Lab on a Chip and Microfluidics

Benoît CHARLOT

http://www.ies.univ-montp2.fr/~charlot/

l'institut d'électronique

Part IV. Electrokinetics

Electrokinetics

Electrophoresis, motion of particles under influence of electric field;

Electro-osmosis, as motion of liquid in porous body under influence of electric field

diffusiophoresis, as motion of particles under influence of a chemical potential gradient;

Capillary osmosis, as motion of liquid in porous body under influence of the chemical potential gradient;

sedimentation potential, as electric field generated by sedimenting colloid particles;

streaming potential/current, as either electric potential or current generated by fluid moving through porous body, or relative to flat surface;

colloid vibration current, as electric current generated by particles moving in fluid under influence of ultrasound;

Electric sonic amplitude, as ultrasound generated by colloidal particles in oscillating electric field.

Electro Osmosis Force (EOF)

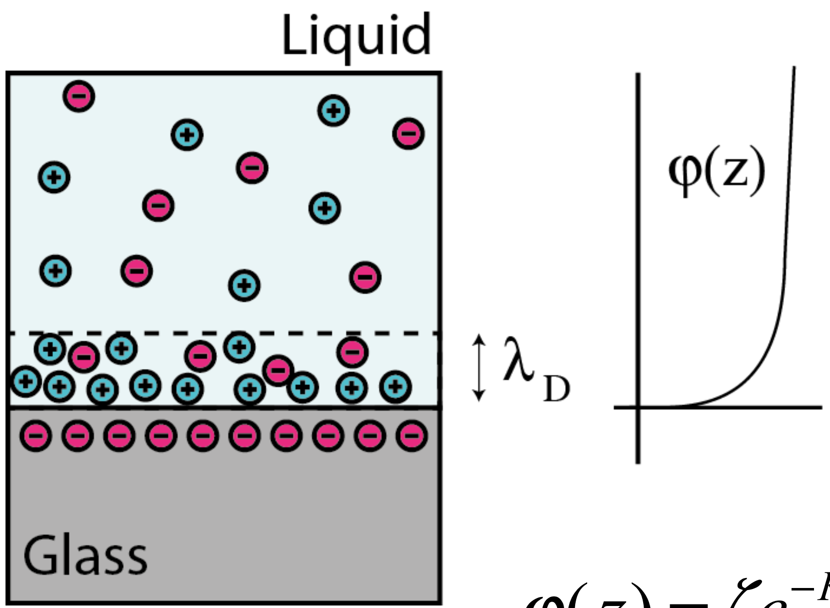
Discovered in 1809

Electric double layer + Coulomb force

-Surface charges : Dissociation of surface molecules

-Si-OH -> Si-O$^-$ + H$^+$ (one negative charge / 16nm^2)

- Mobile charges : ions attracted to the surface charge via the coulomb force, electrically screening the first layer.



$$\varphi(z) = \zeta e^{-Kz}$$

Zeta potential

Electric double layer spread over the **Debye length**

$$\lambda_D = \kappa^{-1} = \sqrt{\frac{\varepsilon_d K_B T}{\sum_i q_i^2 c_i^2}}$$

ε dielectric permittivity

K_B Boltzmann constant

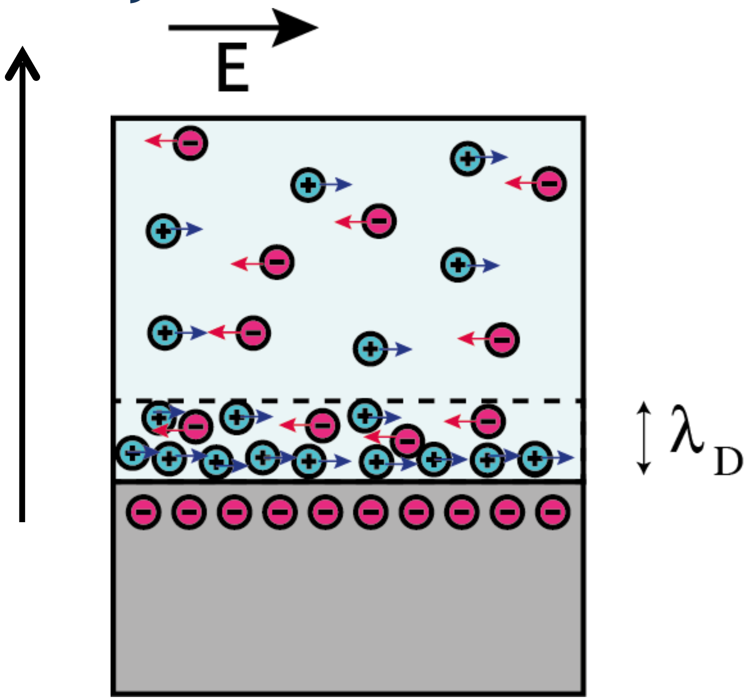
q charge

C concentration

λ_D = 700 nm for pure water

10 nm for salted water

Electro Osmosis Force (EOF)



With a Potential difference : Net force in the Debye zone

What is the velocity profil $v(z)$?

Stokes equation + isobar condition

$$\mu \frac{\partial^2 v(z)}{\partial z^2} - \cancel{\nabla p} + \rho_e E = 0$$

Poisson-Boltzmann equation : distribution of the electric potential in solution in the direction normal to a charged surface

$$\nabla^2 \varphi = -\frac{\rho_e}{\varepsilon_w} = -\frac{e(n_+ + n_-)}{\varepsilon_w}$$

φ is the electric potential

ρ is the local electric charge density ($C.m^{-3}$)

n is the density of charges

ε_w is the dielectric constant of the liquid (water)

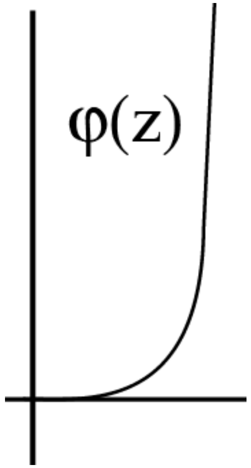
$$\mu \frac{\partial^2 v(z)}{\partial z^2} = \varepsilon_w \frac{\partial^2 \varphi}{\partial z^2} E$$

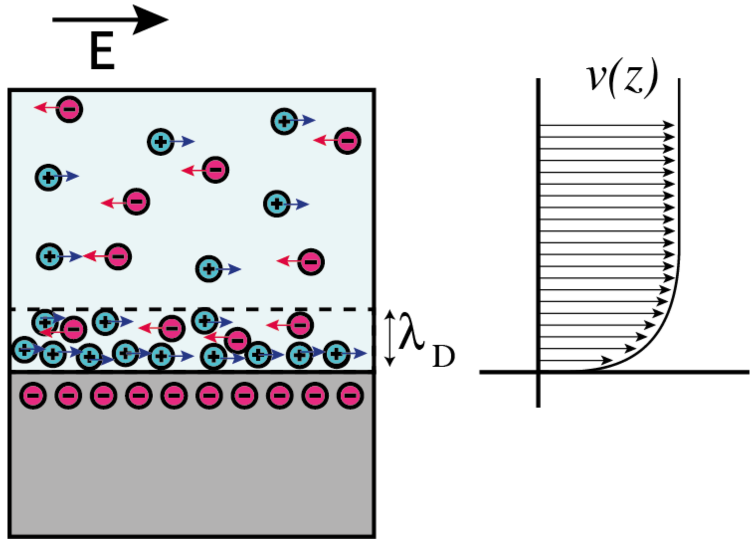
$$v(z) = \frac{\varepsilon_w E}{\mu} \left(\varphi(z) - \varphi(0) \right)$$

$$\boxed{v(z) = \frac{\varepsilon_w \zeta E}{\mu}}$$

Electro Osmosis Force (EOF)

$$v(z) = \frac{\varepsilon_w \zeta E}{\mu}$$

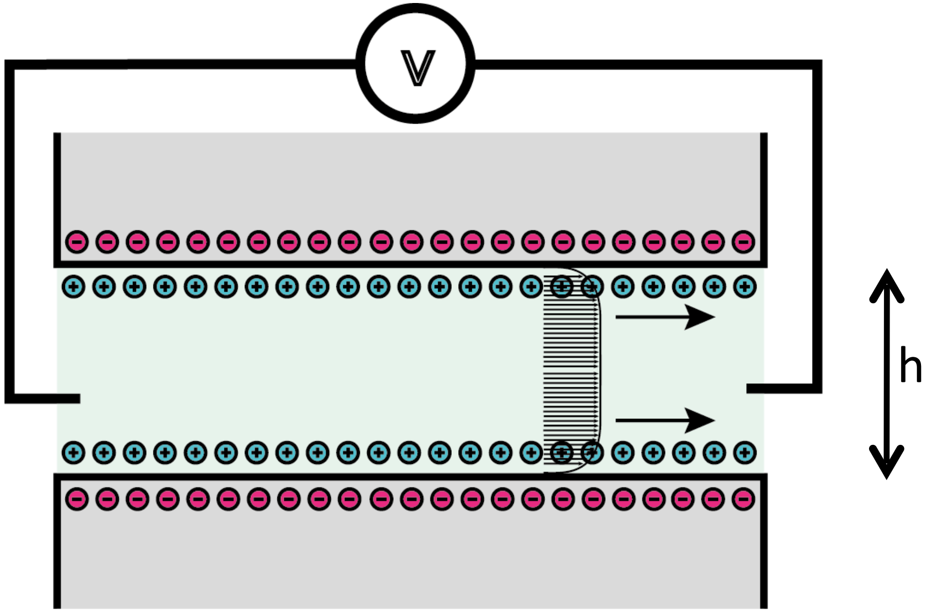




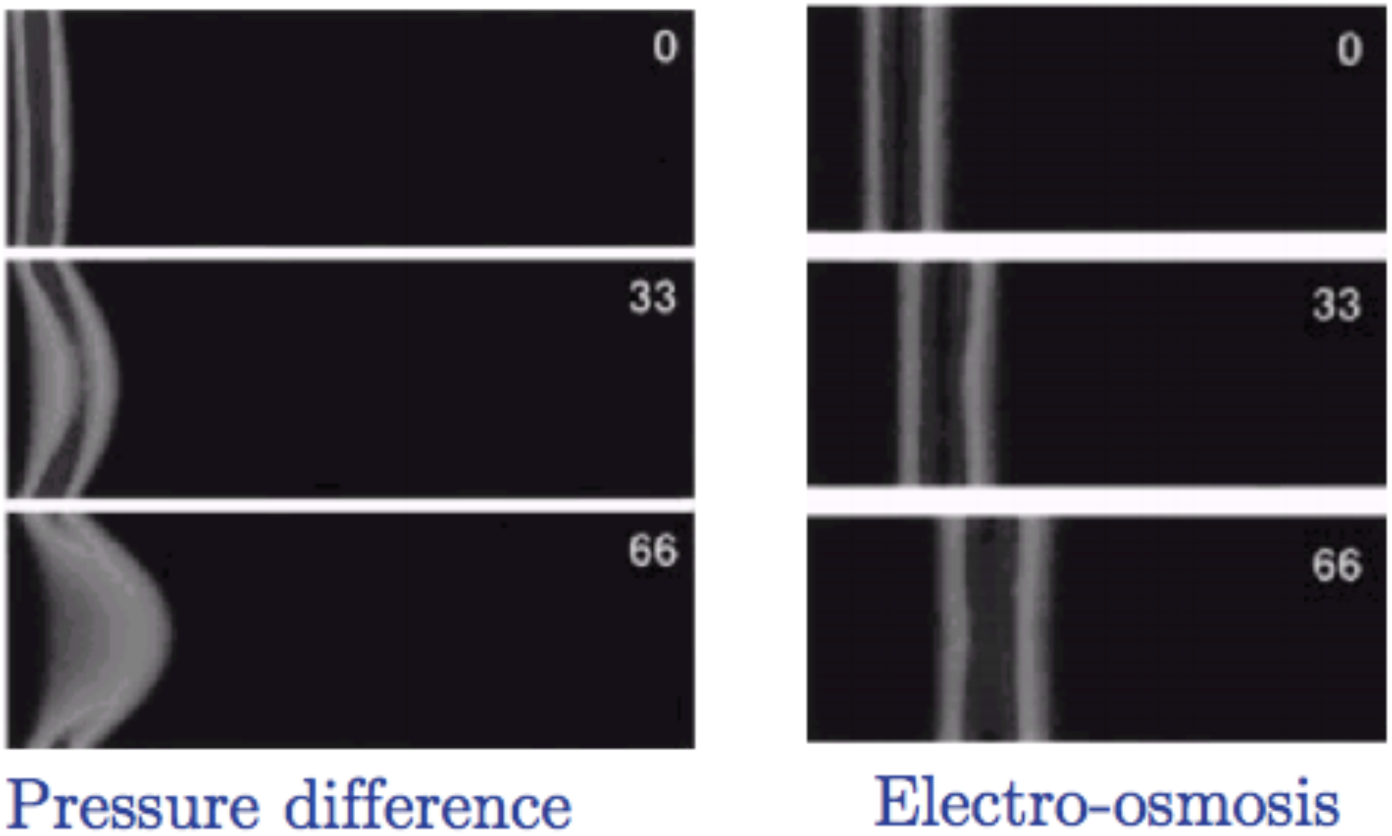
Smoluchowski slip velocity

! Independant of λ_D and h

Plug flow, velocity profile almost uniform



Electro Osmosis Force (EOF)

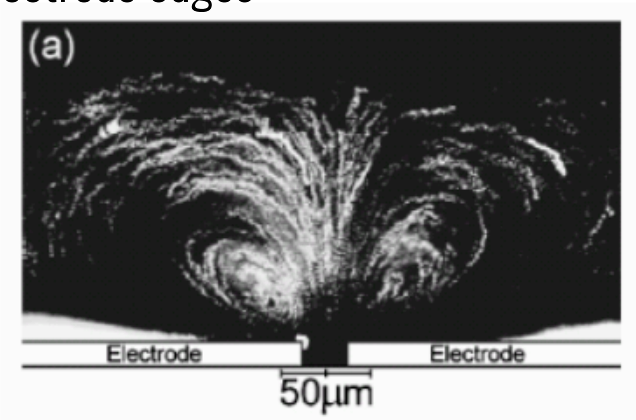


Steven T. Wereley
Mechanical Engineering
Purdue University
"ME 517 Lecture 36: Microfluidic Diagnostics,"
https://nanohub.org/resources/21080.

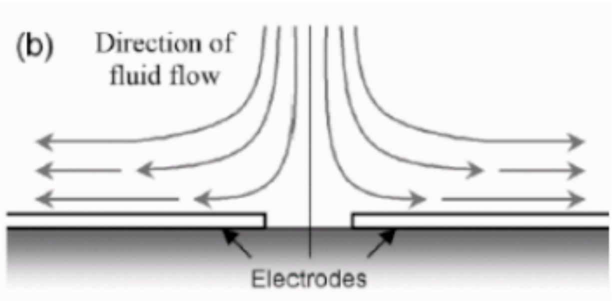
AC Electro Osmosis (ACEO)

Induced charge electro osmosis (ICEO)
Planar electrodes are fed with an alternative signal

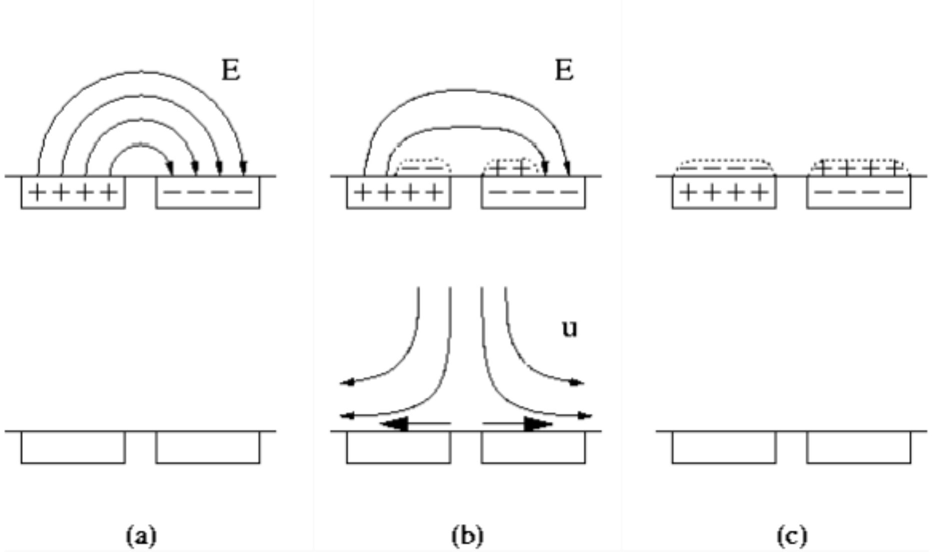
Induced flow looks like convection cells pointed toward electrode edges

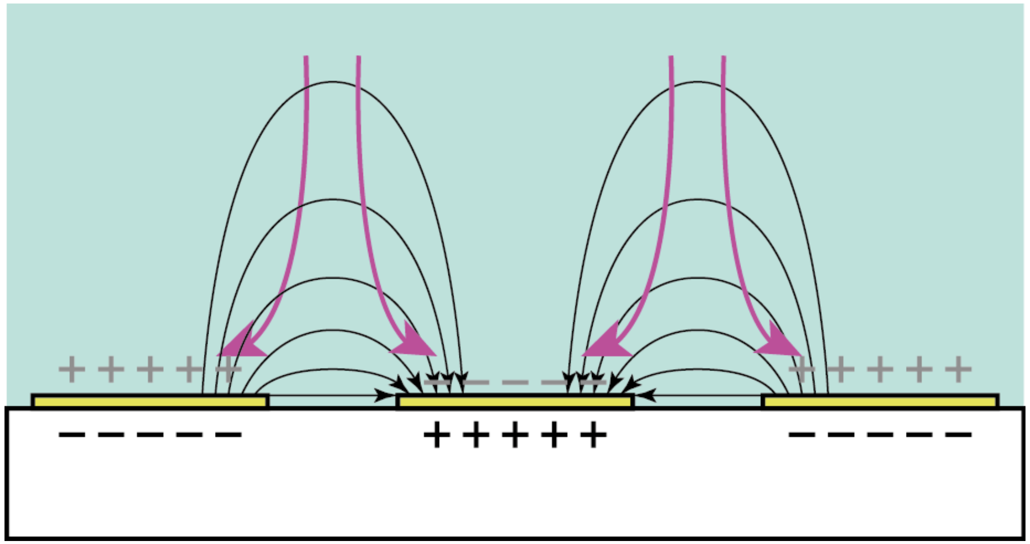


Streamlines of particles
(Captured by a video camera)



Pak Kin Wong, Pennsylvania State University

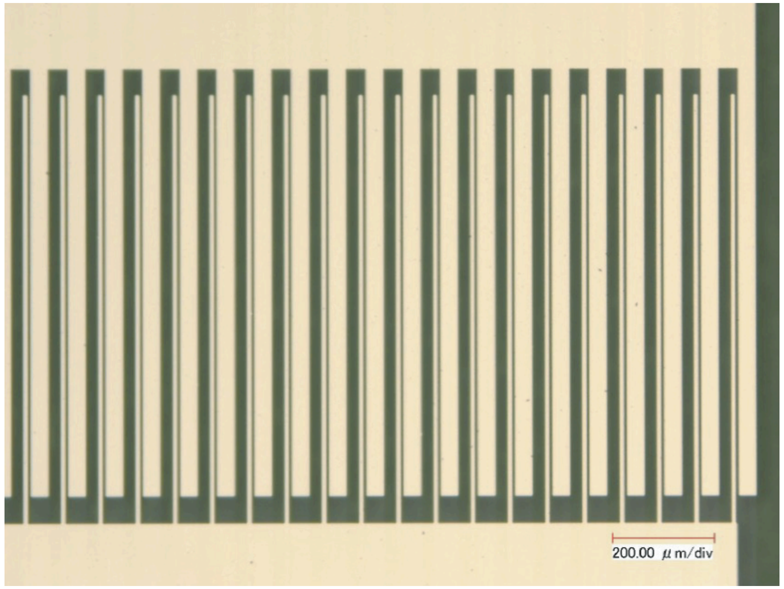




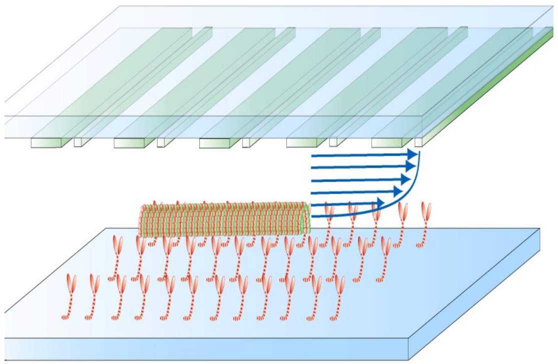
AC Electro Osmosis (ACEO)

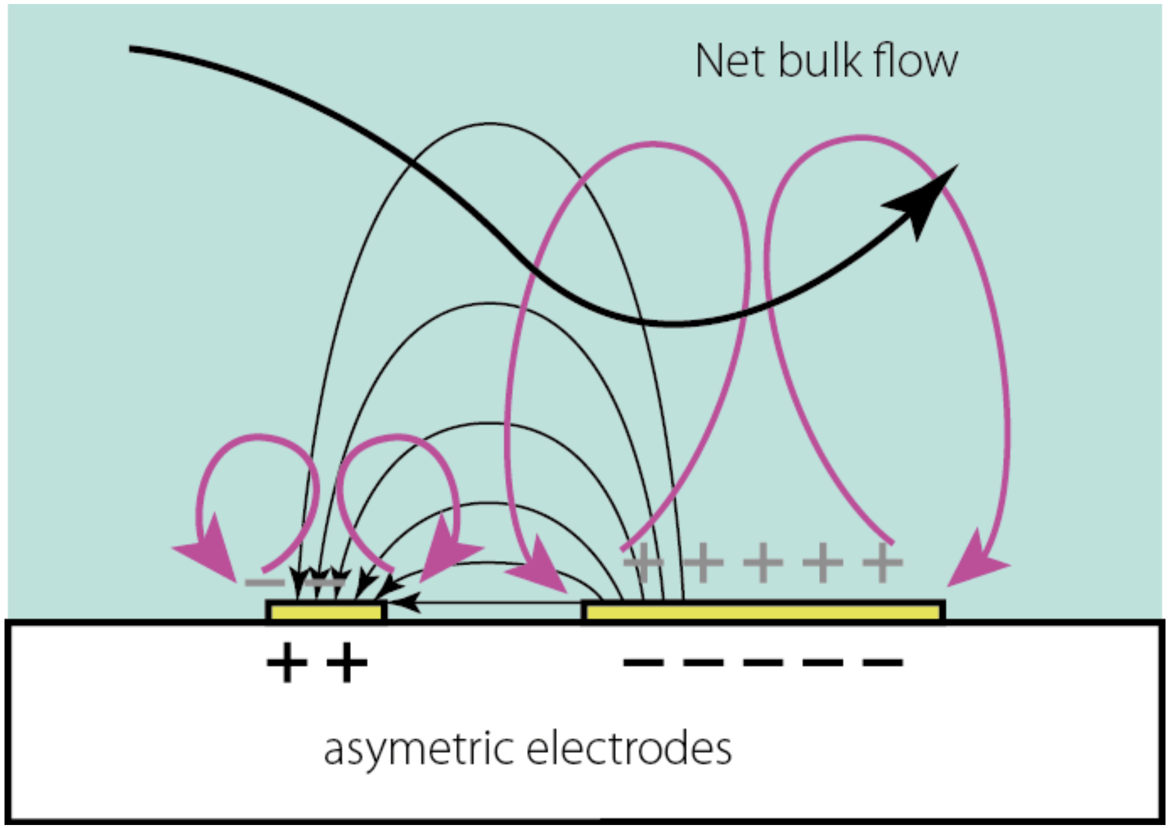
Electroosmotic Pumping

Asymetric planar electrodes



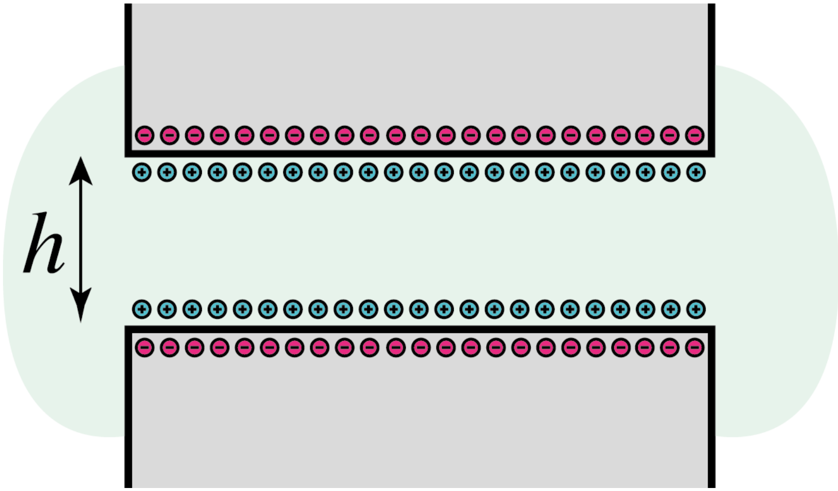
F.O. Morin, H.Fujita, LIMMS

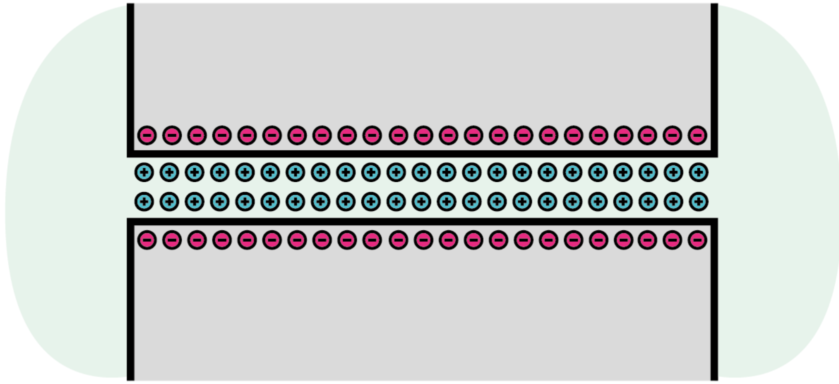


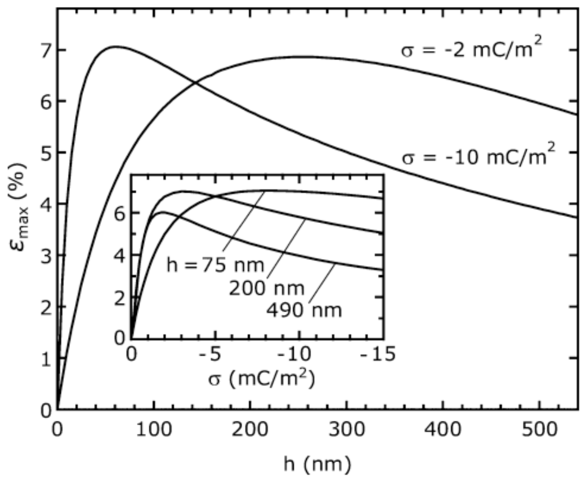


Nanofluidics

What happens if we decrease h toward λ_D ?







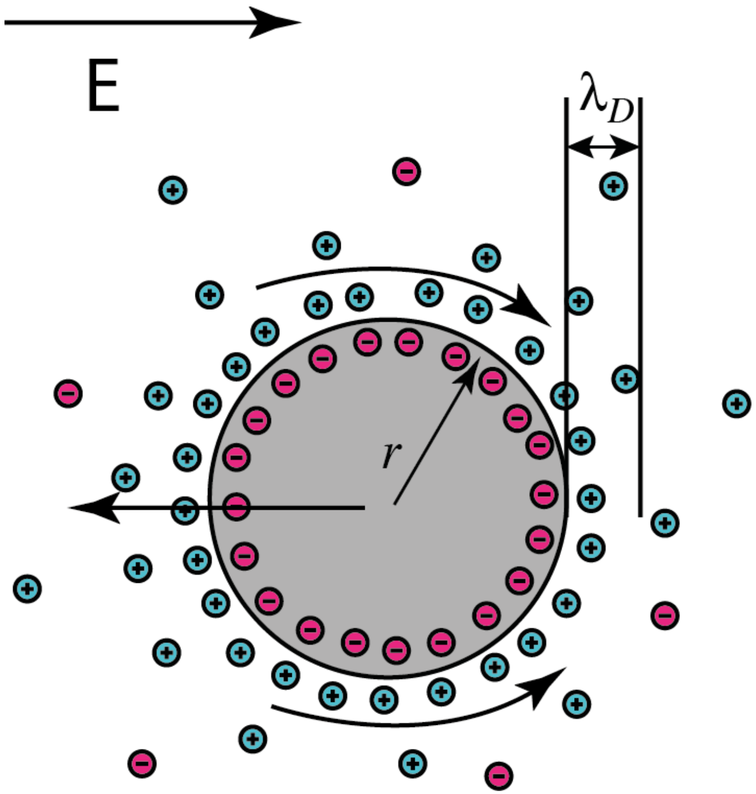
Frank H. J. van der Heyden, Nano Lett., Vol. 6, No. 10, 2006

Electrophoresis

It is the transport by Coulomb forces of **charged particles** (nm, µm) within a fluid under the action of an electric field

$$\vec{F} = Q\vec{E} + \left(\vec{P} \cdot \nabla\right)\vec{E}$$

Electrophoresis   Dielectrophoresis



- Anionic particles(-) move toward anode(+)
- Cationiques particles (+) move toward cathode (-).

Speed of particles?

$$v = \frac{\varepsilon\zeta}{\mu}E = \mu_e E$$

Valid only for $\lambda_D < r$

ζ Zeta potential

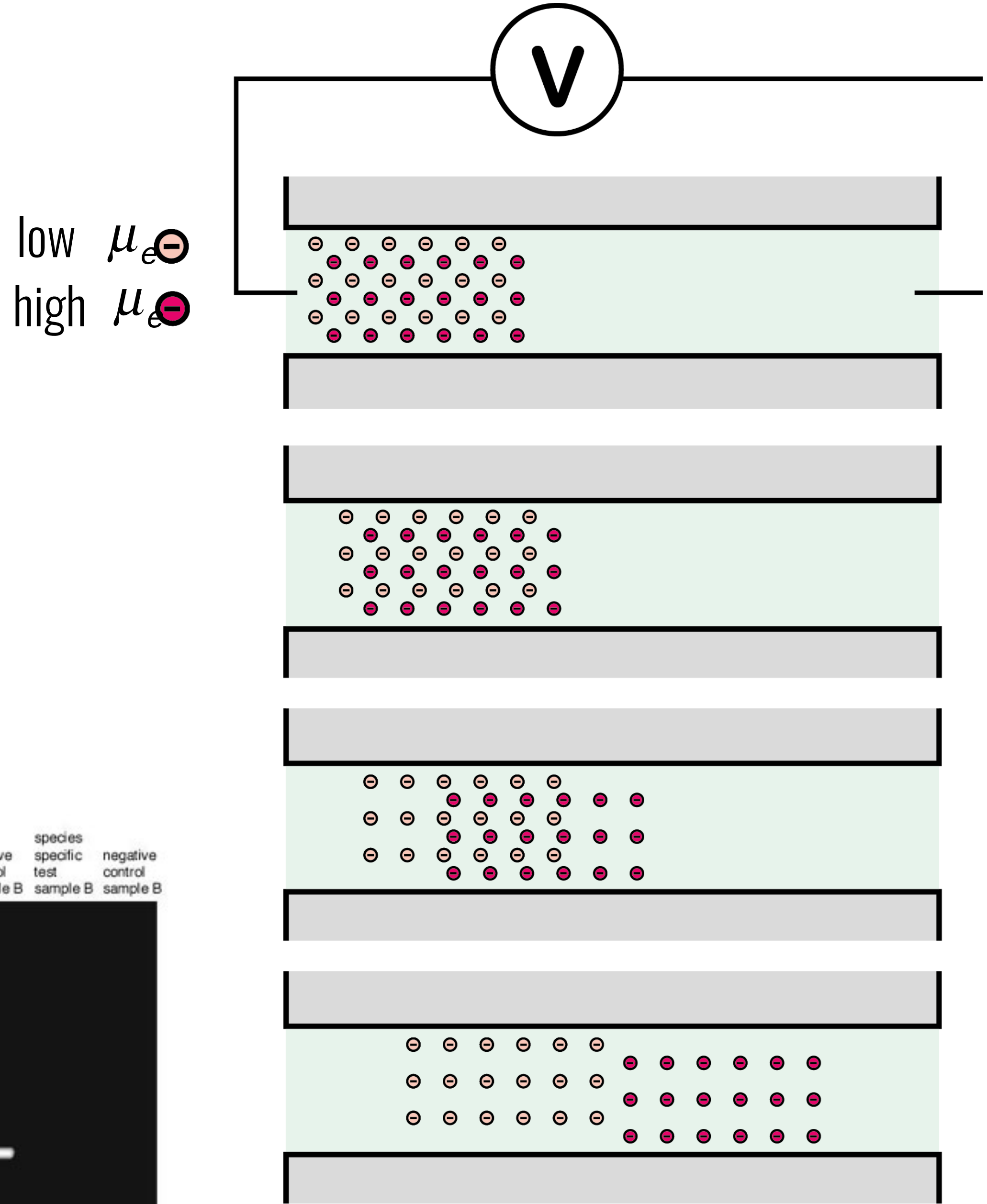
μ Viscosity

E electric field

μ_e Electrokinetic mobility

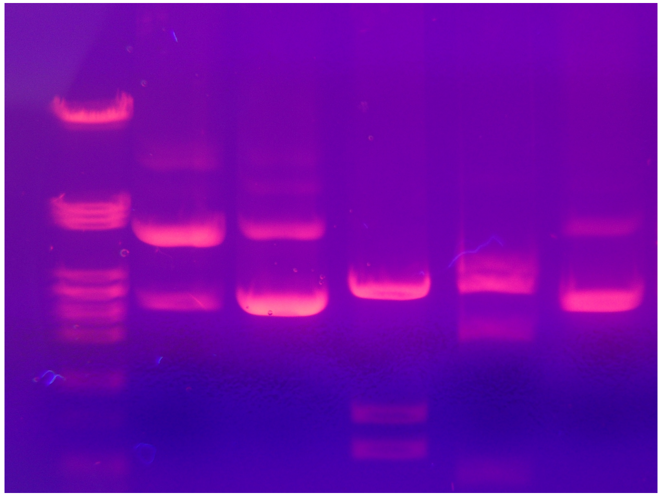
- Speed independent of the size, density and concentration of the particules!!!
- electrophoresis does not allow to sort particles of different mass but only different ζ

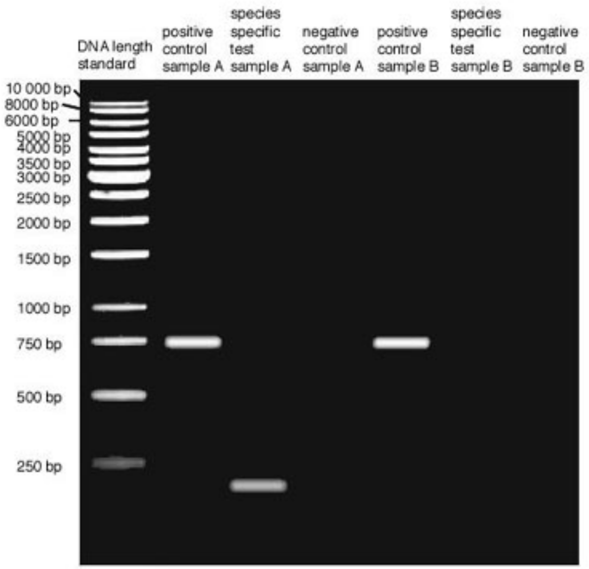
Electrophoresis



Capillary Electrophoresis : Sorting of particles with different electrokinetic mobility using an electric field

Application : DNA sorting by size (kbp)





Dielectrophoresis (DEP)

Dielectrophoresis (DEP) is the movement of a charge neutral particle in a dielectric fluid induced by an inhomogeneous electric field

$$\vec{F} = Q\vec{E} + \left(\vec{P} \cdot \nabla\right)\vec{E}$$

Electrophoresis ($Q\vec{E}$) — Dielectrophoresis ($(\vec{P} \cdot \nabla)\vec{E}$)

! this force does not require the particle to be charged

Driving field can be either DC or AC.

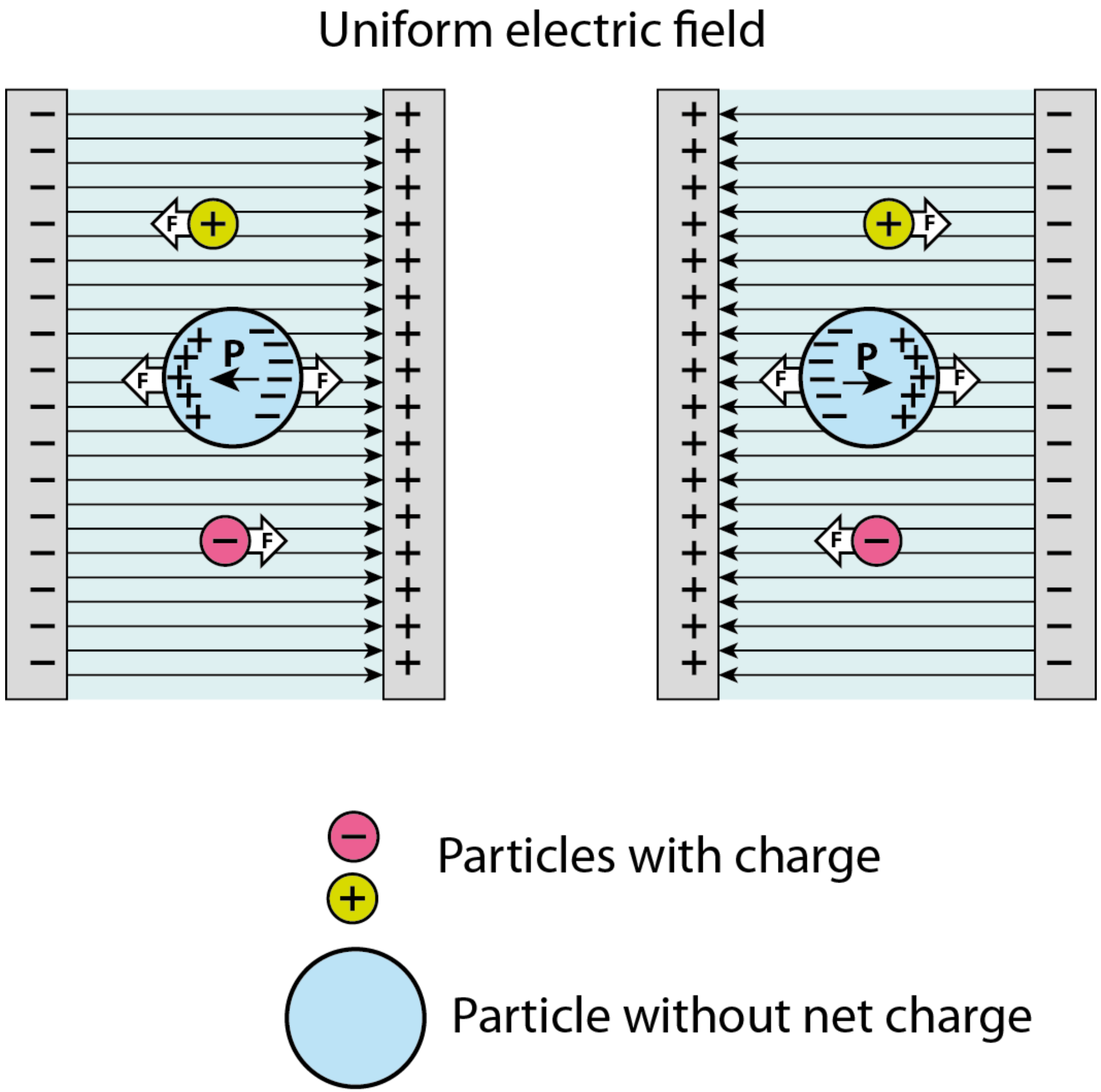
Dielectrophoresis (DEP)

Particles in a uniform Electric field

Only particles with a net charge are attracted by an electrode

Symetry

$$\vec{F} = Q\vec{E} + \cancel{\left(\vec{P}\cdot\nabla\right)}\vec{E}$$



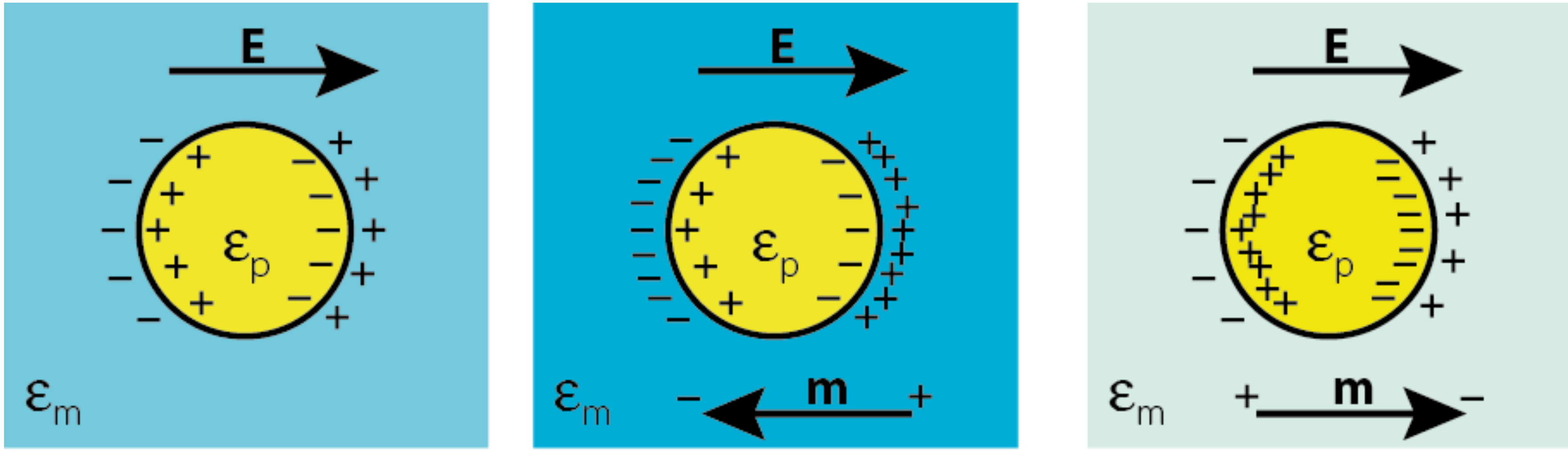
What if the field is non uniform?

Dielectrophoresis (DEP)

Dielectric particle in an electric field

polarizability

charge separation, -> induced dipole moment



$\varepsilon_m = \varepsilon_p$

$\varepsilon_m > \varepsilon_p$

$\varepsilon_m < \varepsilon_p$

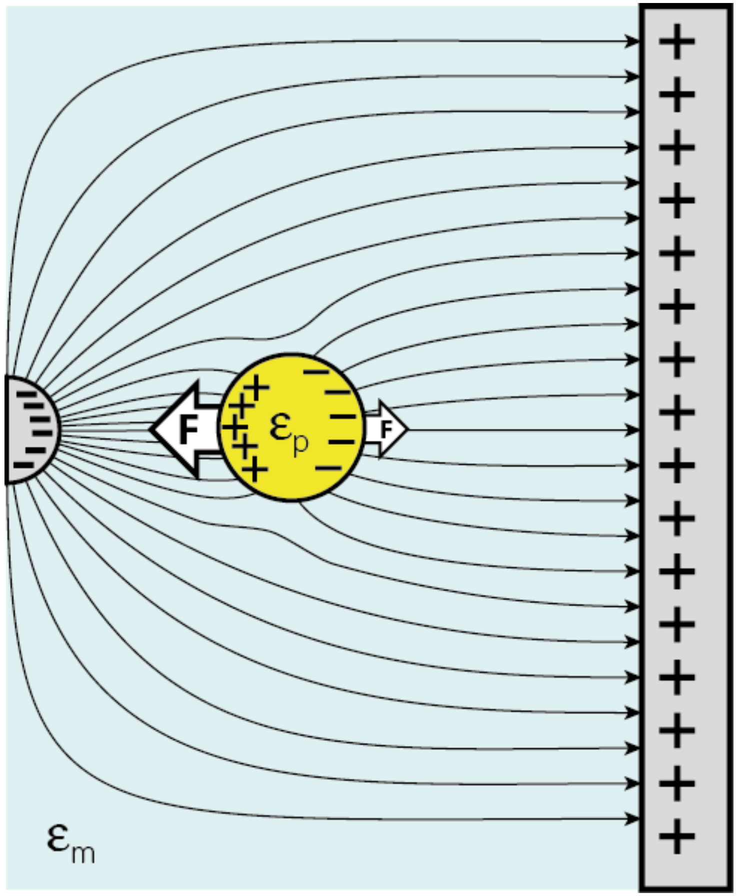
$$\vec{D} = \varepsilon \vec{E}$$

$C \cdot m^{-2}$ $V \cdot m^{-1}$

- For cells : induced surface charge is only about 0.1% of the net surface charge
- generated within about a microsecond.

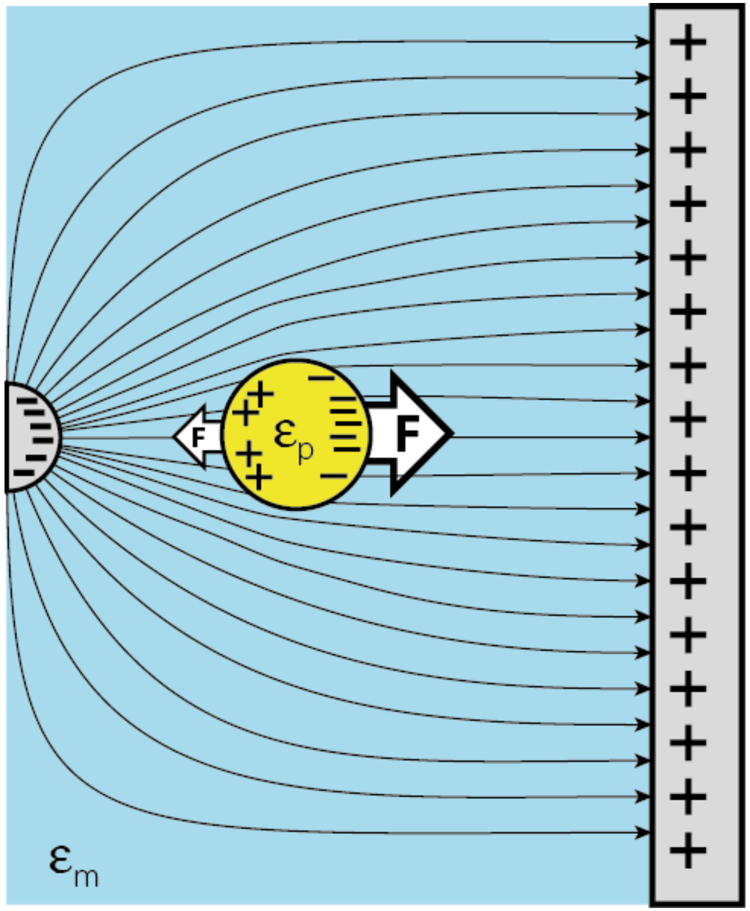
Dielectrophoresis (DEP)

$$\vec{F} = \left(\vec{P} \cdot \nabla\right)\vec{E}$$



Higher polarizability
Particle attracted toward high field strength

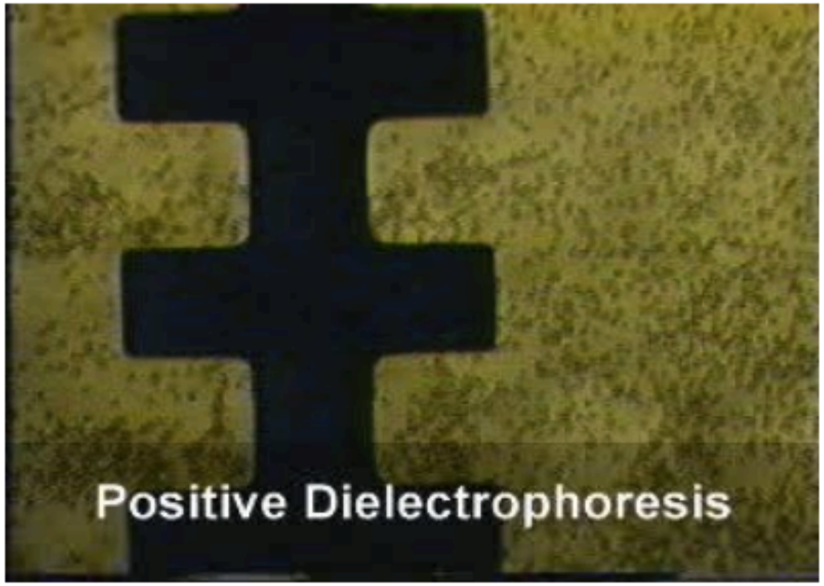
pDEP

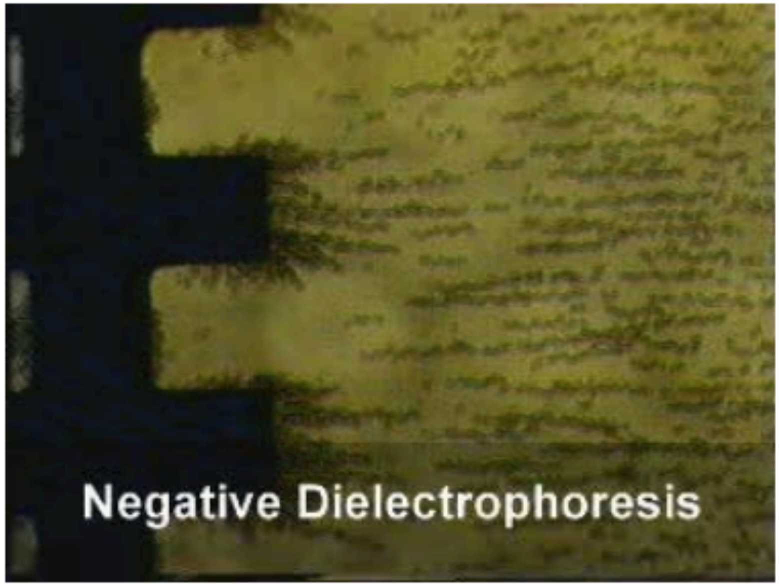


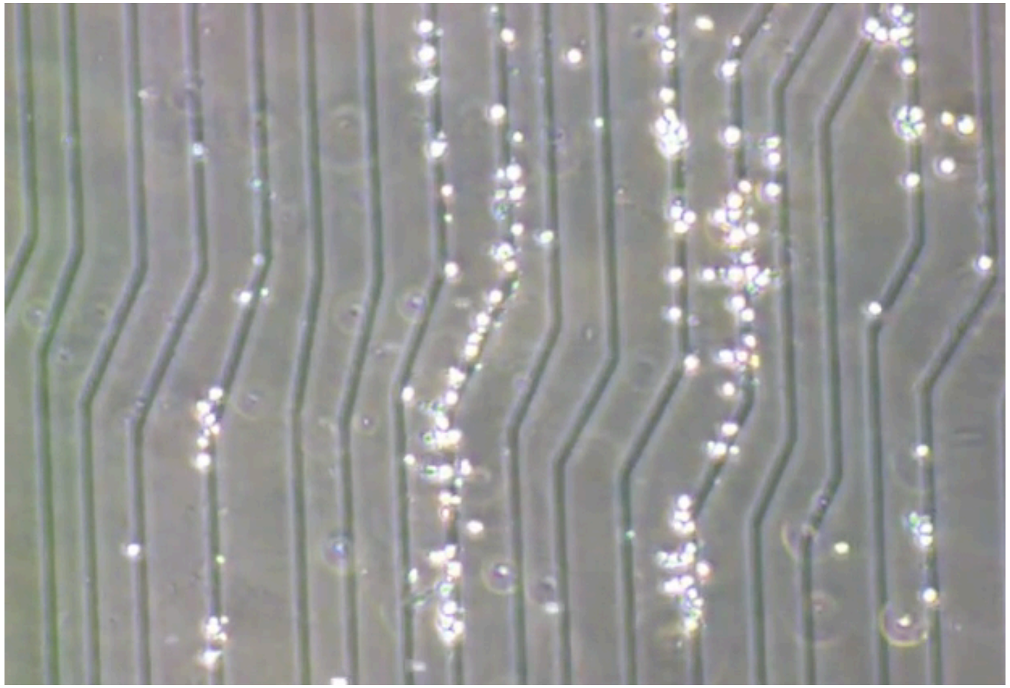
Lower polarizability
Particle attracted toward low field strength

nDEP

Dielectrophoresis (DEP)



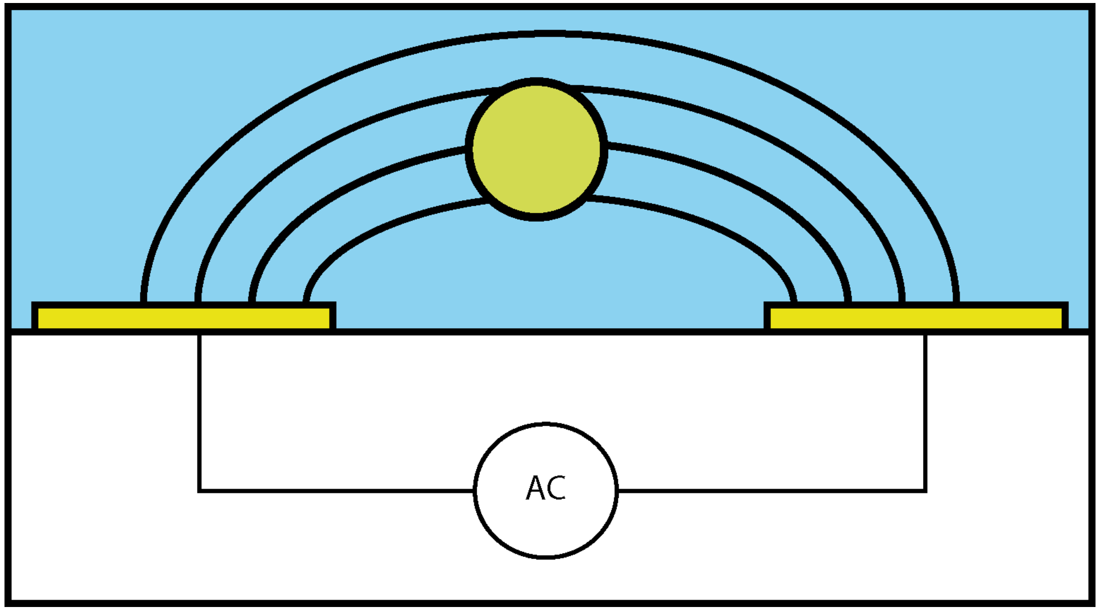




What if AC voltage?

AC-Dielectrophoresis (ACDEP)

Spherical particle radius r, complex permittivity ε_p^*
Suspended in a fluid with permittivity ε_p^*



conductivity

$$\varepsilon_p^* = \varepsilon + i\frac{\sigma}{w}$$

Dielectric constant

Field frequency

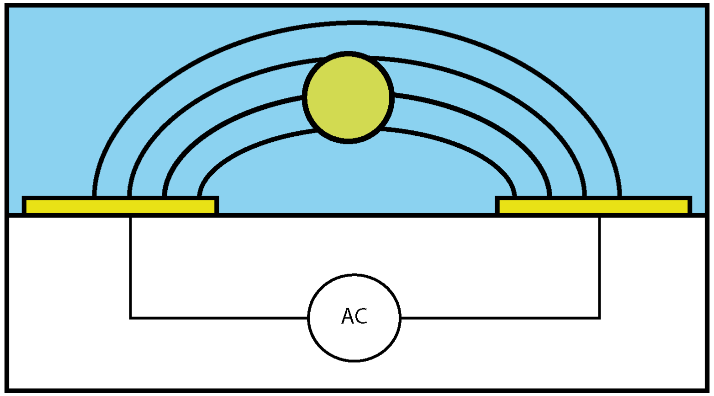
$$\vec{F}_{DEP} = \left(\vec{P}\cdot\nabla\right)\vec{E} = \frac{1}{2}R_e\left[\left(\vec{P}.\nabla\right)\vec{E}^*\right] = 2\pi r^3\varepsilon_m \mathrm{Re}\left\{\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*}\right\}\nabla\left|\vec{E}_{rms}\right|^2$$

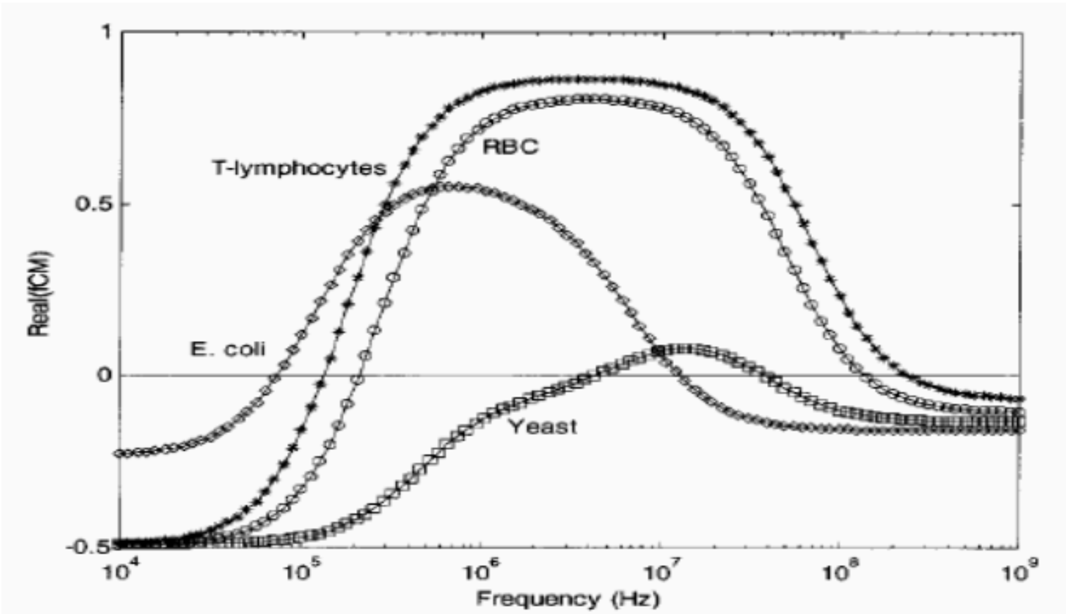
Clausius-Mossotti factor

AC-Dielectrophoresis (ACDEP)

Clausius-Mossotti factor

$$K = \mathrm{Re}\left\{\frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*}\right\}$$





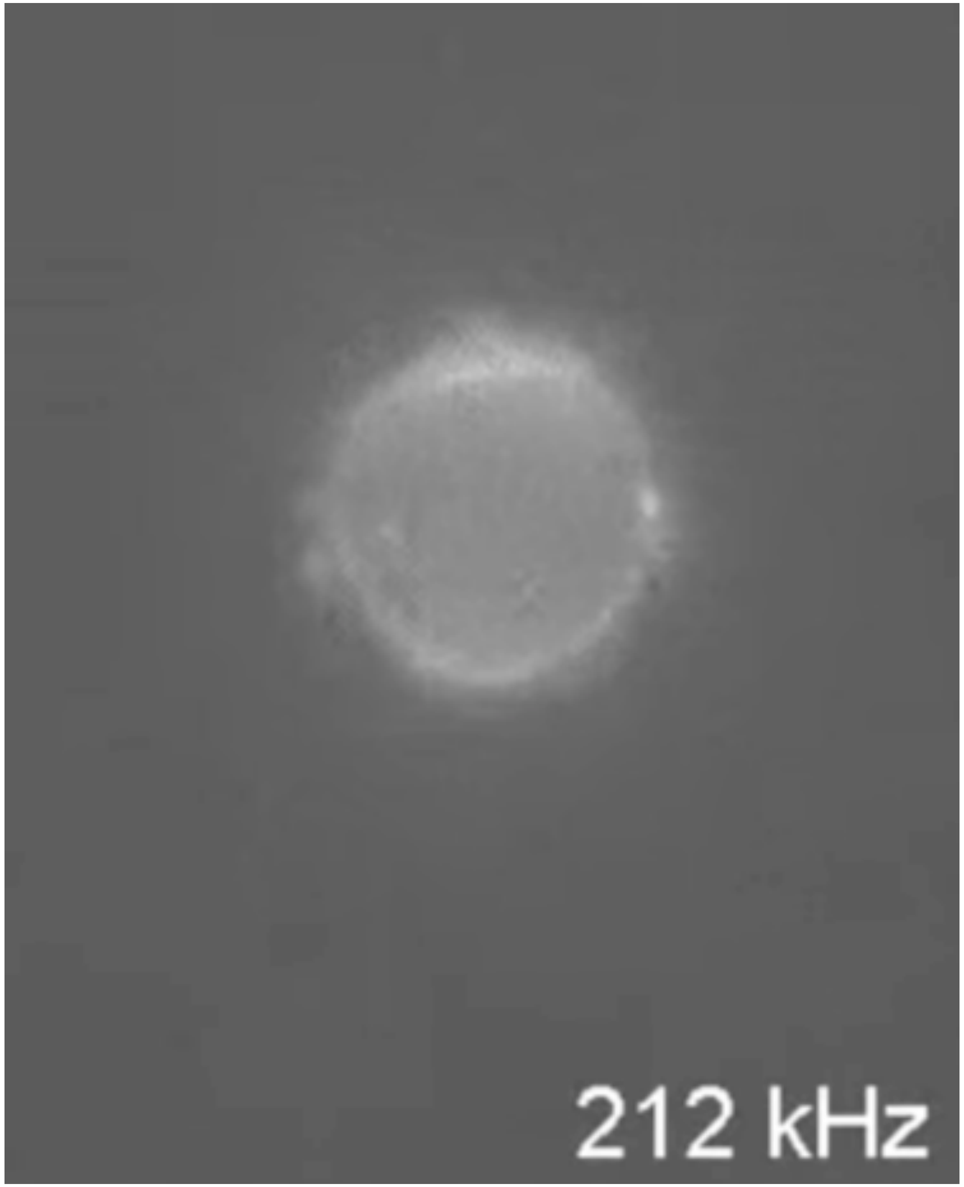
Theoretical K(ω) values for bioparticles
(Huang Y. et al, *Anal Chem* 2001)

The real part of CM factor defines the frequency dependence and direction of the force.

K > 0 particles are attracted to max E field
K < 0 particles are repelled

AC-Dielectrophoresis (ACDEP)

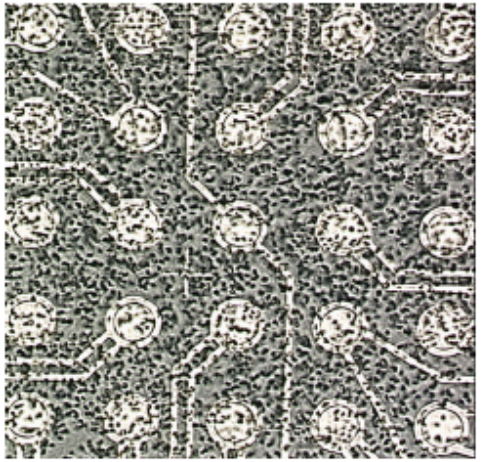
Clausius-Mossotti factor



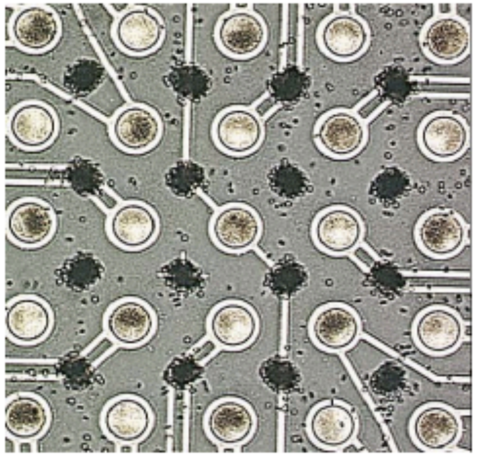
Samuel Kilchenmann

AC-Dielectrophoresis (ACDEP)

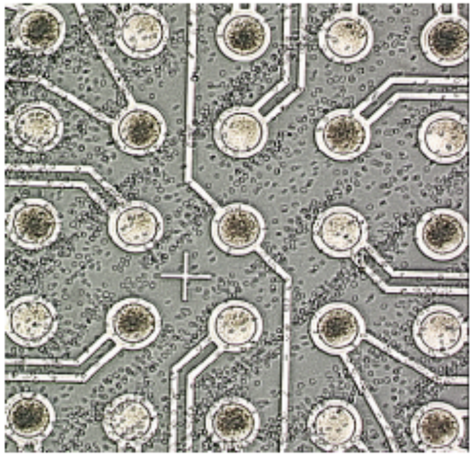
Application example : Separation of Listeria from Whole Blood



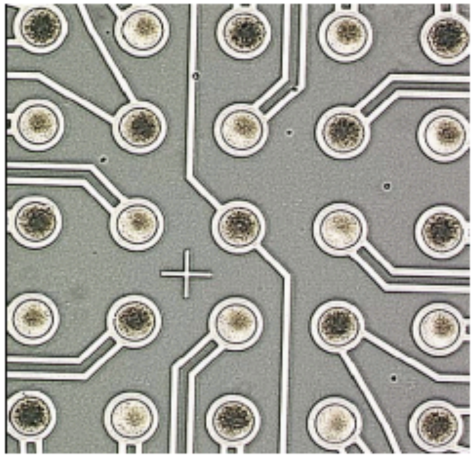
Before



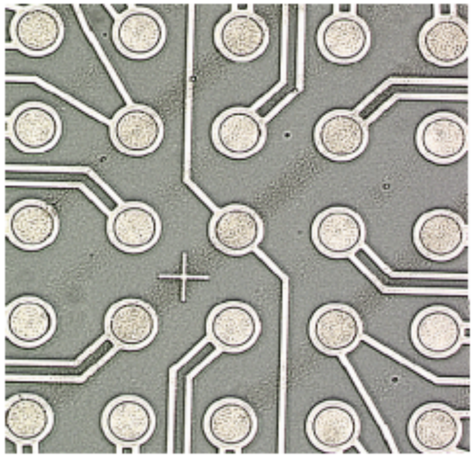
Separation: 10 kHz, 10 Vpp



Wash blood off



After wash blood off



Wash Listeria off

AC-Dielectrophoresis (ACDEP)

Summary

DEP force is zero if the electric field is uniform.

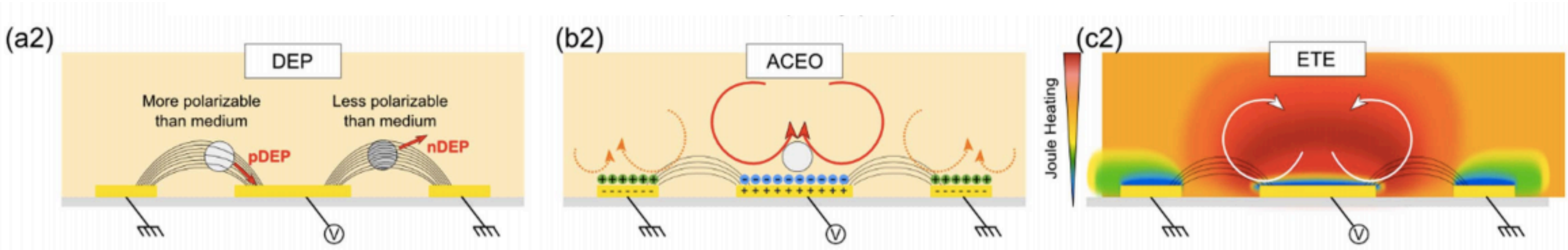
DEP force scales with the square of the voltage.

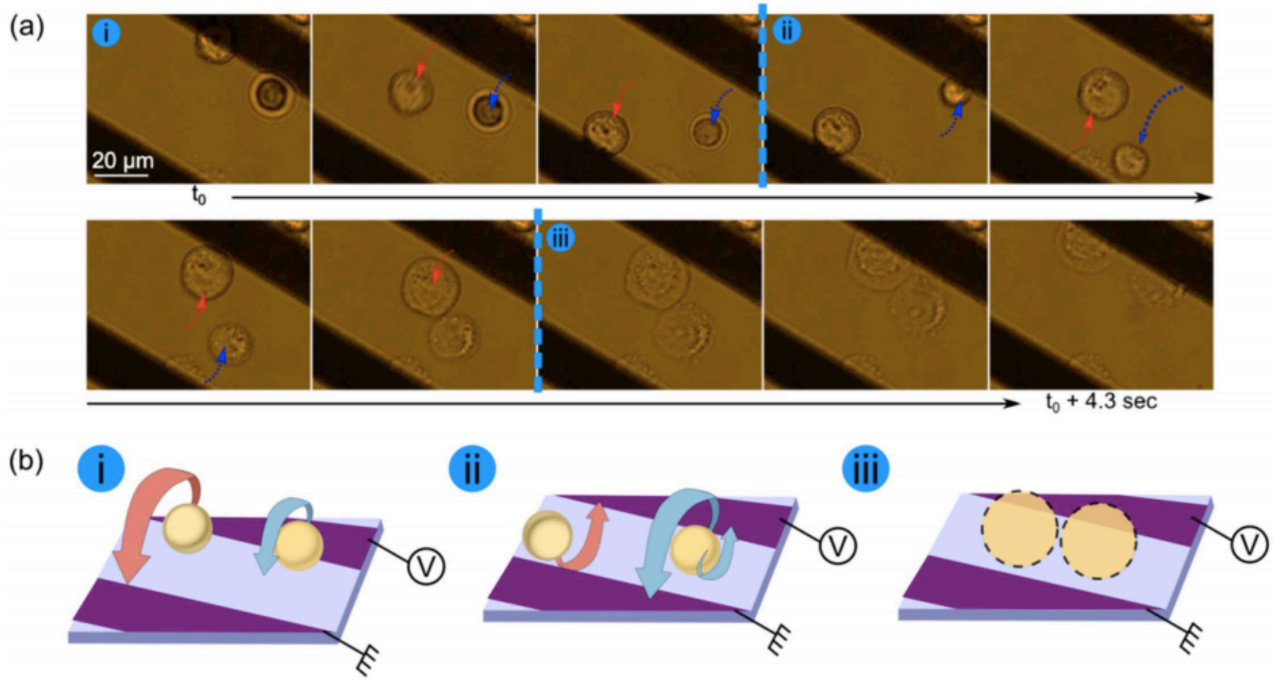
Reversing the bias does not reverse the force.

The DEP force scales inversely with the cube of the electrode gap.

The DEP force is proportional to the particle volume. Strong electric fields (100 V/m) are required to manipulate micron-scale particles

Electrokinetics on Cells





C.Benoit, T.Honegger, D.Peyrade, LTM Grenoble

Electrokinetics Summary

Electro Osmosis (EOF) : create flow with surface charges in capillaries

AC Electro Osmosis (ACEOF) : circulation around planar electrodes, Electro osmotic pumping

Electrophoresis (EP) : transport of charged particles by Coulomb forces (DNA separation by capillary EP)

Dielectrophoresis : (DEP) Force on polarizable particles (pDEP, nDEP)

AC-Dielectrophoresis (ACDEP) sorting of particles by CM factor