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Microchannel electrokinetics of charged analytes in buffered solutions near floating electrodes

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We present both experimental and numerical studies of nonlinear electrokinetic flow of buffered solutions seeded with dilute analytes in a straight microchannel (0.6 μm high, 250 μm wide, and 9000 μm long) with a 0.15 μm high 60 μm wide electrode situated at the bottom center of the channel. Such studies will enable a fundamental understanding of nonlinear transport effects of ions in electrolyte systems with a significant Debye screening layer. Initial experimental studies have shown an order of magnitude increase of concentration near the electrodes, but numerical studies have so far failed to accurately predict such behavior in these flow regimes. Experimentally, using conventional fluorescence microscopy, we investigated the concentration gradient (as well as the associated electroosmosis, induced-charge electro-osmosis, and electrophoresis) of the charged analyte near the floating electrode as a function of analyte (1 to 10 μM fluorescein and bodipy) and buffer (1 to 10 mM borate and posphate) concentrations and an externally applied voltage drop (50 to 100 V) along the channel. We have implemented a nonlinear continuum kinetics model of the system involving the electric potential, the buffer flow velocity, the pressure, and the four ionic concentration fields and compared the resulting numerical simulations with experiments.

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9 February 2009

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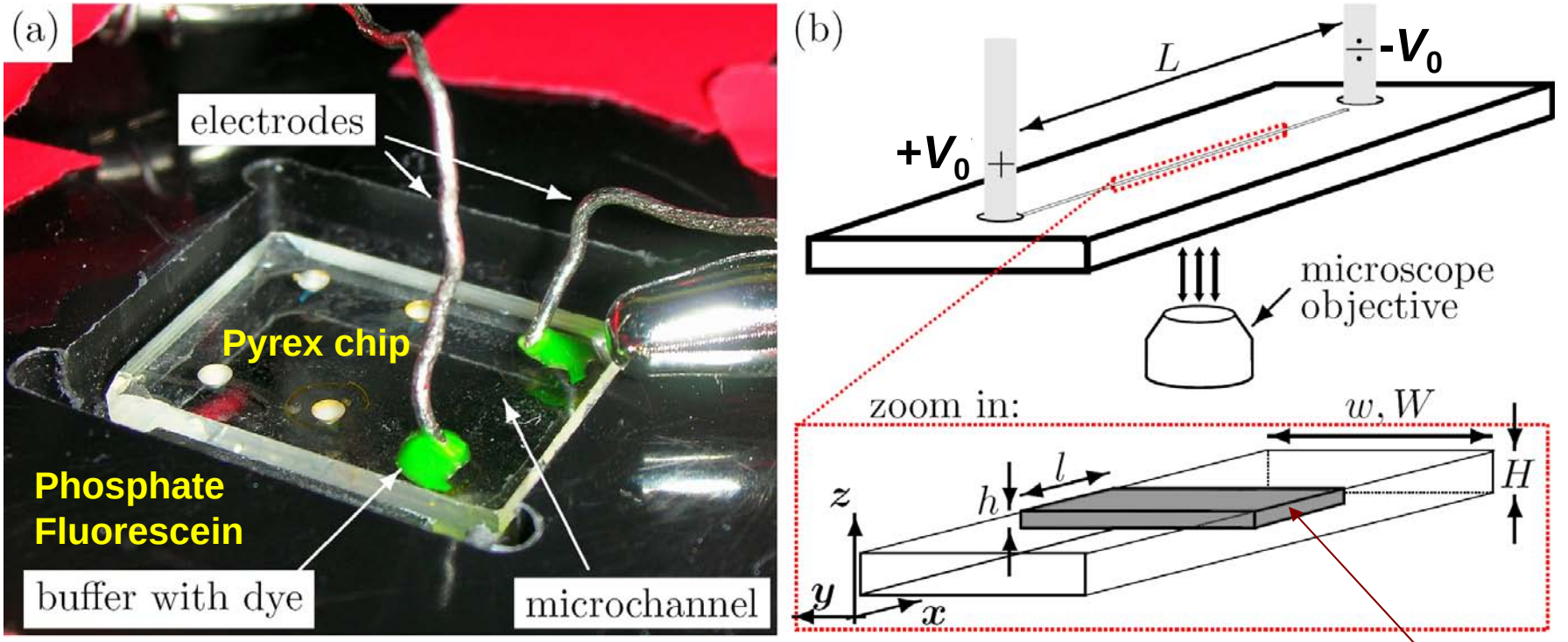
Sumita Pennathur

Assoc. Professor

Induced-charge electro-osmosis: UCSB experimental setup I

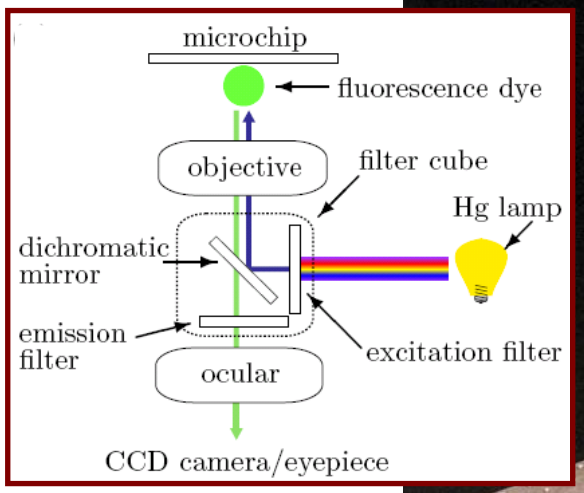


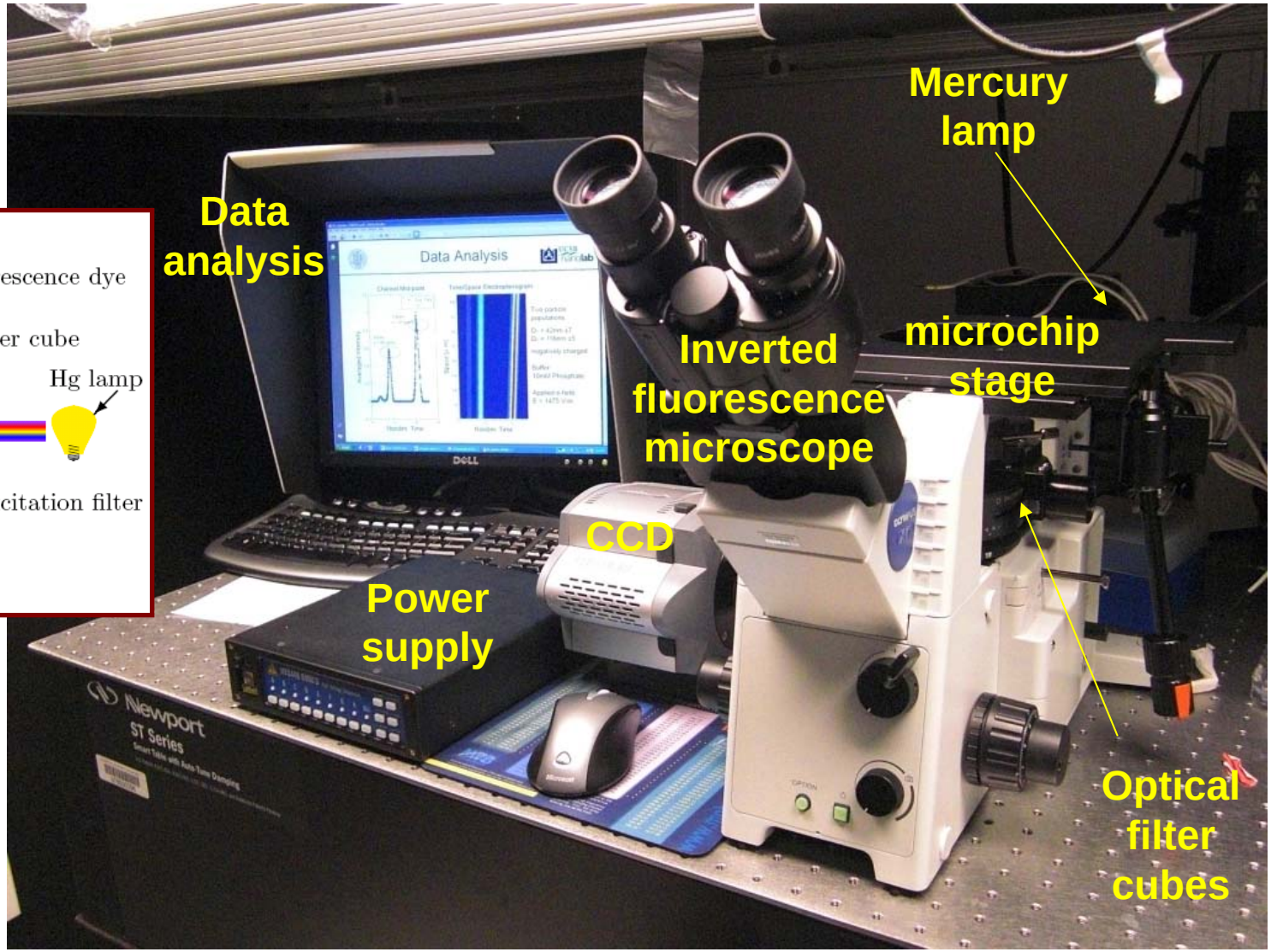
Extreme aspect ratios – Debye layer overlap

- L = 9000.00 μm
- H = 0.50 μm
- w = 250.00 μm
- λ_D = 0.03 μm
- l = 60.00 μm

un-biased Pt electrode

Induced-charge electro-osmosis: UCSB experimental setup II





The continuum description of the electric screening in electrolytes: the double layer

- **Governing equations**
  - **Navier-Stokes equation** **u**
  - **Incompressibility** *p*
  - **Electrostatic Maxwell eq.** ϕ
  - **Nernst-Planck equation** **J**
  - **Continuity equation** *c*

$$\rho\left[\partial_t \mathbf{u} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right] = -\nabla p + \eta\nabla^2\mathbf{u} - Ze(c_+ - c_-)\nabla\phi$$

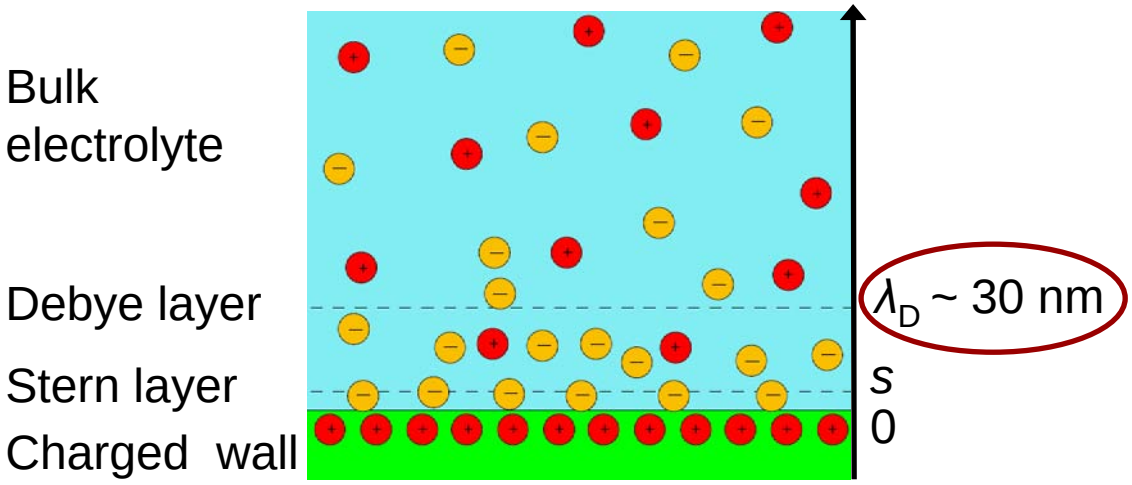
$$\nabla\cdot\mathbf{u} = 0$$

$$\nabla\cdot(\epsilon\nabla\phi) = -Ze(c_+ - c_-)$$

$$\mathbf{J}_i = -\frac{D_i}{k_B T}c_i\nabla\mu_i + \mathbf{u}c_i$$

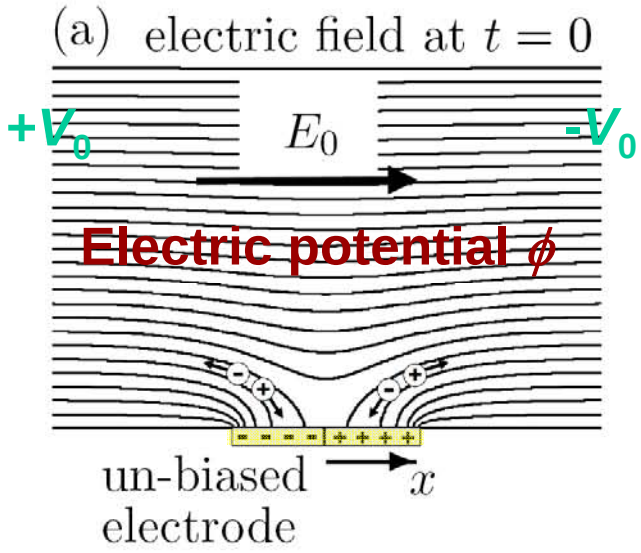
$$\mu_i = \mu_0 \pm Ze\phi + k_B T\ln\frac{c_\pm}{c_0}$$

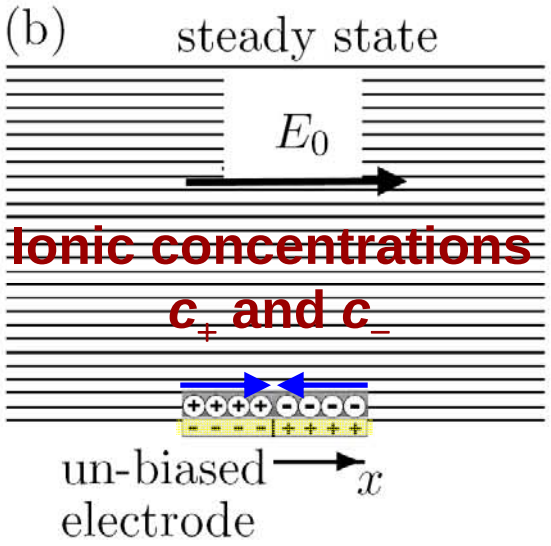
$$\nabla\cdot\mathbf{J}_i = -\partial_t c_i$$

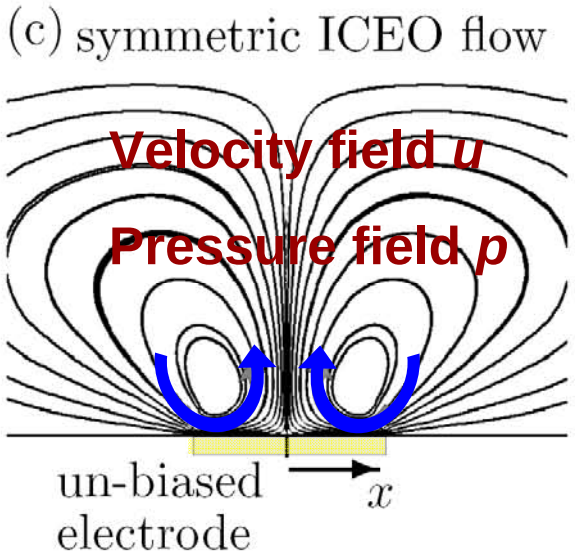


Induced-charge electro-osmosis: Basic principle

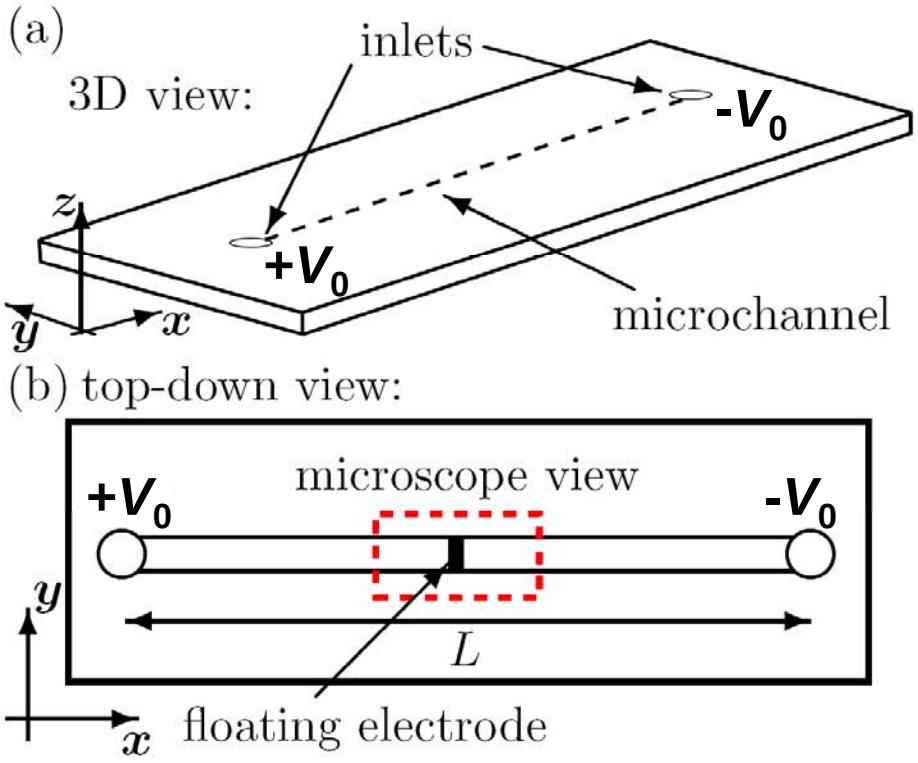
- An external potential difference is applied ($+V_0$ and $-V_0$) to electrolyte
- Induced polarization charge appears in the metallic electrode
- Ions in the electrolyte screens out the *E*-field normal to the electrode
- The tangential *E*-field drives an ionic current along the dielectric
- The moving ions drags the liquid along the dielectric
- Flow-rolls are consequently induced in the electrolyte

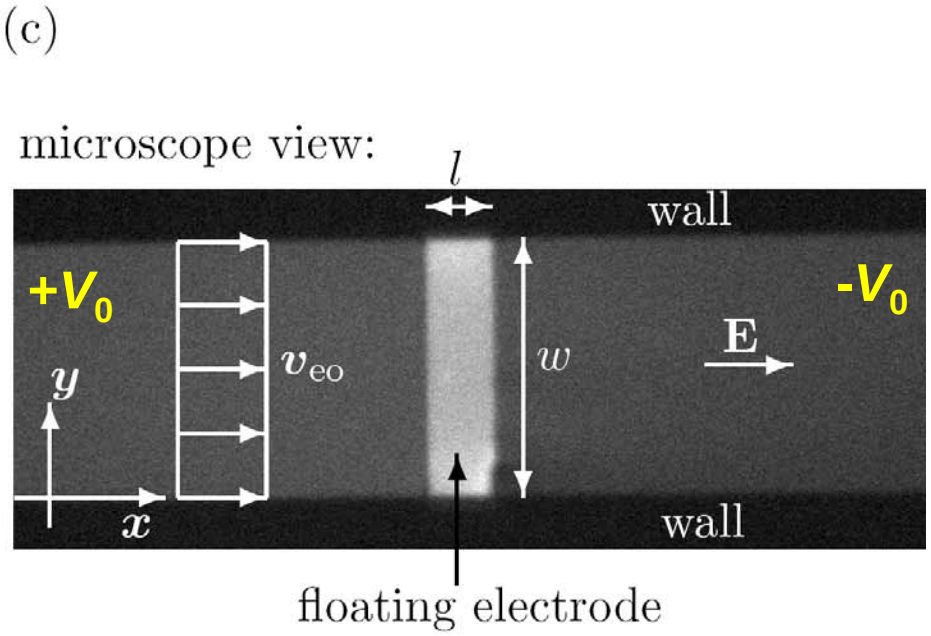






Induced-charge electro-osmosis: UCSB experimental setup III





Experimental parameters and calibration of fluorescent detection

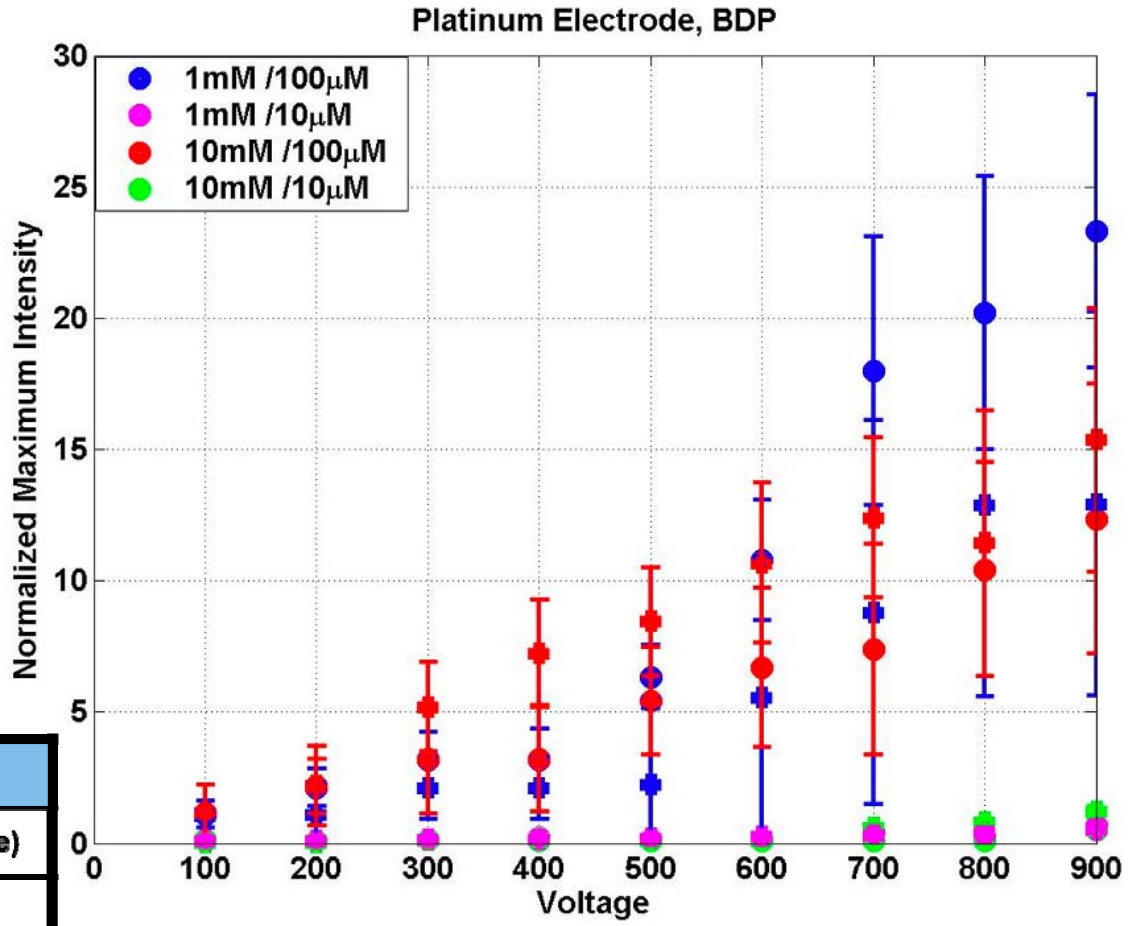
Experimental Parameters

Electric Fields
± 13.3 kV/m
± 26.6 kV/m
± 39.9 kV/m
± 53.2 kV/m
± 66.5 kV/m
± 79.8 kV/m
± 93.1 kV/m
± 106.4 kV/m
± 119.7 kV/m

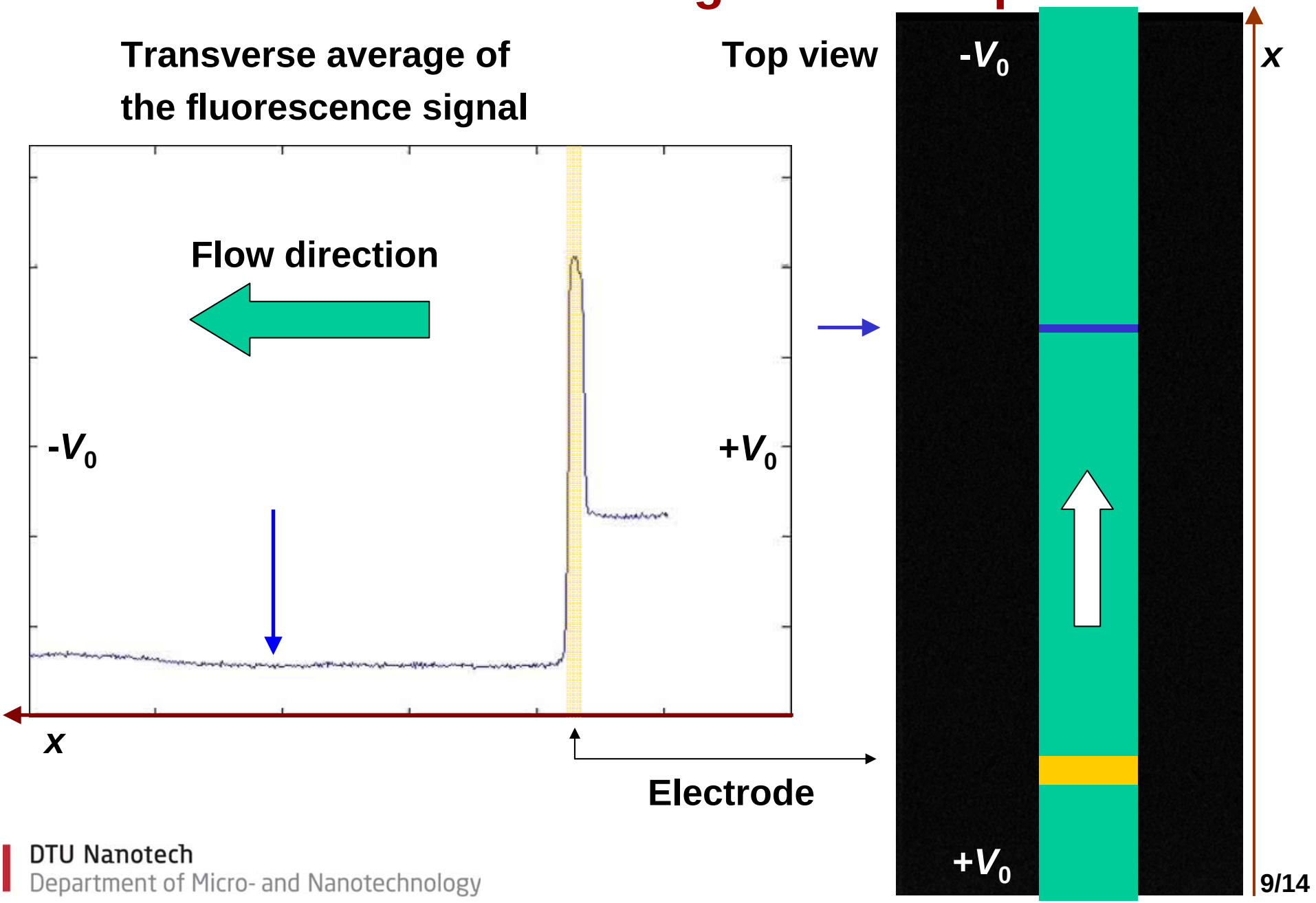
Ion/Analyte Densities
1 mM / 1 mM
1 mM / 100 mM
1 mM / 10 mM
1 mM / 1 mM
10 mM / 1 mM
10 mM / 100 mM
10 mM / 10 mM
10 mM / 1 mM

Electorde Geomeries
Ellipsoid
circle
Square

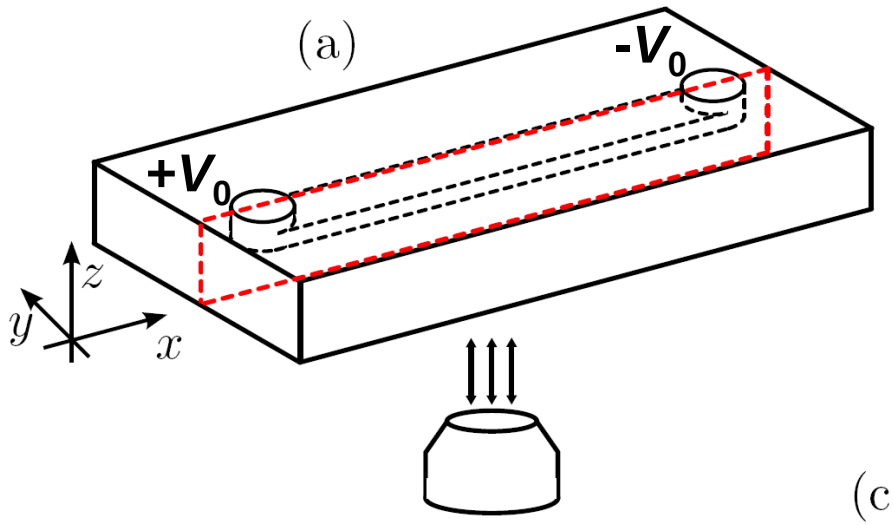
Analytes
Rhodamine 6G (positive)
Bodipy DISulfonate
Fluorescein (negative)

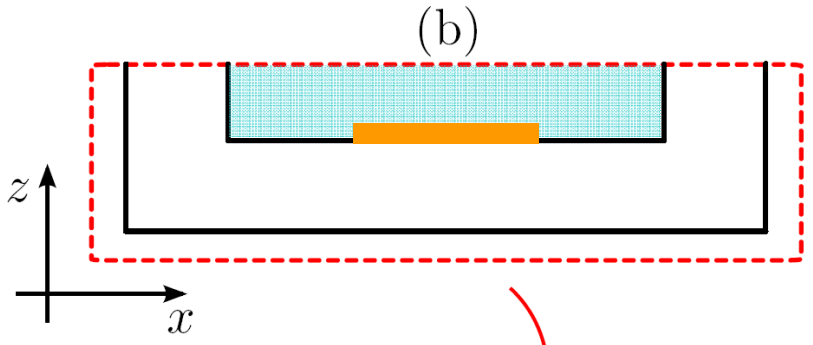


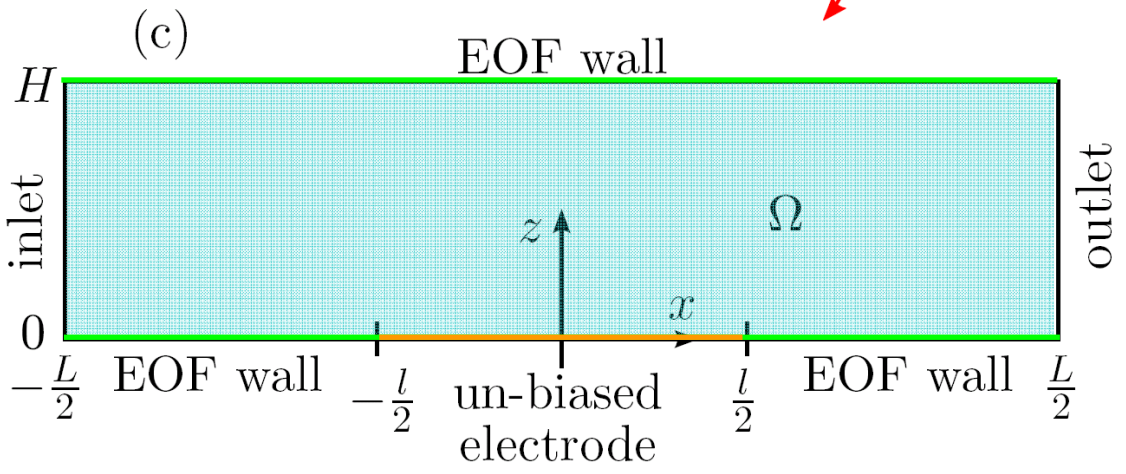
Real-time CCD recordings of one experiment



Theoretical model: the 2D computational domain



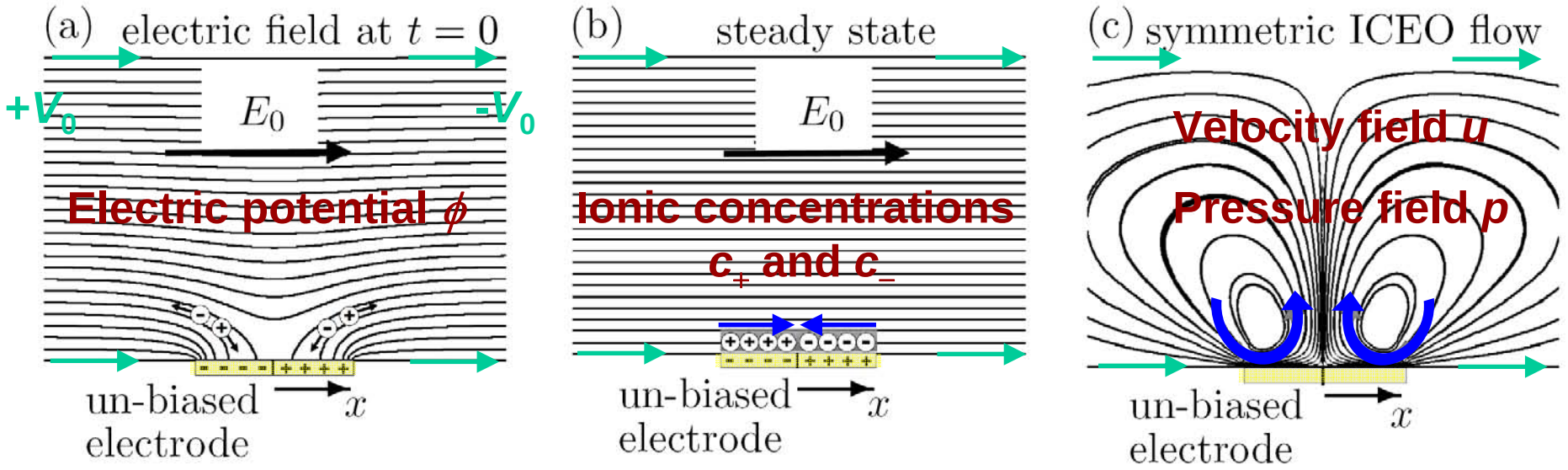




Extreme aspect ratios

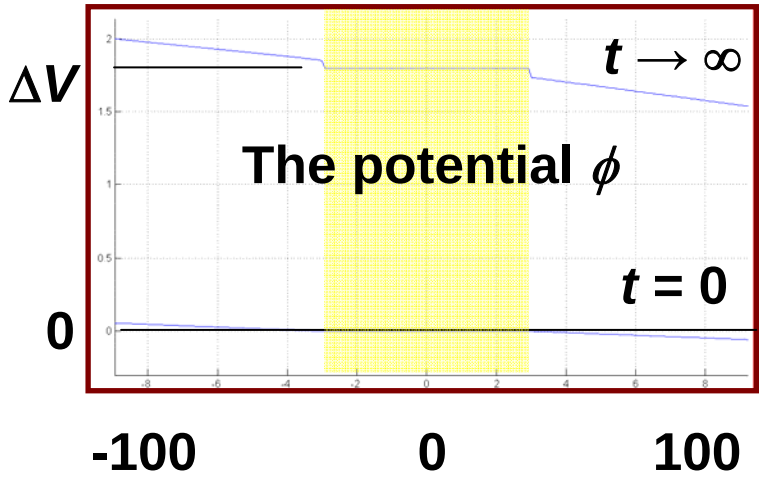
- L = 9000.00 μm
- l = 60.00 μm
- H = 0.50 μm
- λ_D = 0.03 μm

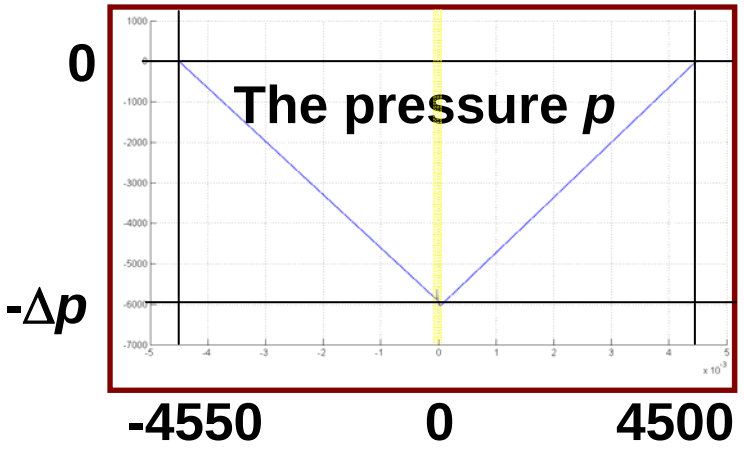
Theoretical model: Induced-charge electro-osmosis in microchannels

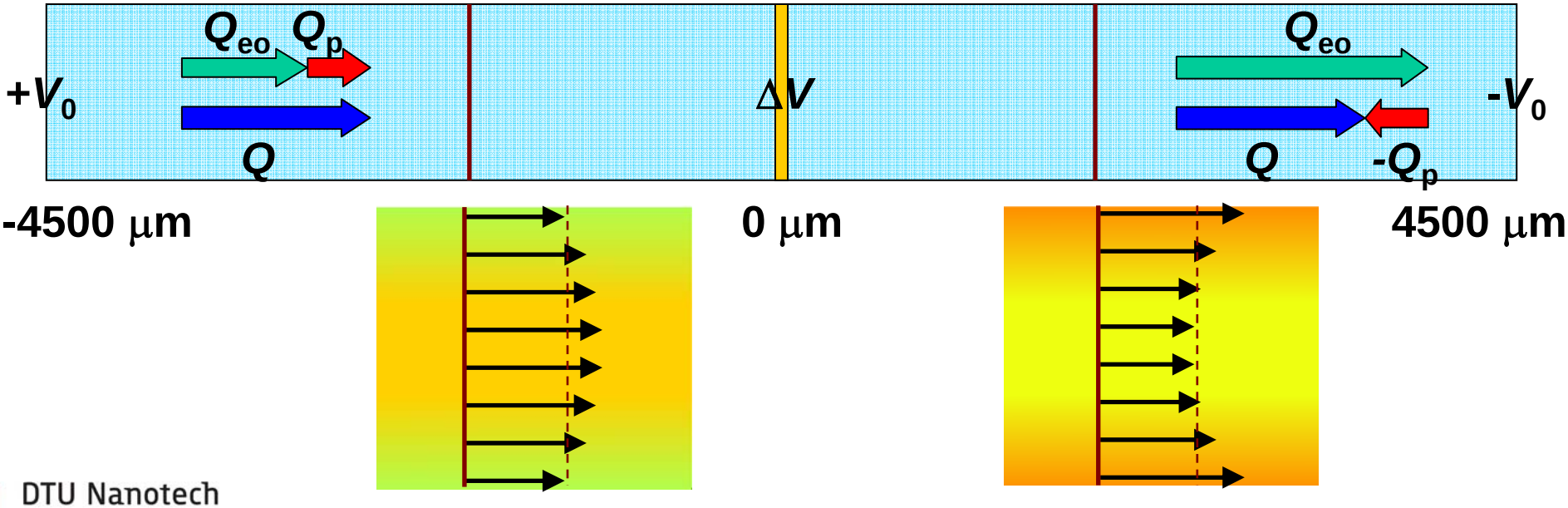


The symmetry is broken by the EO-flow from the surrounding walls

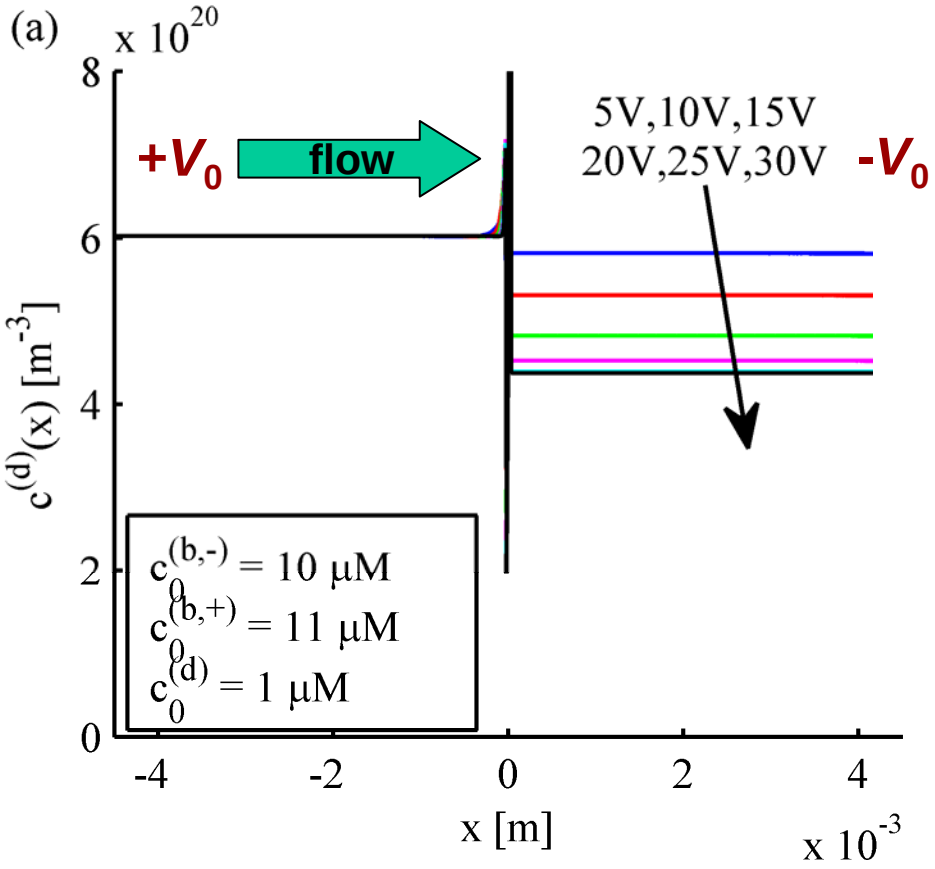
Theoretical model: potential, pressure and velocity profiles

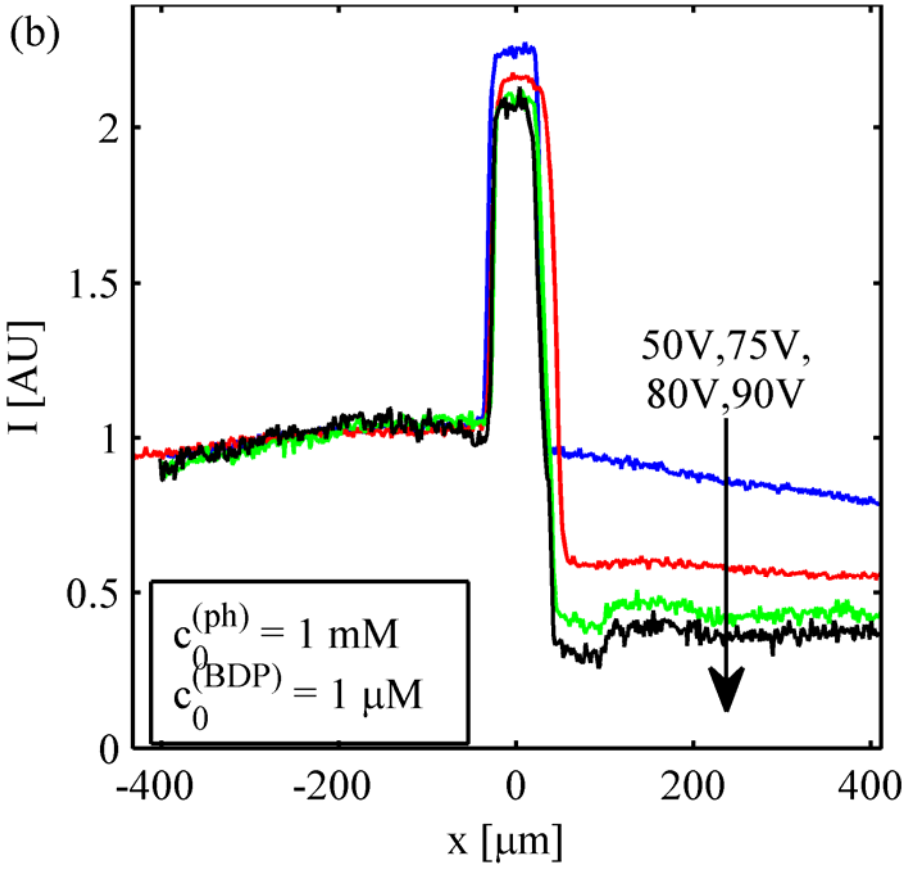






Dye concentration: comparing simulation with experiment

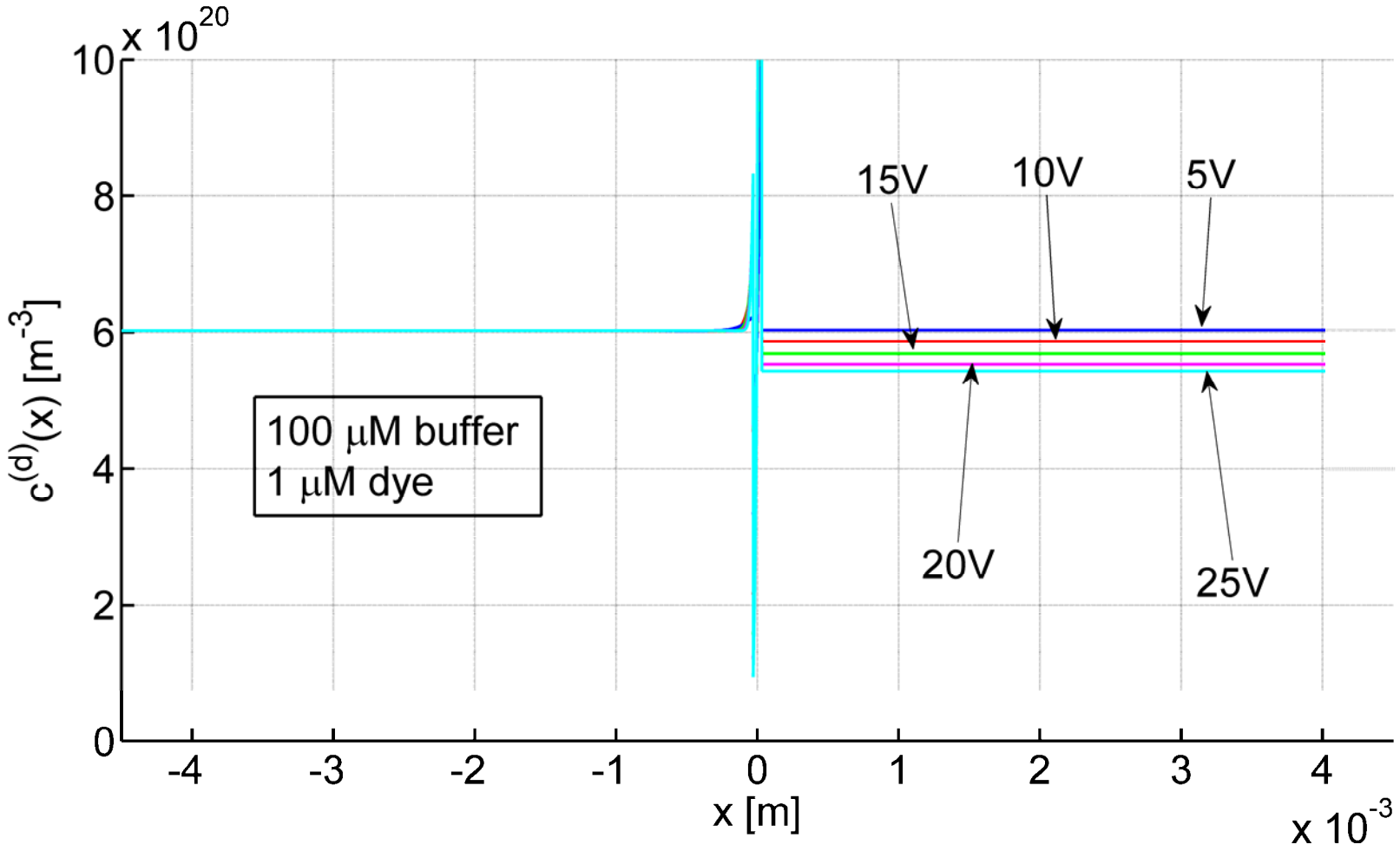




Concluding remarks

- Experimental setup for observing induced-charge electro-osmosis (ICEO) in micro/nanochannels
- Transient development of dye concentration has been measured
- Theoretical model combining EO flow with ICEO has been established for extreme aspect ratios
- Qualitative agreement between experiments and numerical simulation has been achieved
- A good basis for further ICEO studies have been developed and successfully tested

Theoretical model



Theoretical model