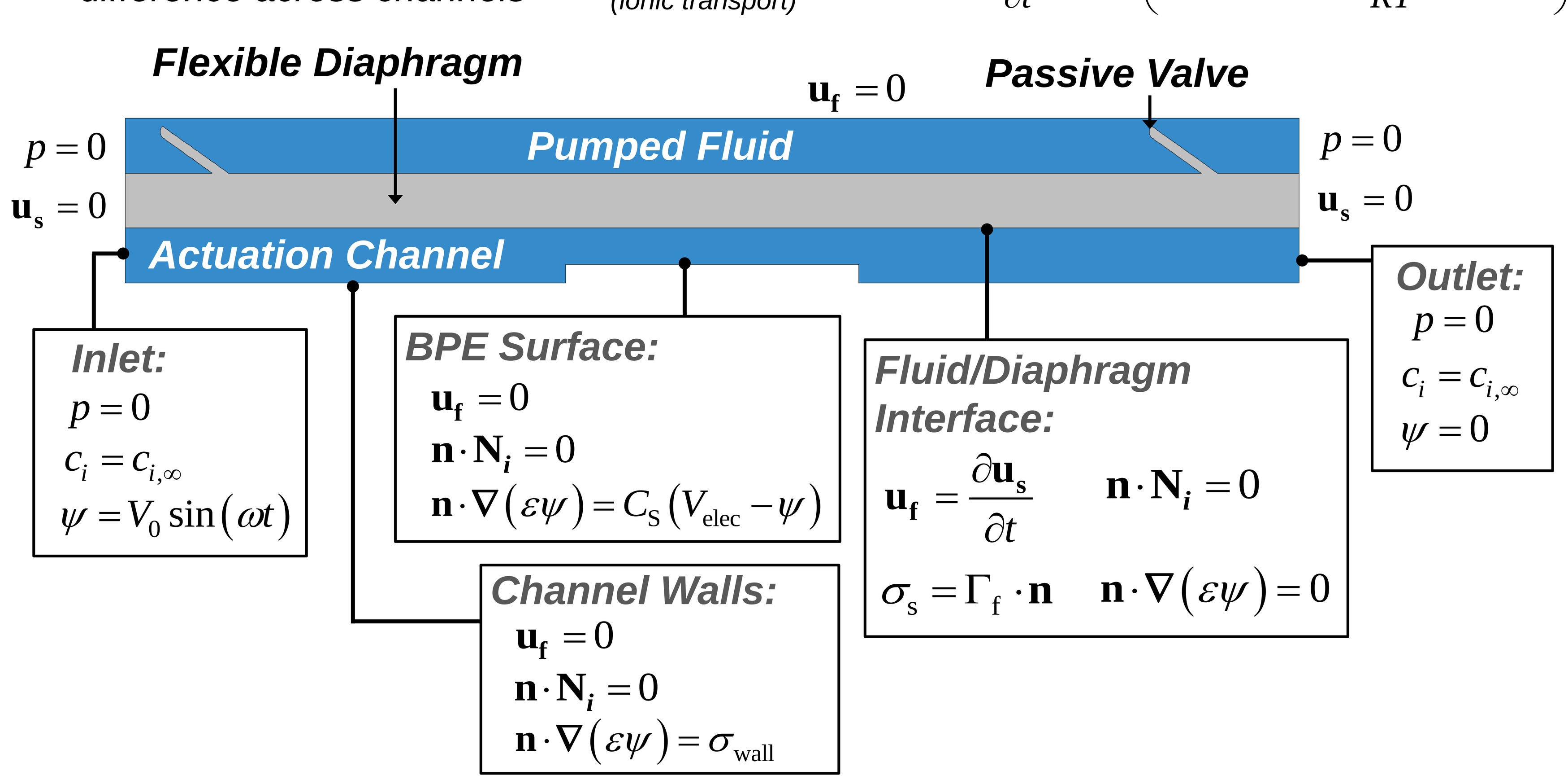


Fig. 4: 2D COMSOL Multiphysics® model, with governing equations and boundary conditions used in our numerical simulations. The full model resolves surface polarization, charge screening dynamics, and more – but can take several days to solve transient pumping dynamics studies.

Acknowledgement

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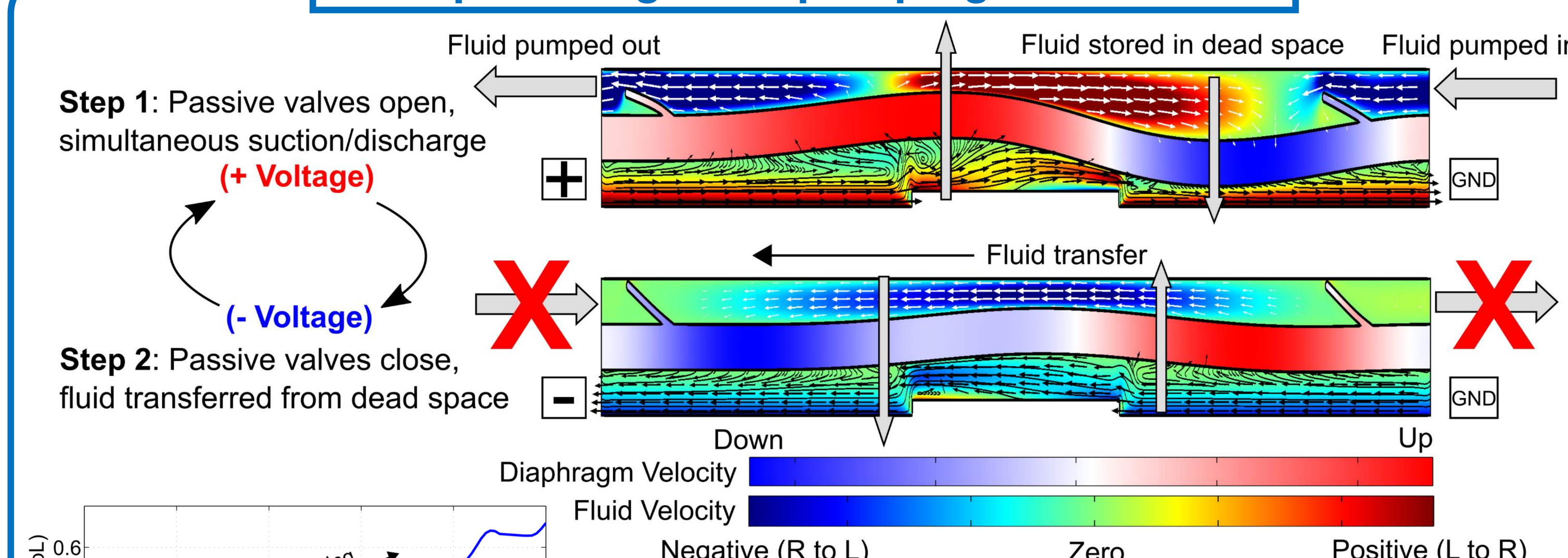
Results

Our simulation of a configuration with passive valves demonstrates near-unidirectional throughput from the peristalsis-like diaphragm motion driven by periodic pressure disturbances in the channel below. Additionally, we use our numerical model to investigate the effects of various design parameters on the pumping performance, including system length, channel heights, and diaphragm material properties.

Reciprocating Micropumping Mechanism



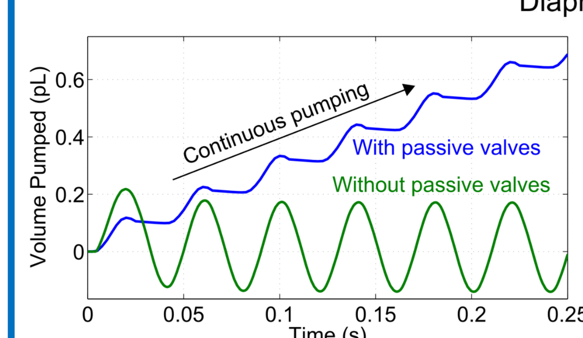


Fig. 5: Passive valves allow for continuous, near-unidirectional pumping using a fluidic array with a single AC voltage between two driving electrodes: actuation process (above) and net volume pumped (left).

Design Considerations

Potential Across BPE:

$$\Delta V_{BPE}\approx\frac{L_{BPE}}{L_{ch}}V_{applied}\approx E_0L_{BPE}$$

- Long BPE + large E field → Faradaic reactions

Confinement Effect: $P_{mid}\sim\frac{U_{EOF}\eta L}{H^2}$

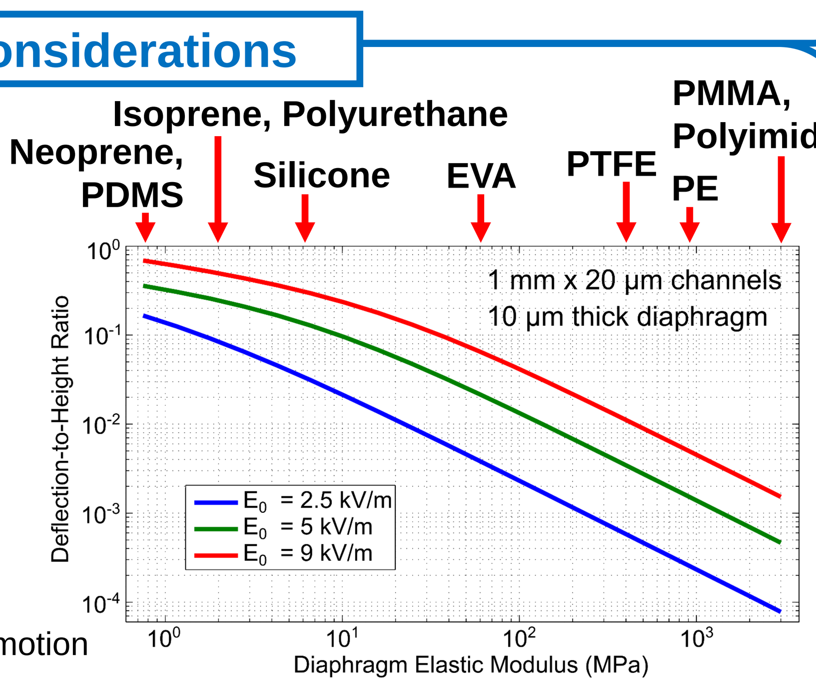
- More shallow channels → higher pressure load

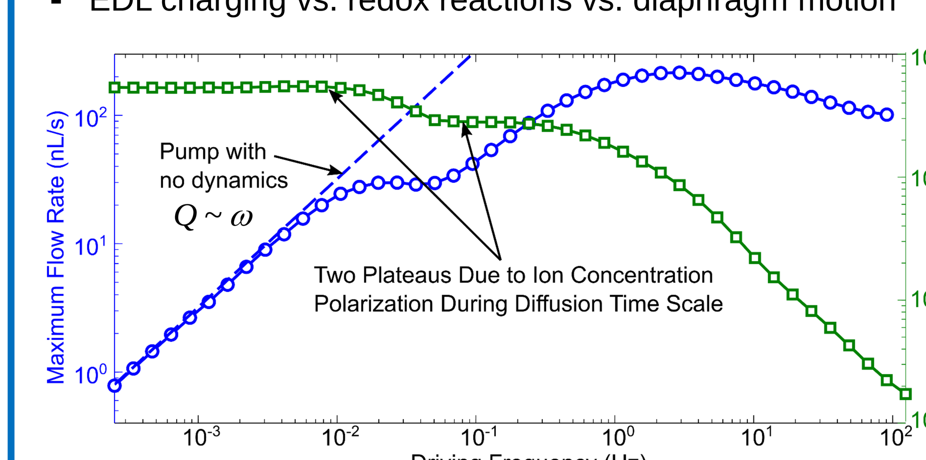
Diaphragm Stiffness: $\delta_{max}\sim\frac{PL^4}{Et_d^{\,3}}$ (Assumes relatively wide diaphragm)

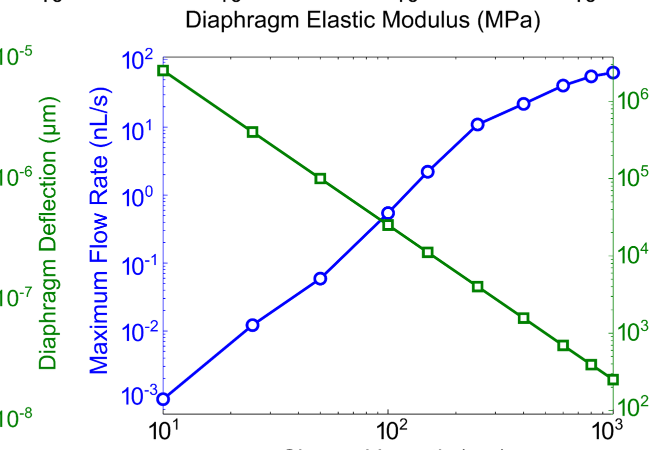
- PDMS most flexible option
- 8 um thinnest feasible diaphragm

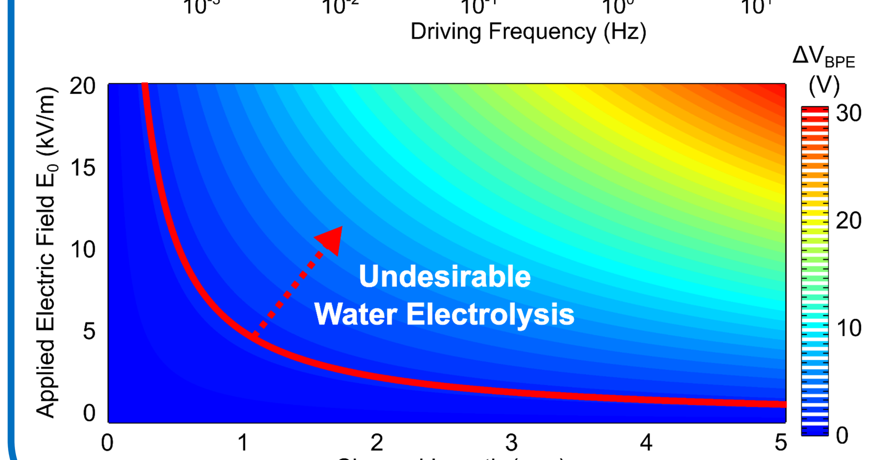
Time Scales/Driving Frequencies

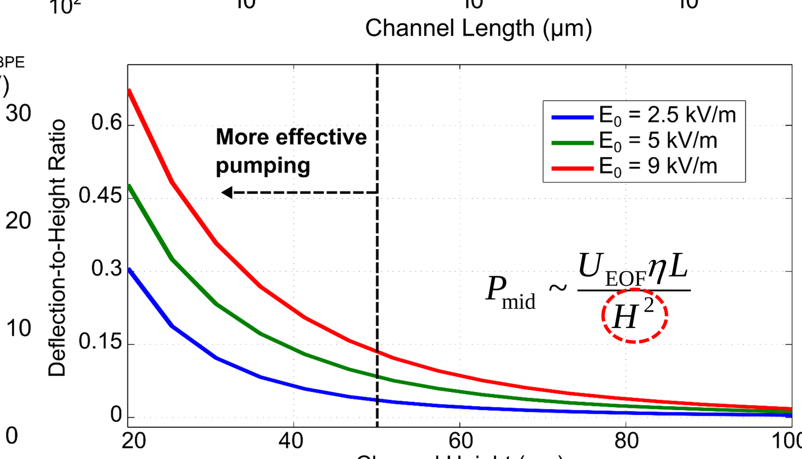
- EDL charging vs. redox reactions vs. diaphragm motion











Conclusions

- ➢ Pressure generated by ICEOF actuates diaphragm for pumping
- ➢ Fully coupled model developed to simulate highly nonlinear physics
- ➢ Passive valves enable continuous, reciprocating peristaltic-like flow
- ➢ Ultra-low simulated flow rates range from pL/s to µL/s
- ➢ Promising mechanism provides many potential benefits:
  - ✓ Low power requirements (AC, small currents)
  - ✓ BPEs actuated "wirelessly" via electric field
  - ✓ Precise fluid manipulation at very low flow rates
  - ✓ Pumped sample completely isolated from electrical contact & contamination

References

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