CISM Summer School, Udine Italy, June 22-26 2009.
Electrokinetics and Electrohydrodynamics of Microsystems

Induced-Charge Electrokinetic Phenomena

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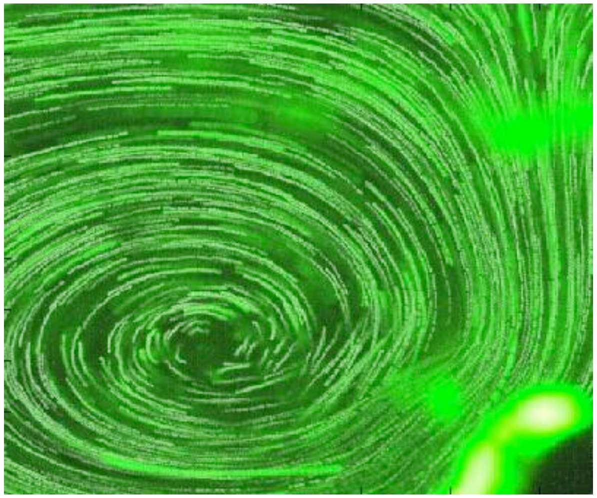
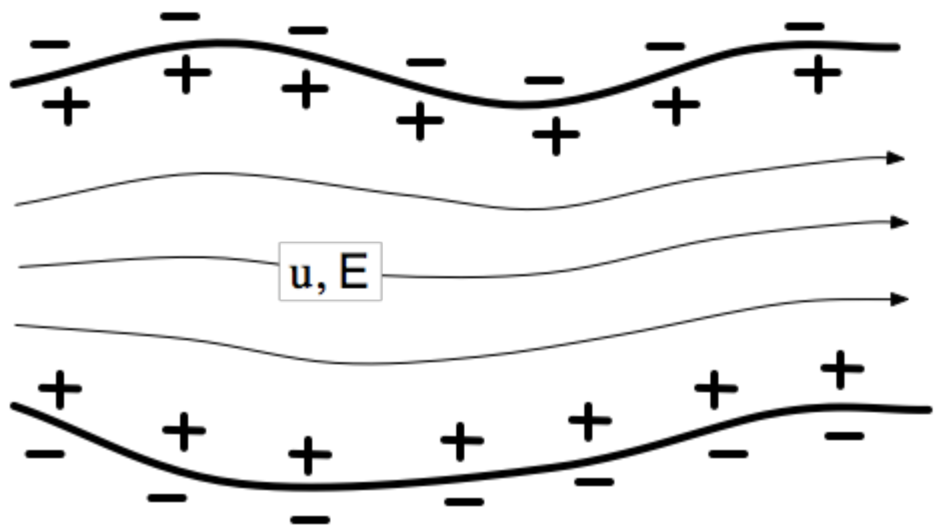
Lectures

1. Introduction
2. Low-voltage theory
3. Particle motion
4. Fluid motion
5. Large-voltage theory



Linear (DC)
Electrokinetic Microfluidics

Electro-osmosis



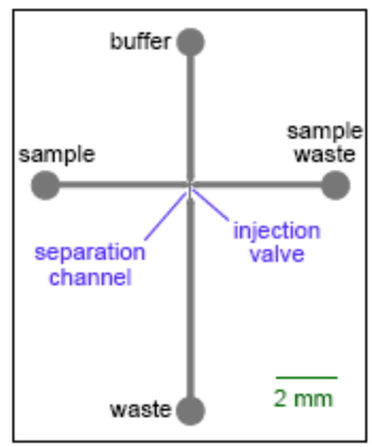
Slip: $$\vec{u}_s = -\mu_e \vec{E}_t, \quad \mu_e = \frac{\varepsilon\zeta}{\eta}$$

Potential / plug flow for uniformly charged walls:

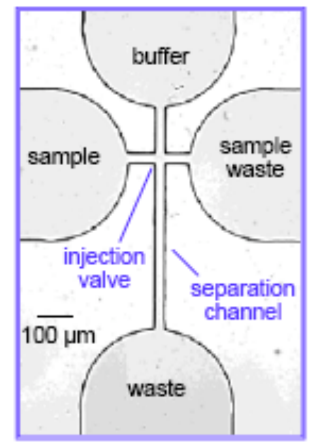
$$\vec{u} = \mu_e \nabla\phi, \quad \nabla^2\phi = 0$$

Electro-osmotic Labs-on-a-Chip

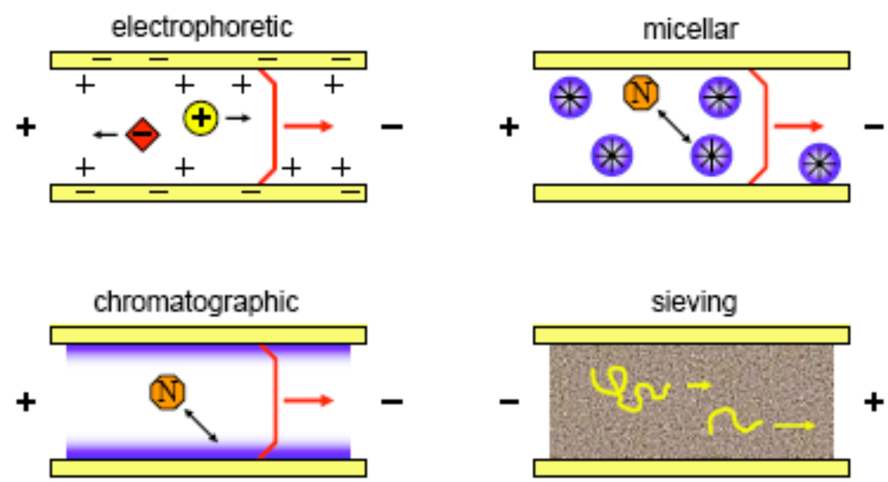
- Apply E across chip
- Advantages
  - EO plug flow has low hydrodynamic dispersion
  - Standard uses of in separation/detection
- Limitations:
  - High voltage (kV)
  - No local flow control
  - "Chip in a Lab"



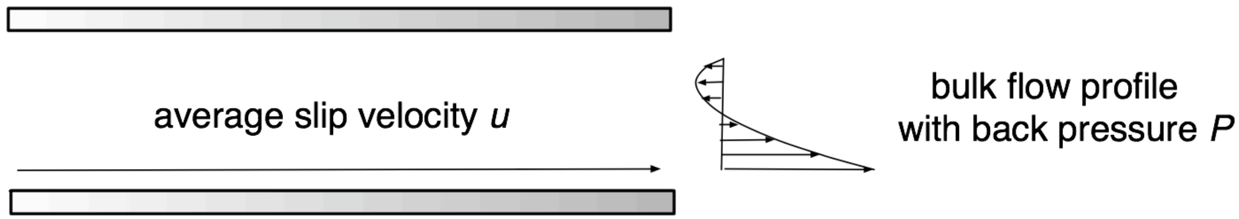
Anal. Chem. 70, 3476-3480, 1998.

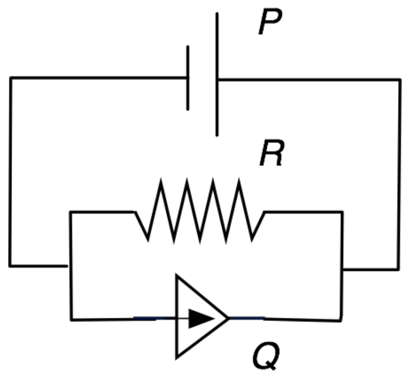


separation channel: 500 µm
narrow channel: 26 µm
wide channel: 440 µm

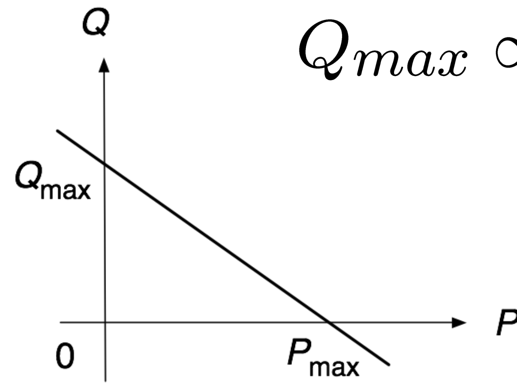


Pressure generation by slip





equivalent circuit



flow rate versus back pressure

$$Q_{max} \propto hwu$$

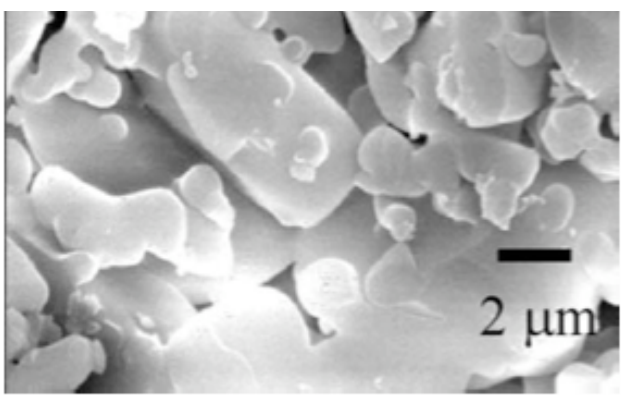
$$P_{max} = R_H Q_{max} \propto \frac{\eta u L}{h^2}$$

Use small channels!

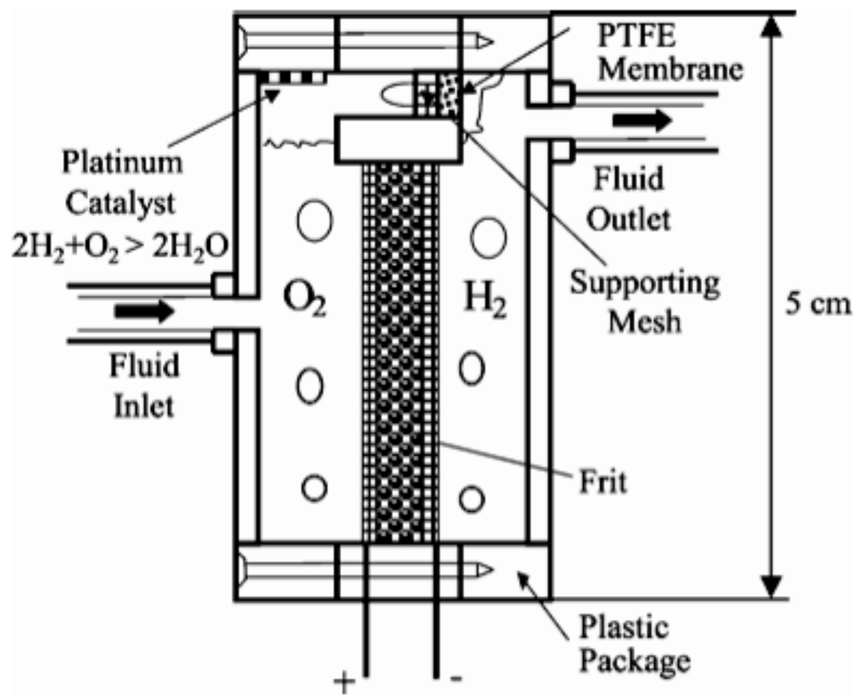
DC Electro-osmotic Pumps

- Nanochannels or porous media can produce large pressures (0.1-50 atm)

- Disadvantages:
  - High voltage (100 V)
  - Faradaic reactions
  - Gas management
  - Hard to miniaturize



Porous Glass



Yau et al, JCIS (2003)
Juan Santiago's group at Stanford

Electro-osmotic mixing

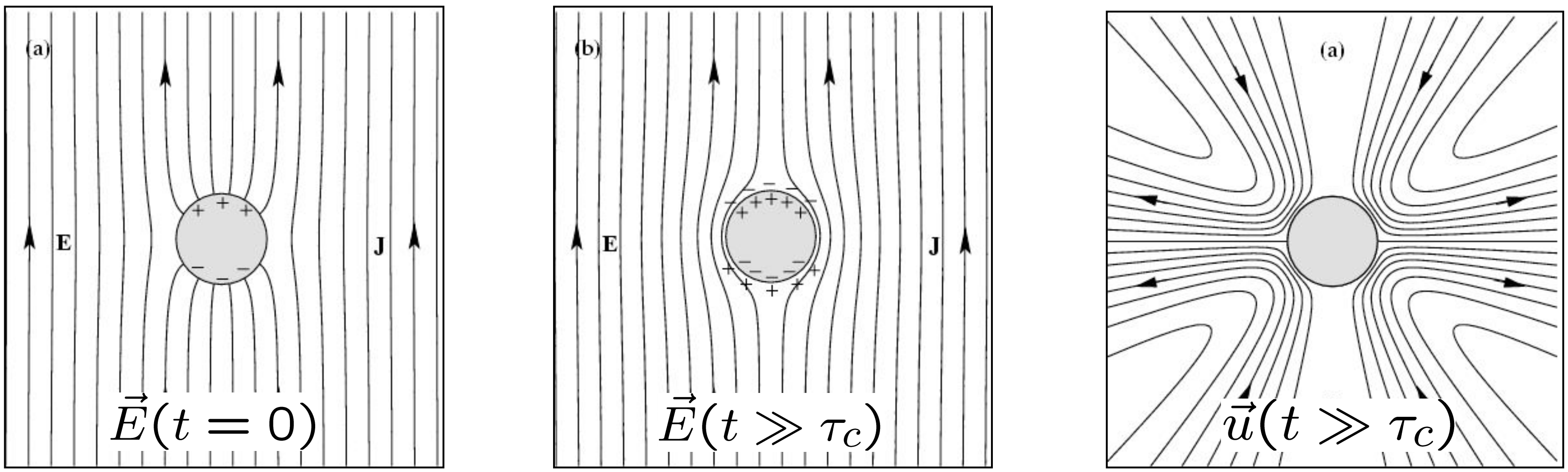
- Non-uniform zeta produces vorticity
- Patterned charge + grooves can also drive transverse flows (Ajdari 2001) which allow lower voltage across a channel
- BUT
  - Must sustain direct current
  - Flow is set by geometry, not “tunable”

Induced-Charge Electro-osmotic Microfluidic Devices

Microfluidic Applications of Induced-Charge Electro-osmosis

Bazant & Squires, Phys, Rev. Lett. (2004)

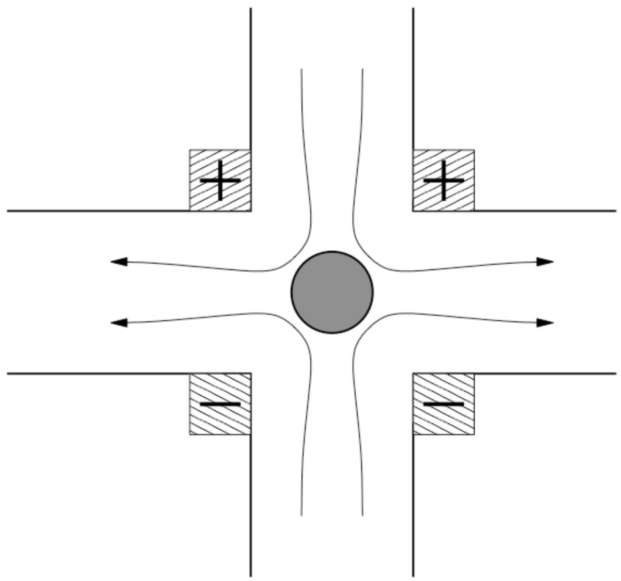
Example: An uncharged metal <u>cylinder</u> in a DC (or AC) field

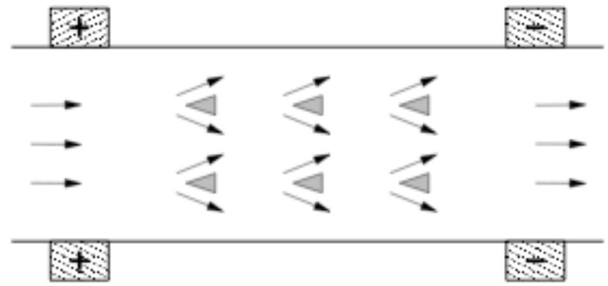


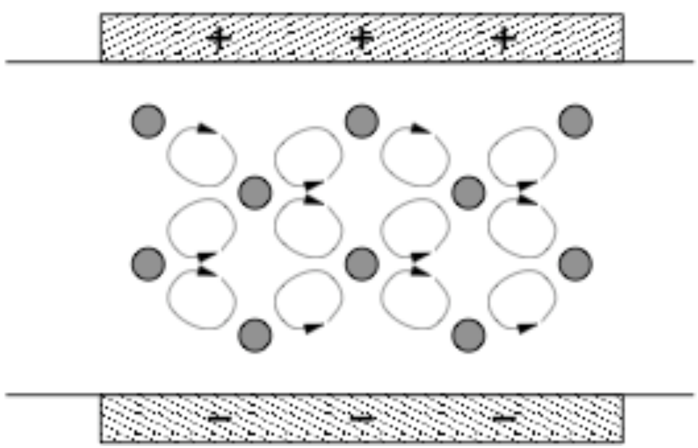
$$u_s = \frac{\varepsilon\zeta}{\eta}E_t, \;\; \zeta - \zeta_0 \sim ER \;\; \Rightarrow \;\; u \sim \frac{\varepsilon R E^2}{\eta}$$

Can control local vorticity and pressure with low AC voltages.

ICEO Mixers, Switches, Pumps…



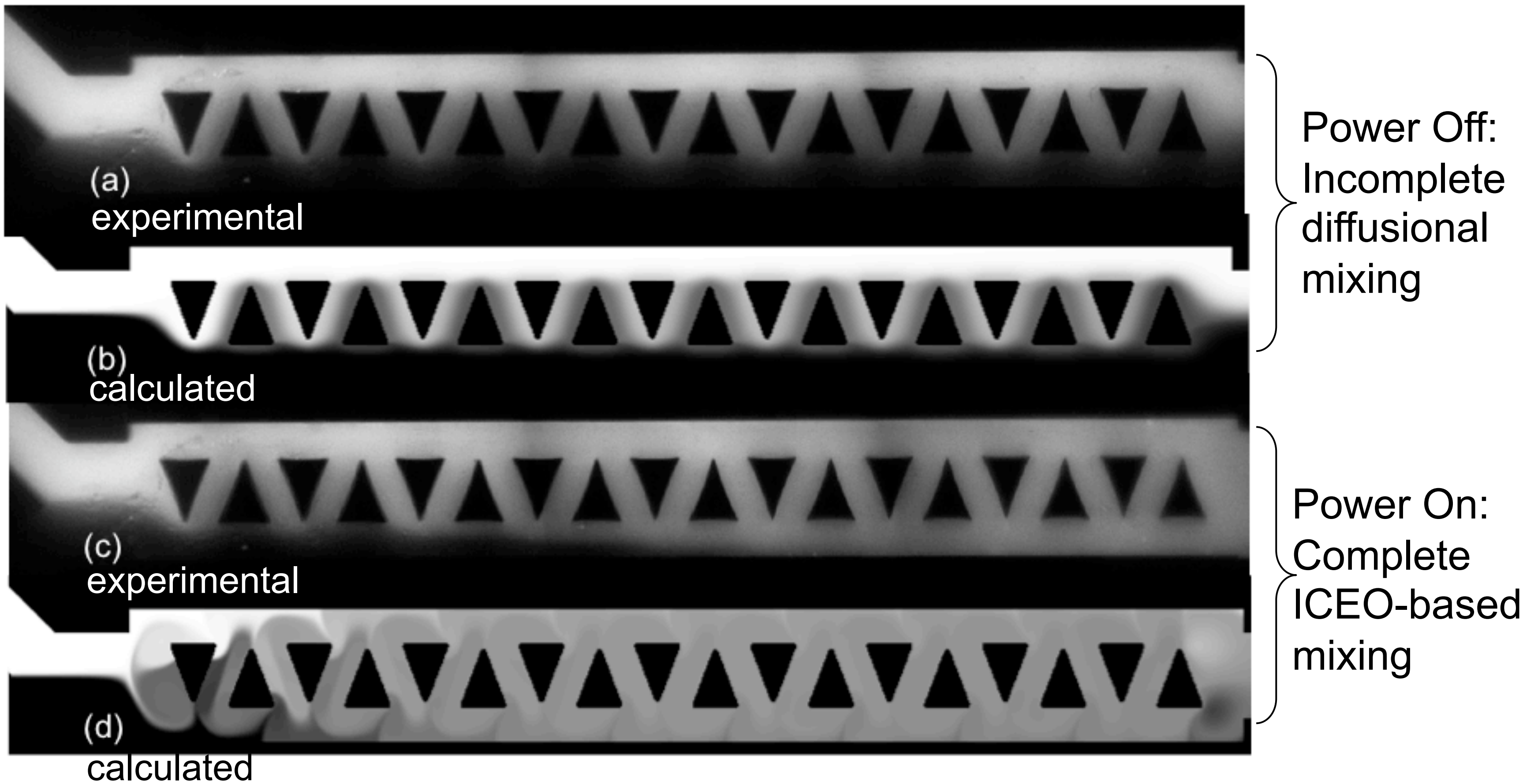




- Advantages
  - tunable flow control
  - 0.1 mm/sec slip
  - low voltage (few V)
- Disadvantages
  - small pressure (< Pa)
  - low salt concentration

ICEO-based microfluidic mixing

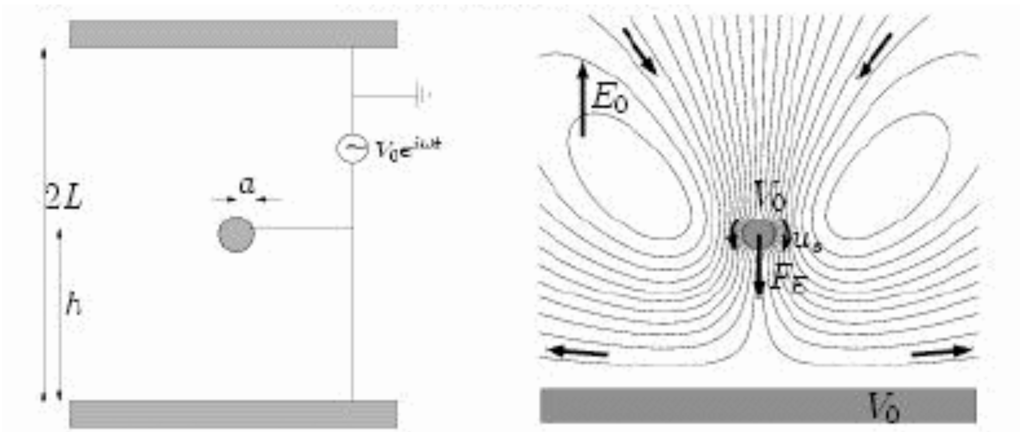
C. K. Harnett et al. Lab on a Chip (2008)



Comparison of experimental (a,c) and calculated (b,d) results during steady flow of dyed and un-dyed solutions (2 μl/min combined flow rate) without power (a,b) and with power (c,d). Flow is from left to right. 10 V_{pp}, 37 Hz square wave applied across 200 um wide channel. Left-right transit time ~2 s.

“Fixed-Potential ICEO” / AC “Flow FET”

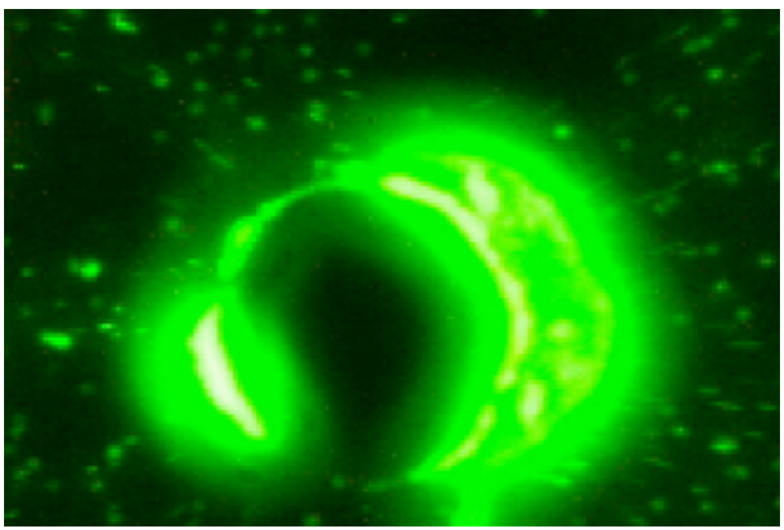
Squires & Bazant, J. Fluid Mech. (2004)

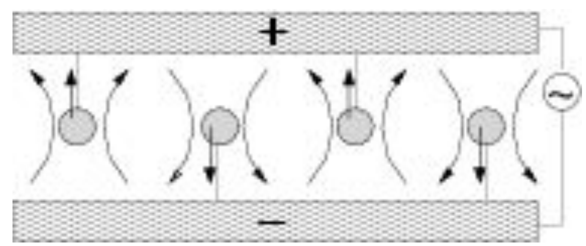


Idea: Vary the induced *total* charge in phase with the local field.

Generalizes “flow field-effect transistor” Ghowsi & Gale, J. Chromatogr. (1991)

Example: metal cylinder grounded to an electrode supplying an AC field.





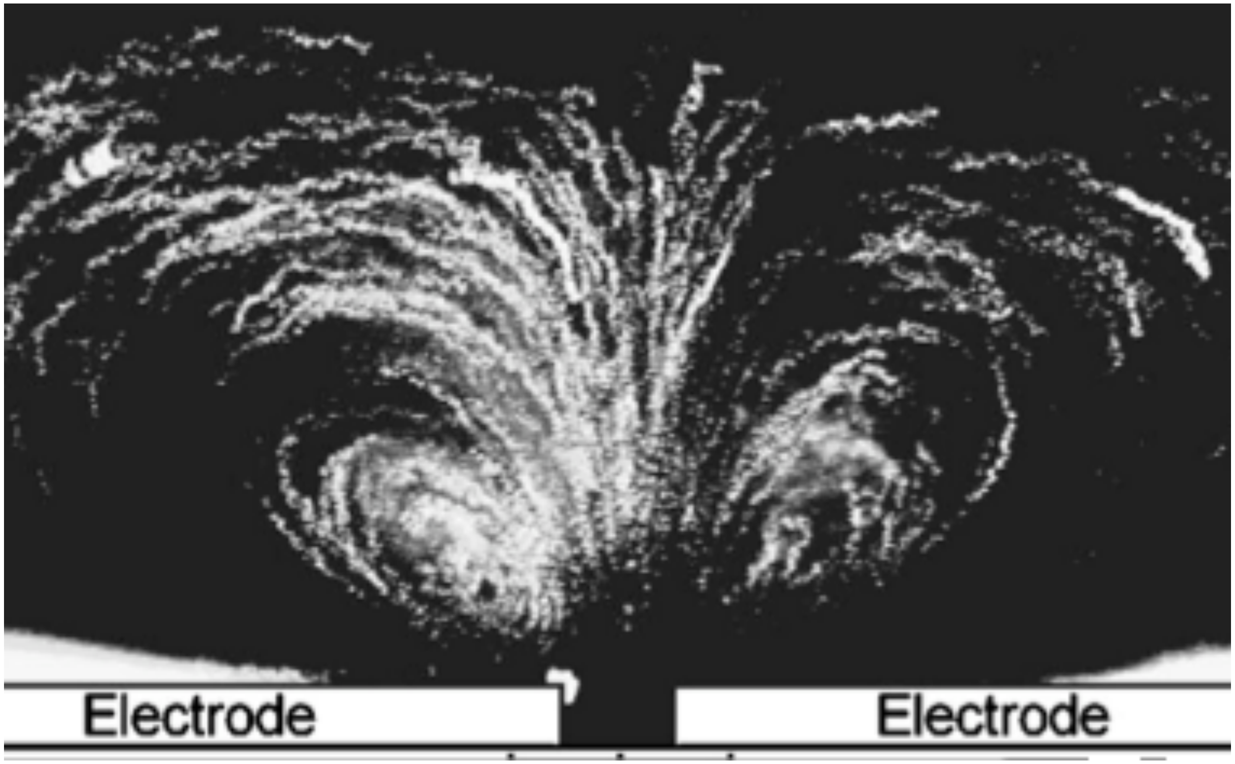
Fixed-potential ICEO mixer

Flow past a 20 micron electroplated gold post (J. Levitan, PhD Thesis 2005)

AC Electro-osmotic Electrode-array Micropumps

AC electro-osmosis

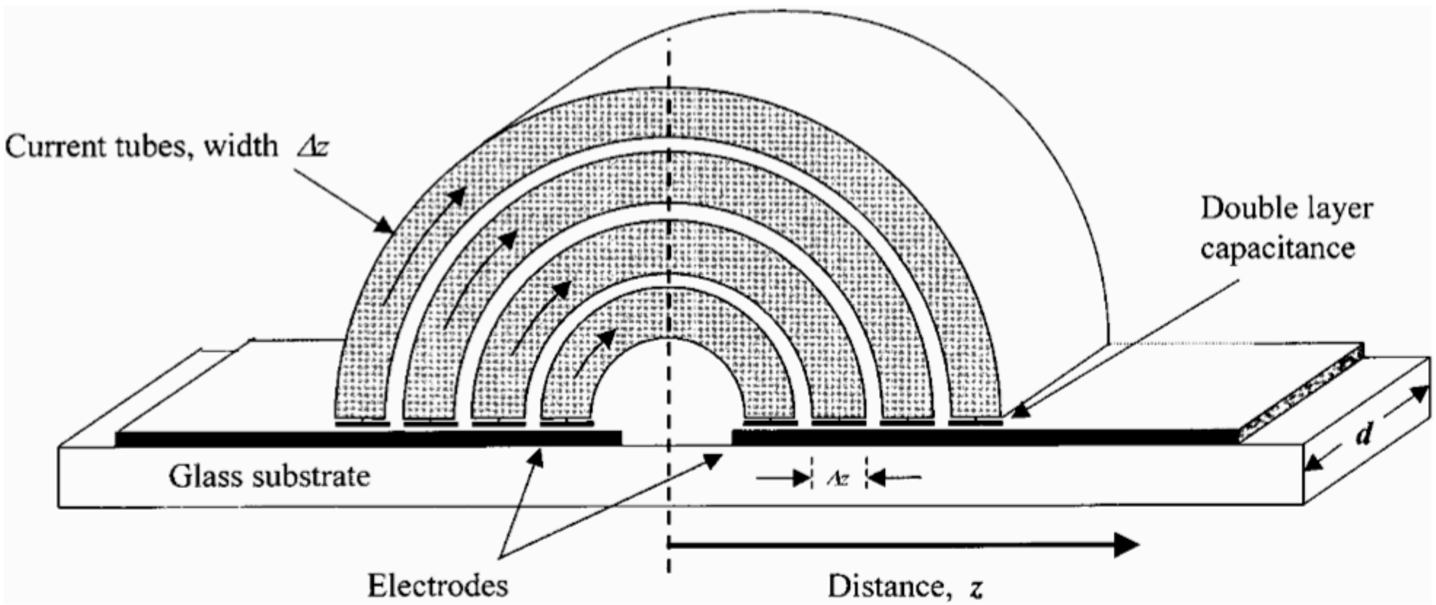
A. Ramos, A. Gonzalez, A. Castellanos (Sevilla), N. Green, H. Morgan (Southampton), 1999.



$$u \propto \frac{\varepsilon V^2}{\eta L} \left[(\omega\tau)^2 + (\omega\tau)^{-2} \right]^{-1}$$

Circuit model

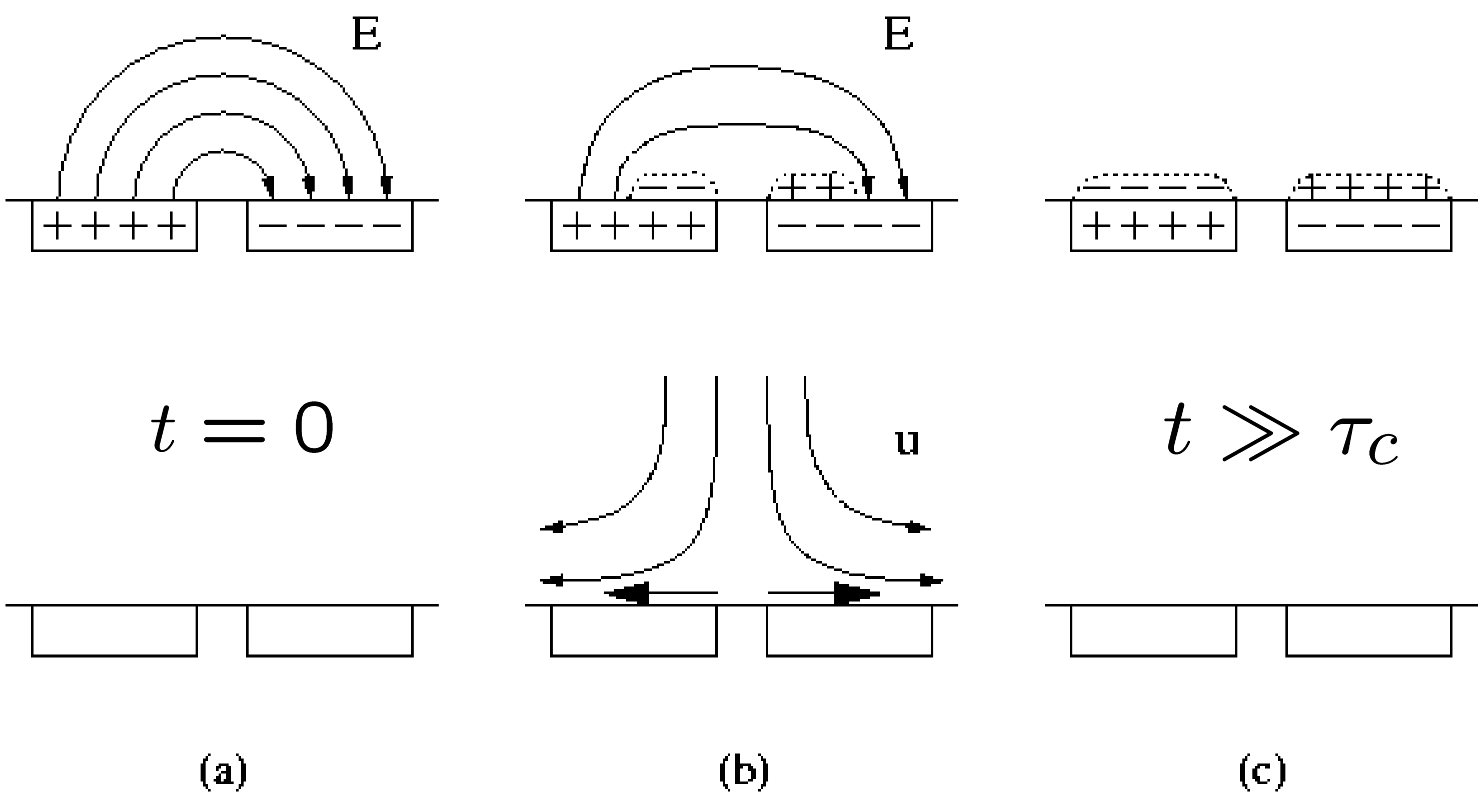
Ramos et al. (1999)



"RC time" $$\tau(r) = \frac{2\pi r}{\sigma}\frac{\varepsilon}{\lambda} \propto \frac{\lambda r}{D} = \tau_D \frac{r}{\lambda}$$

Debye time: $$\tau_D = \frac{\varepsilon}{\sigma} = \frac{\lambda^2}{D}$$

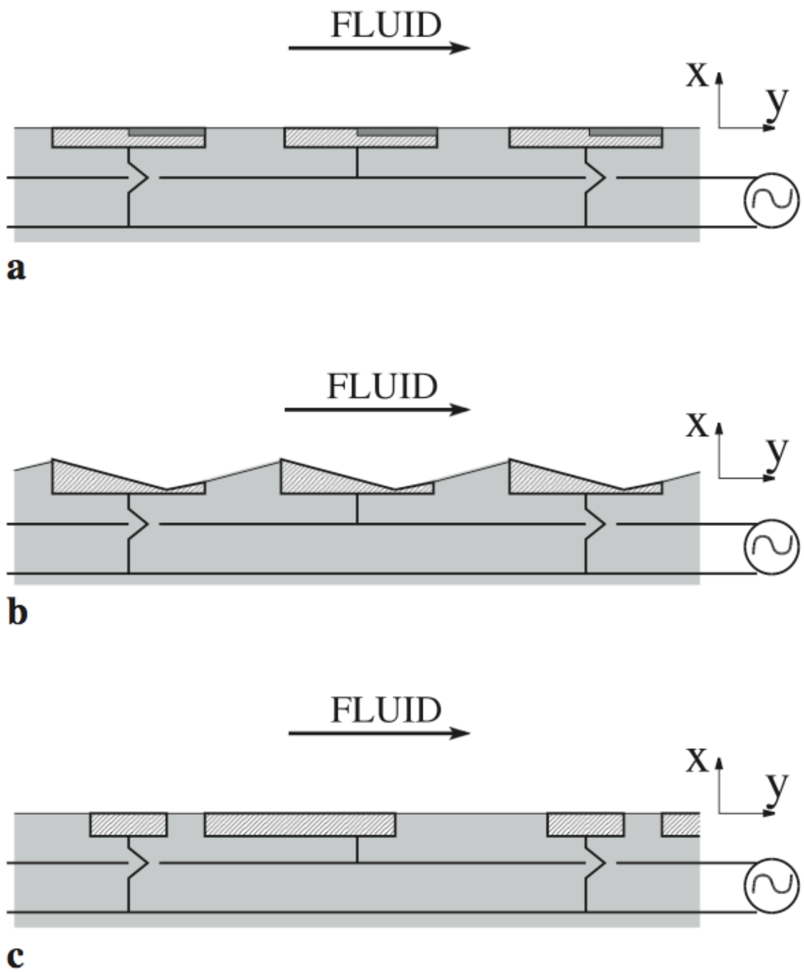
Flows induced over electrodes



- Example: “ICEO” flow in response to a sudden DC voltage
- With AC voltage, flow peaks if period = charging time
- ACEO maximizes flow/voltage due to large local field

AC electro-osmotic pumps

Ajdari (2000)

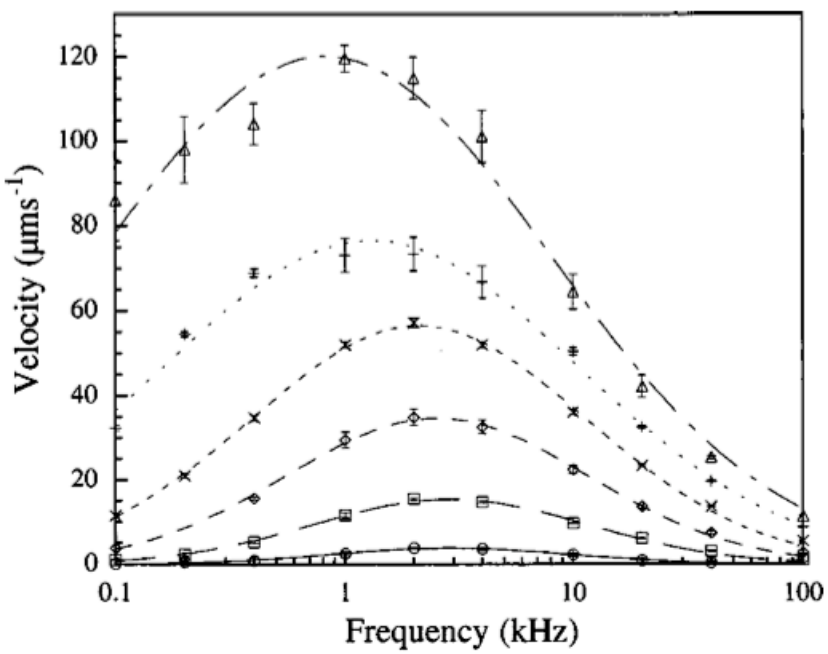


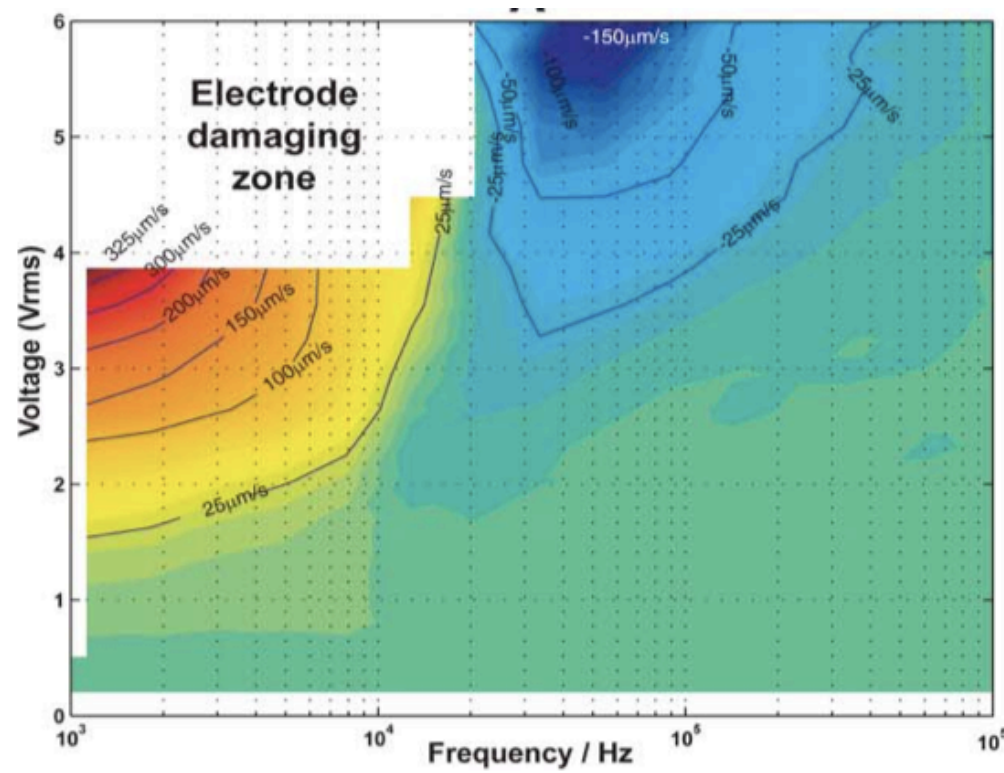
"Ratchet" concept inspired by molecular motors:

Broken local symmetry in a periodic structure with "shaking" causes pumping without a global gradient.

Brown, Smith, Rennie (2001): asymmetric planar electrodes

ACEO Experiments



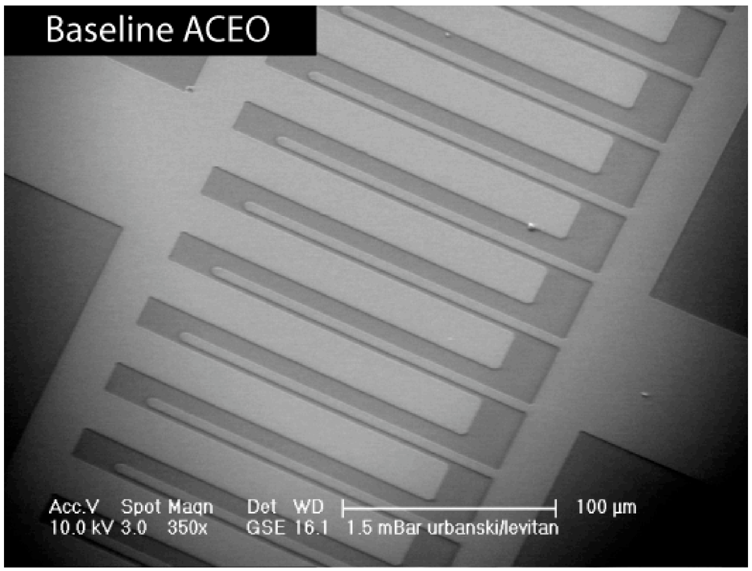


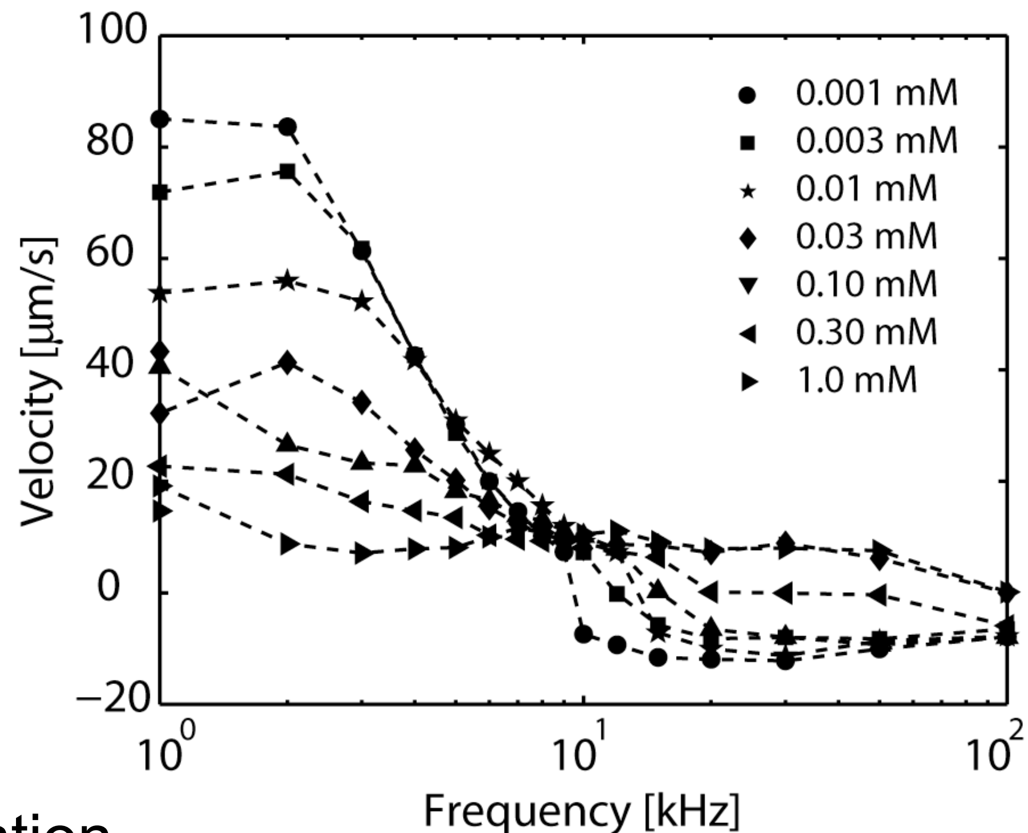
Brown et al (2001), water
- straight channel
- planar electrode array
- similar to theory (0.2-1.2 Vrms)

Vincent Studer et al (2004), KCl
- microfluidic loop, same array
- flow reversal at large V, freq
- no flow for C > 10mM

More data for planar pumps

Urbanski et Appl Phys Lett (2006); Bazant et al, MicroTAS (2007)





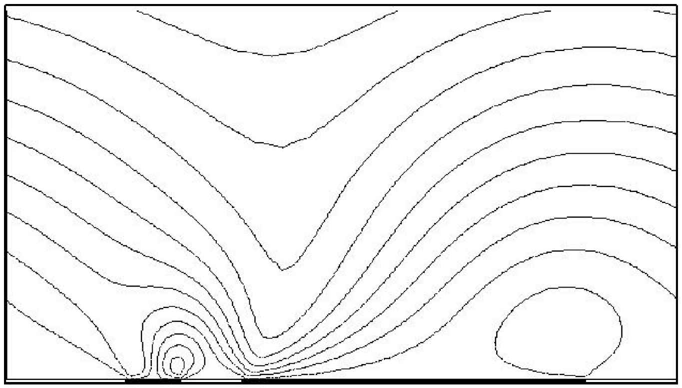
Puzzling features
- flow reversal
- decay with salt concentration
- ion specific

Can we improve performance?

KCl, 3 Vpp, loop chip 5x load

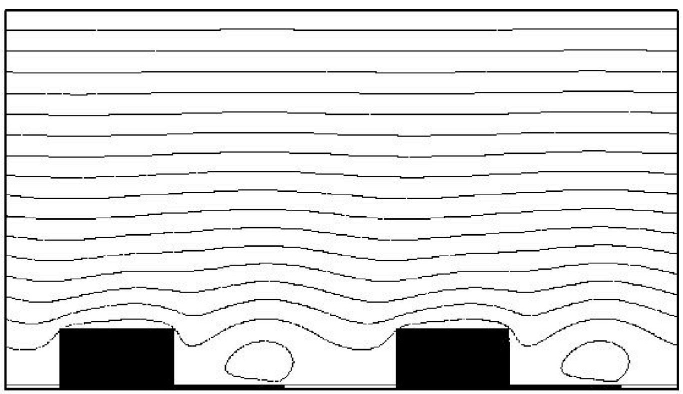
Fast, robust "3D" ACEO pumps

Bazant & Ben, Lab on a Chip (2006); Burch & Bazant, Phys Rev E (2008)

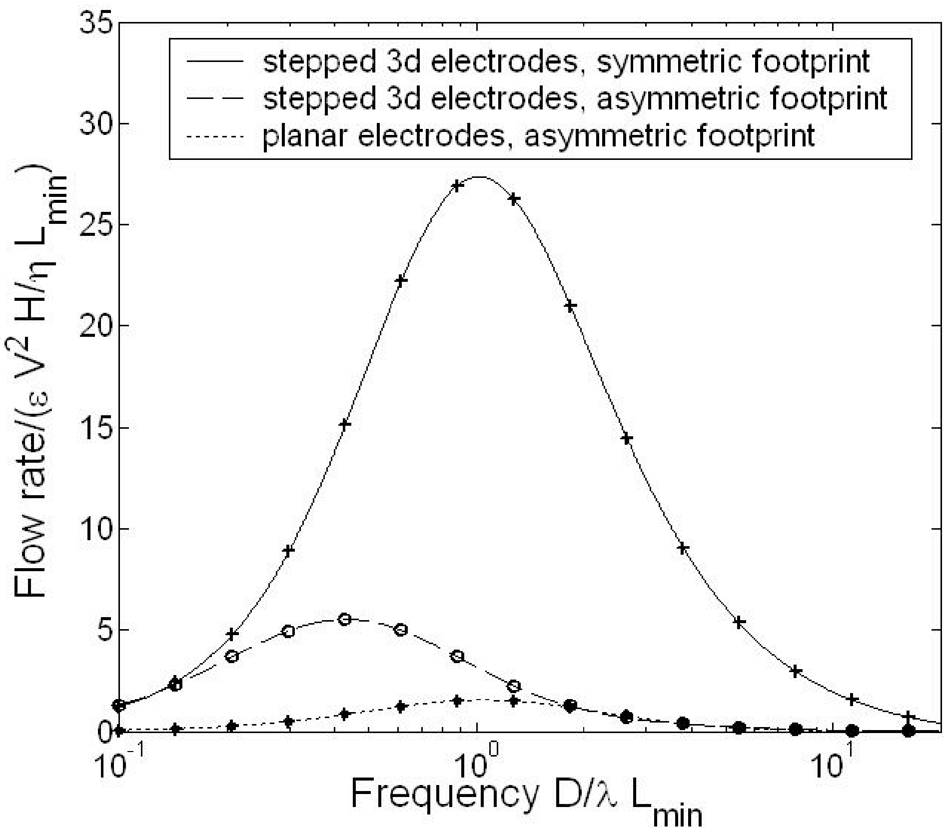


Fastest planar ACEO pump

Brown, Smith & Rennie (2001). Studer (2004)

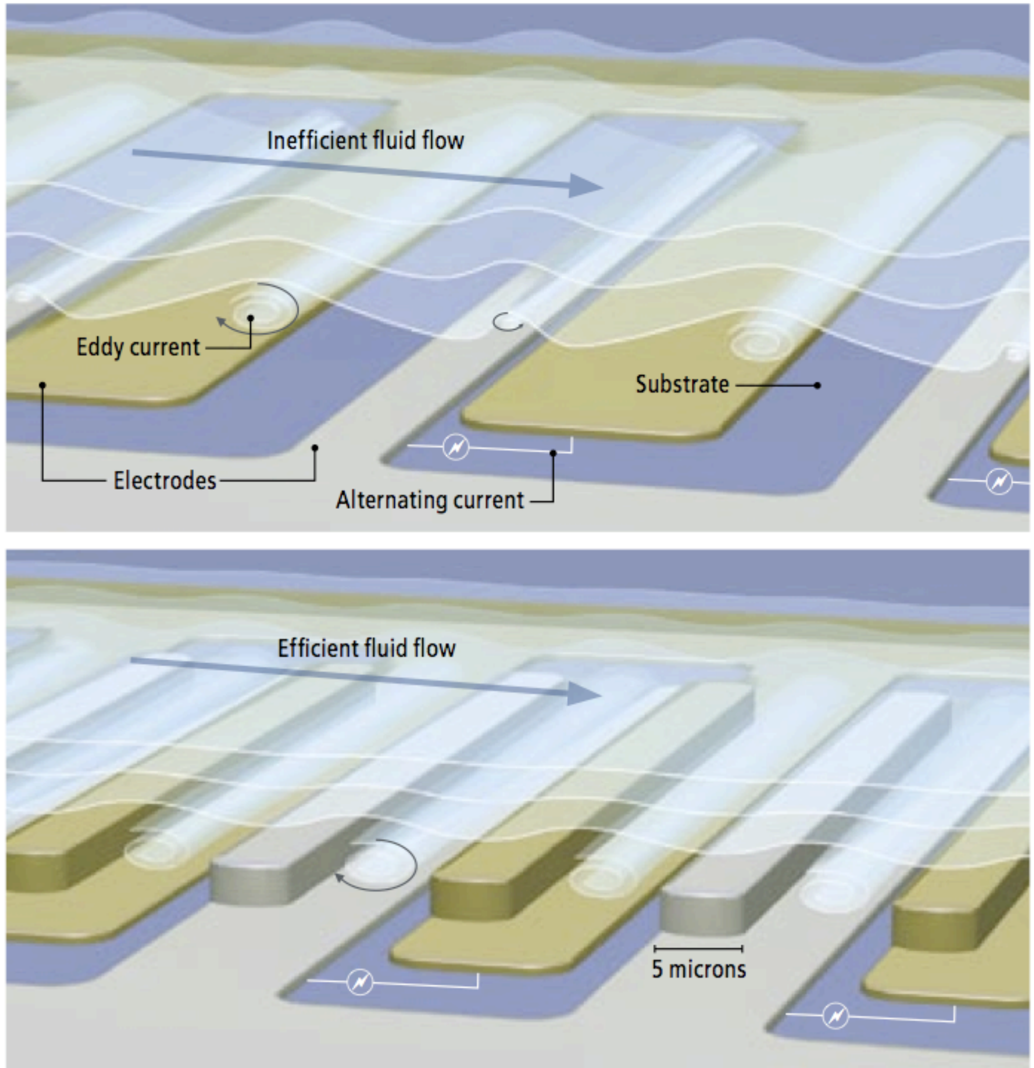


New design: electrode steps create a "fluid conveyor belt"



Theory: "3D" design is 20x faster (>*mm/sec at 1 V rms*) and should not reverse

The ACEO “Fluid Conveyor Belt”



CQ Choi, “Big Lab on a Tiny Chip”, *Scientific American, Oct. 2007.*

High-pressure ACEO pumps

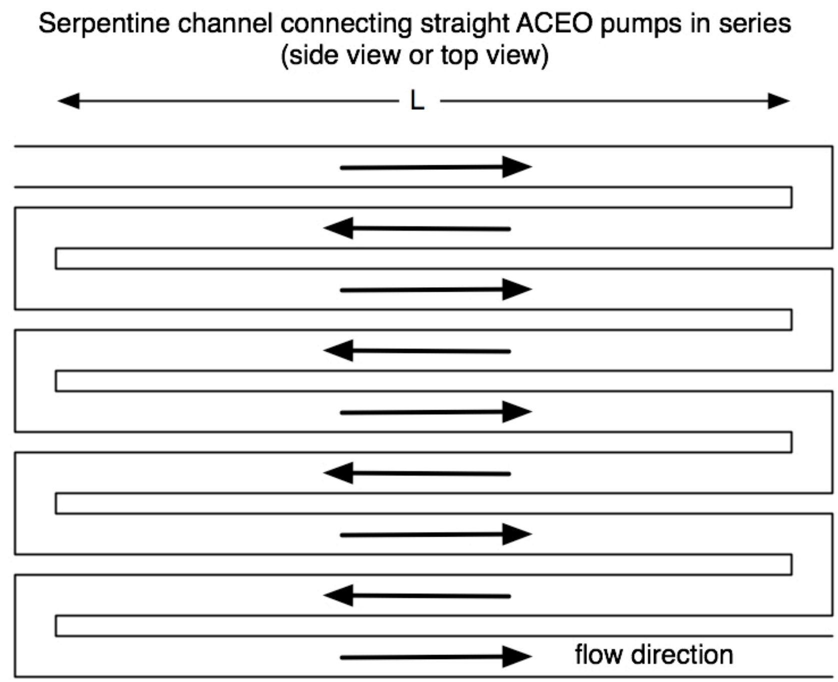
$$P_{max} = R_H Q_{max} \propto \frac{\eta u L}{h^2}$$

Need *h* > micron BUT with **serpentine channels**
L =10m is possible in mL chip volume, so P = atm is possible at few volts AC!

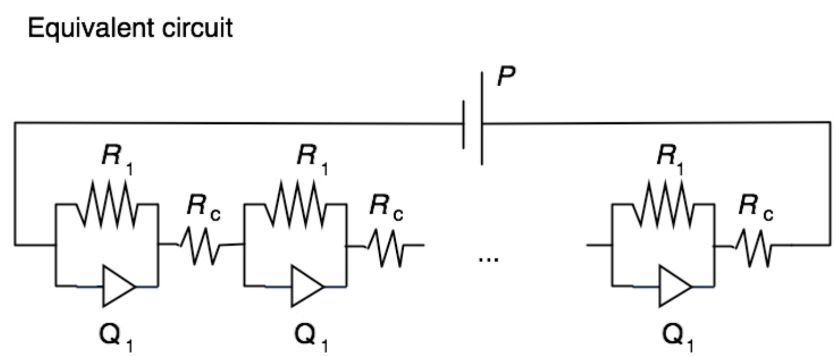
In a fixed device volume, sacrifice Q for P

$$P_{max} Q_{max} \propto \frac{u^2 V}{h^2}$$

(a)

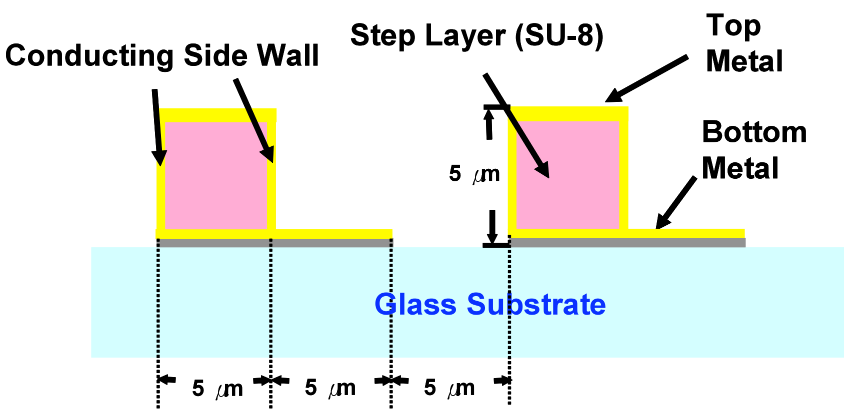


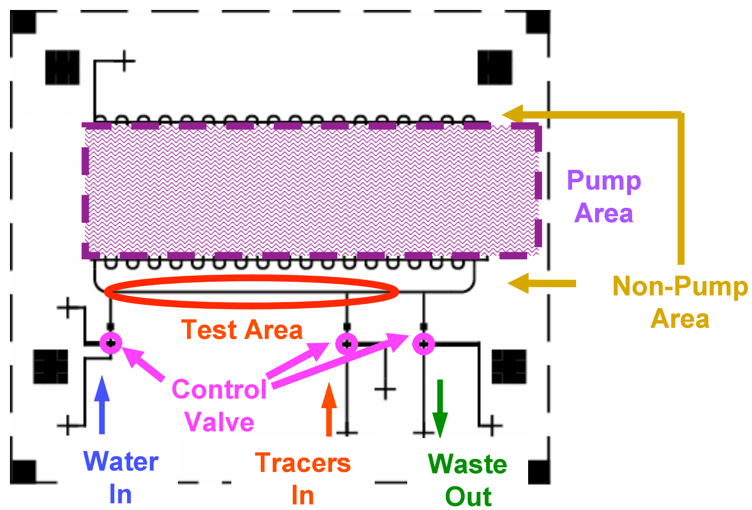
(b)

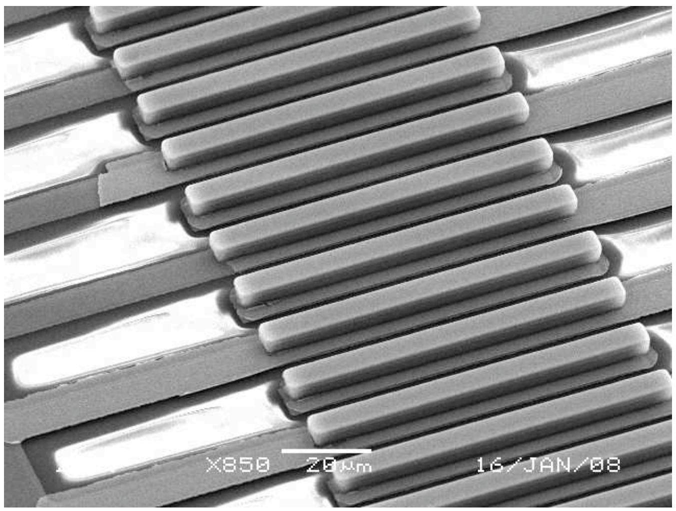


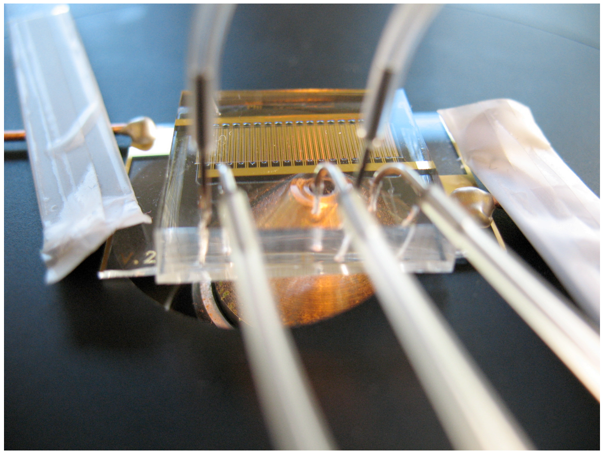
High-Pressure Ultrafast ACEO Pumps

JP Urbanski, JA Levitan, MZB & T Thorsen, Appl. Phys. Lett. (2006)
CC Huang, MZB & T Thorsen, submitted (2009)



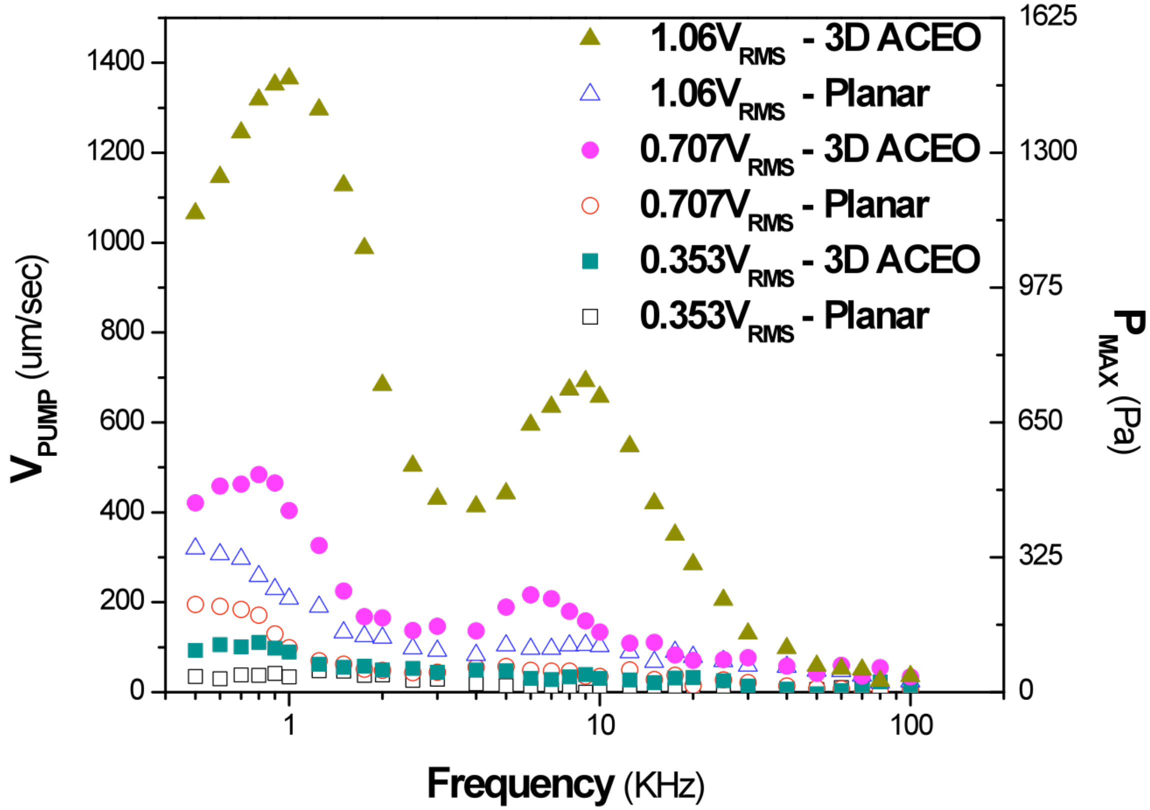






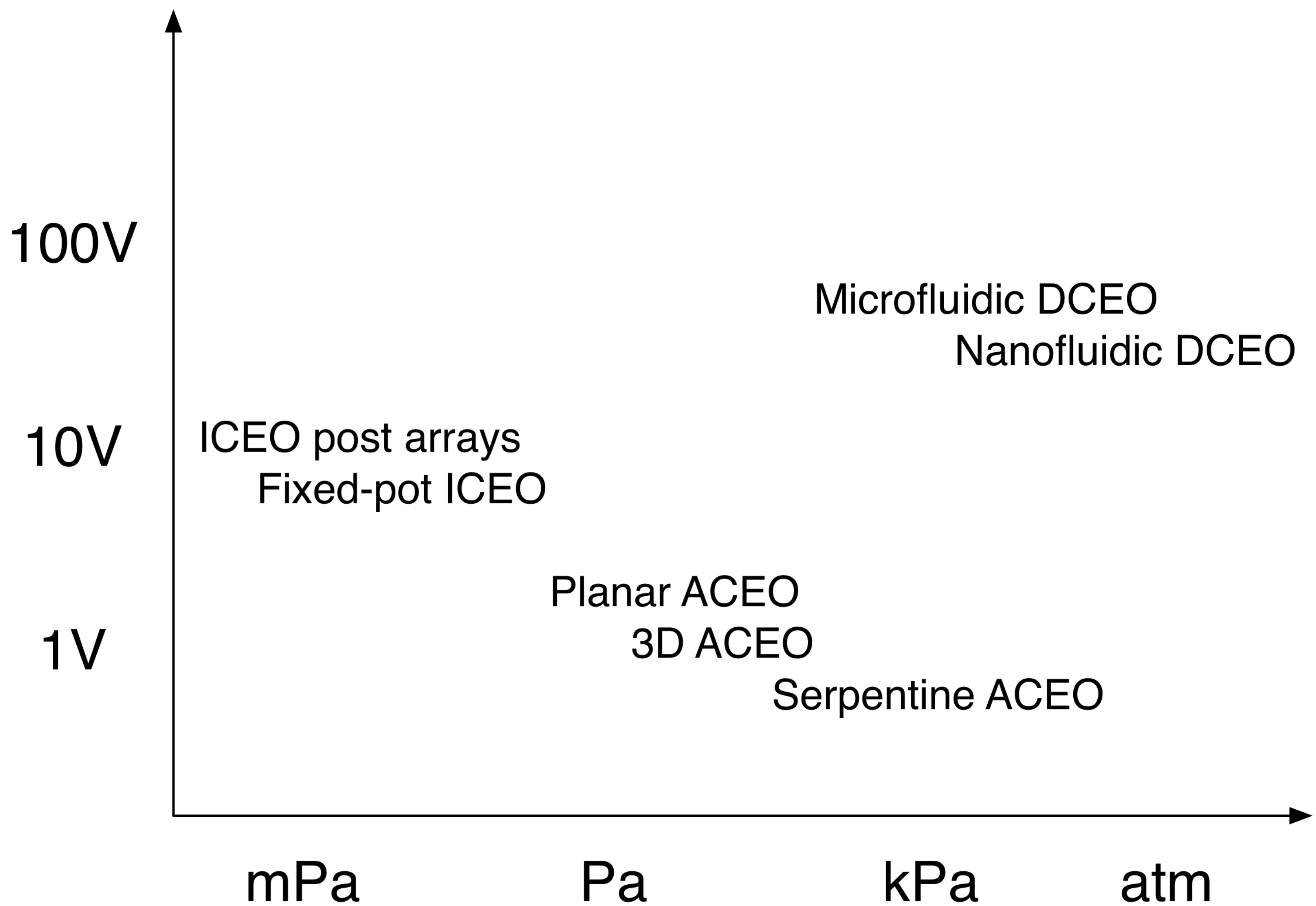
3D ACEO pumping of water

CC Huang, MZB & T Thorsen, submitted (2009)

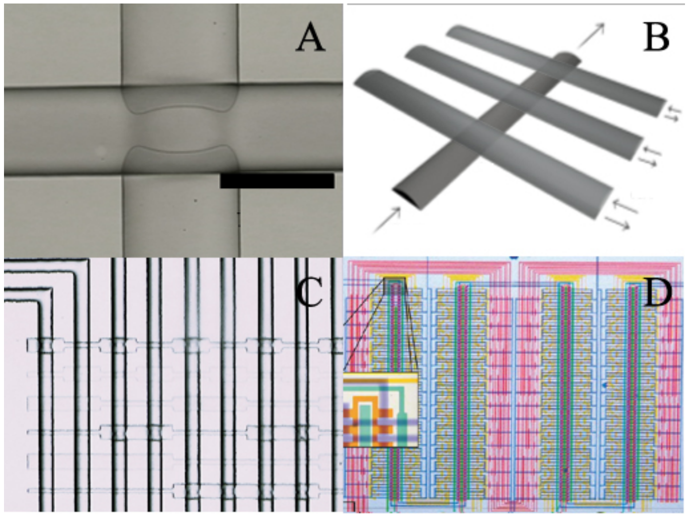


- mm/sec velocity, > 1% atm pressure at 1 Volt rms
- 5 mW power consumption, 3.5 mA current
- Can run for days on small Li-ion battery
- Demonstrated portable DNA microarray chip

AC vs. DC Electro-osmotic Pumps

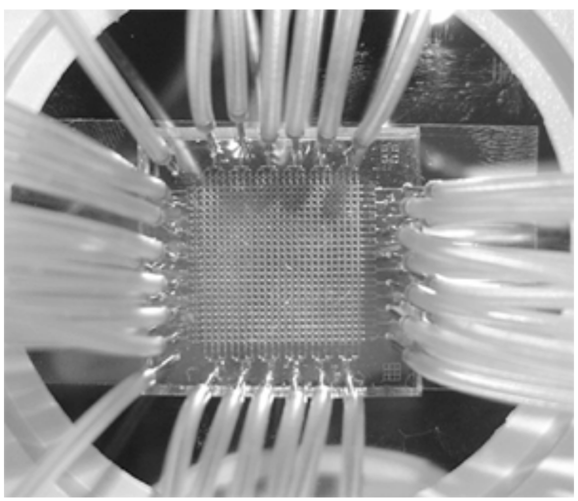


A platform for *portable* microfluidics?



http://www.physics.ubc.ca/~chansen/

Fluidigm Topaz System



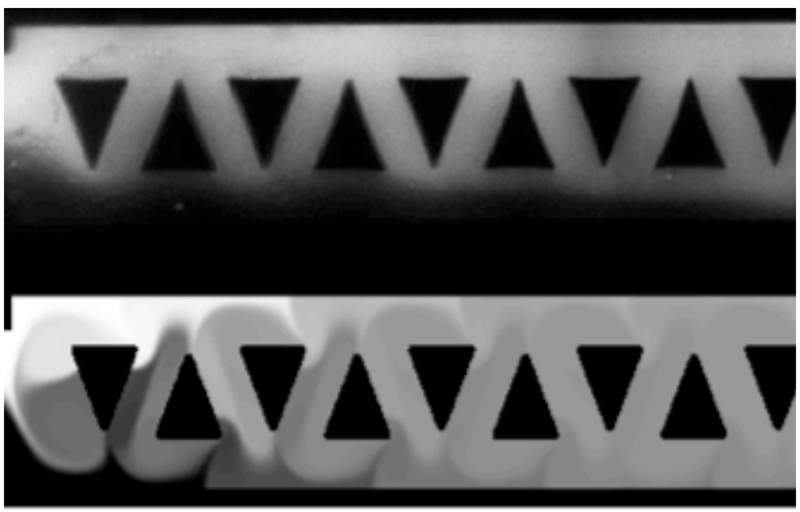
Thorsen/Quake LSI

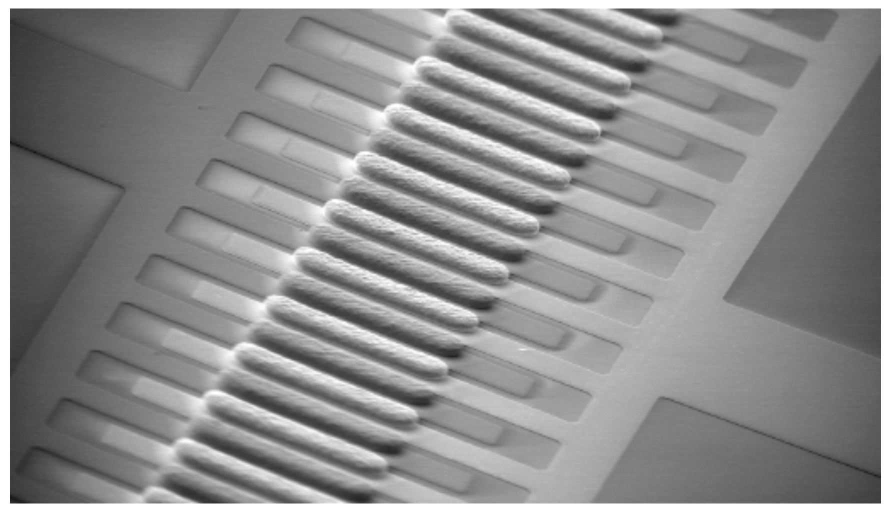
- elastomeric valves
- 1000s of channels
- pressure-driven flows
- “Chip in a Lab”

Can we replace external plumbing with low-voltage ACEO pumps, mixers, switches, etc.?

Conclusion

- Induced-charge AC electro-osmotic flows enable local manipulation of particles and fluids in portable microfluidic devices
- … but limited to dilute electrolytes
- Why? Lecture 5…





Papers, slides… http://web.mit.edu/bazant/www/ICEO