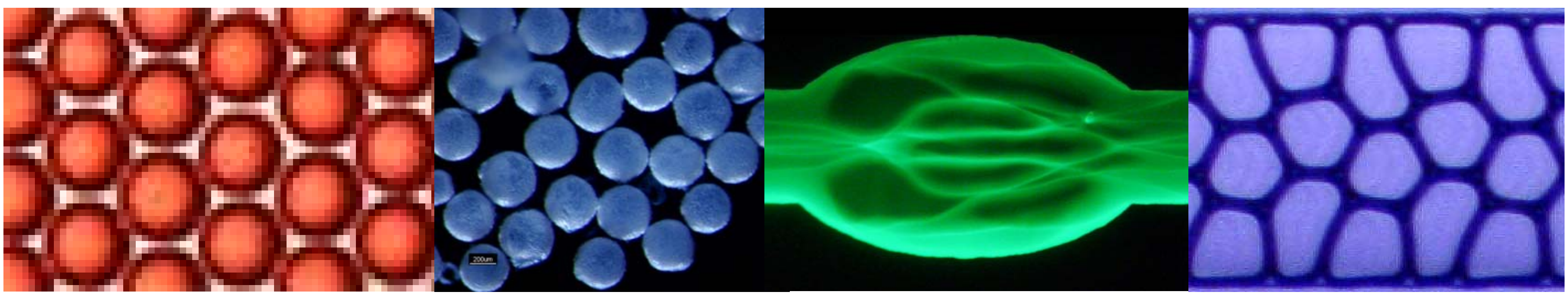
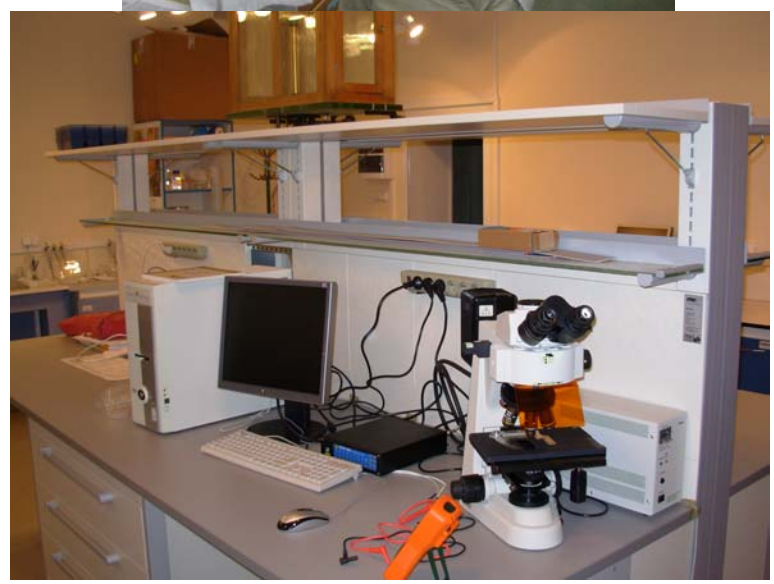
bubbles and droplets in microfluidics: formation, non-linear phenomena and applications.

Piotr Garstecki, Institute of Physical Chemistry, PAS

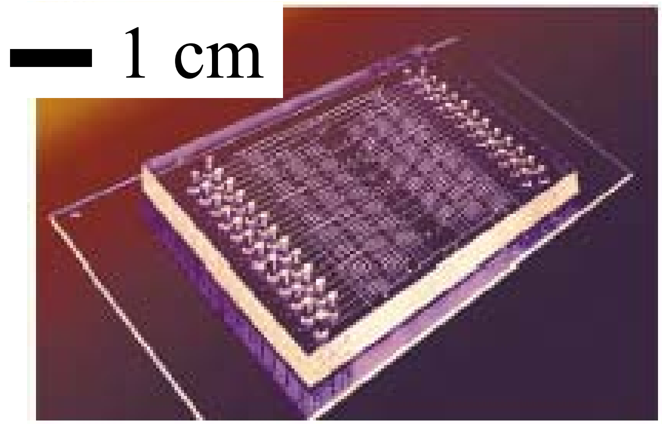


Institute of Fundamental Technological Research, 11/01/2006



- **microfluidics**
  - simple fluids
  - droplets and bubbles
- **formation of drops and bubbles**
  - flow-focusing
  - T-junction
- **stable oscillations with long periods**
- **time-reversible non-linear dynamics**
- **applications**
  - micromixing, portable assays
  - micro-particles and micro-capsules
  - diffraction gratings

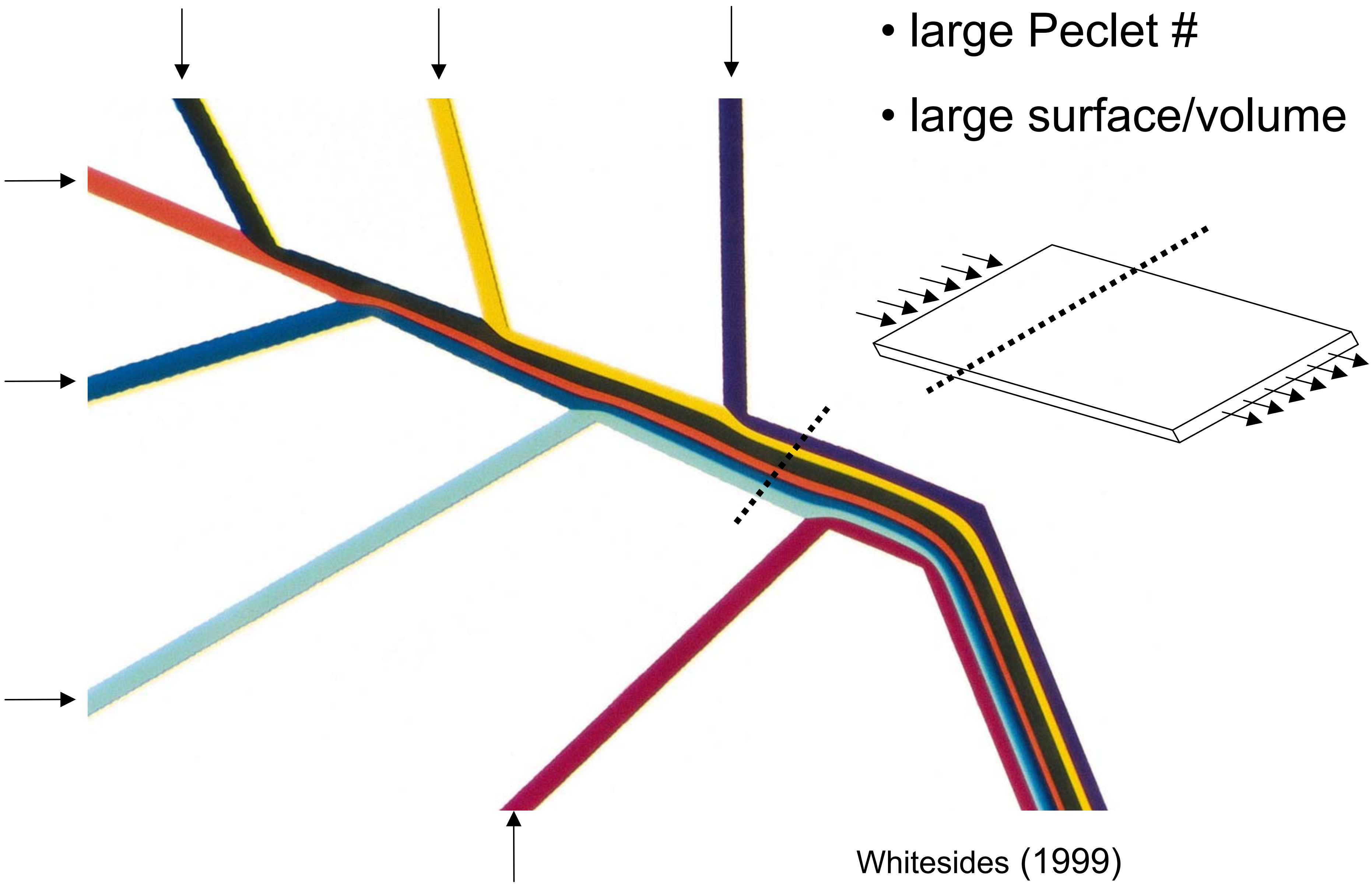
microfluidics



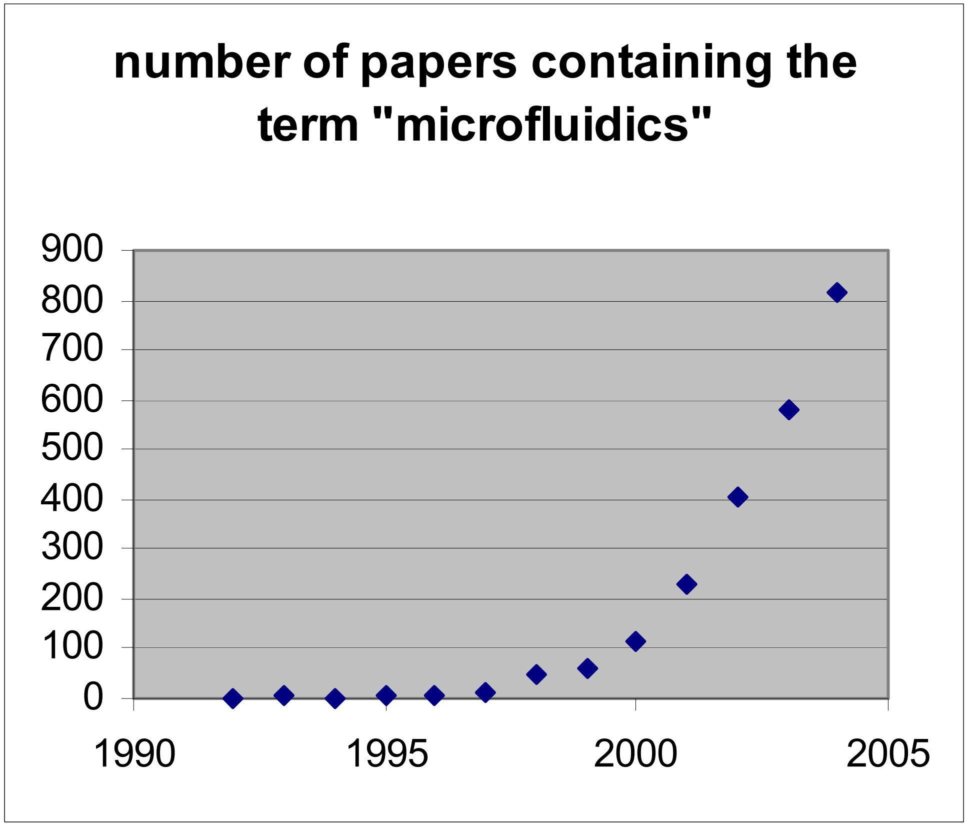
- small dimensions (10 – 100 μm)
- small rates of flow (~ 1 μL/s)

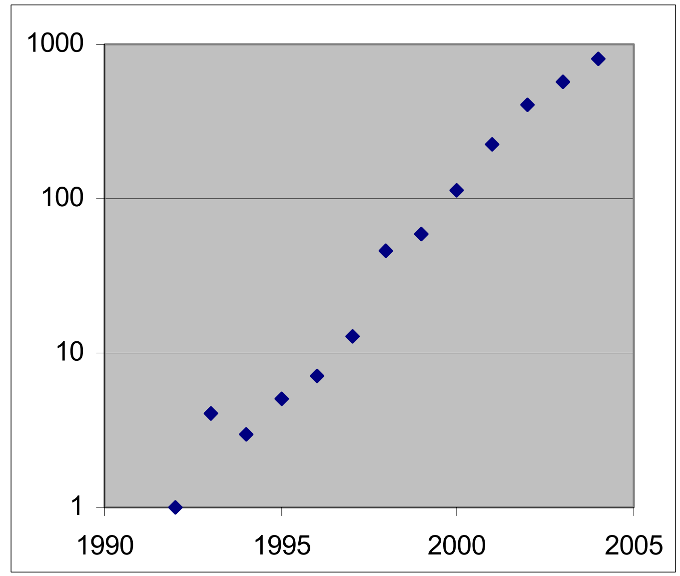
laminar flow

- small Reynolds #
- large Peclet #
- large surface/volume



Whitesides (1999)

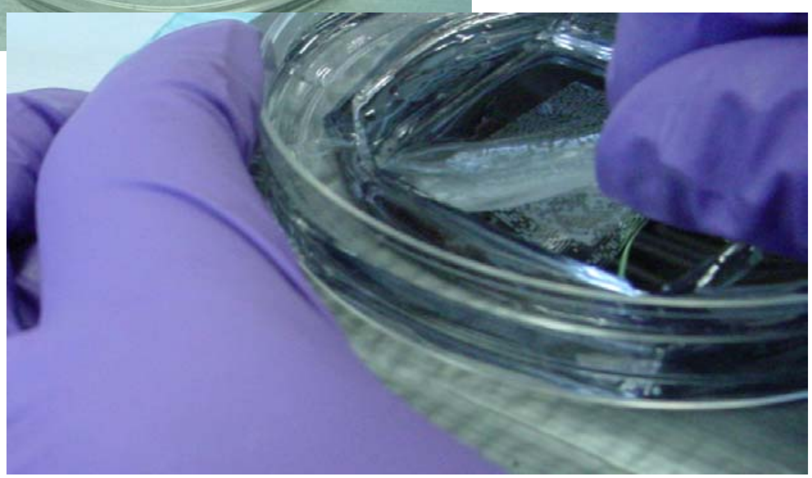


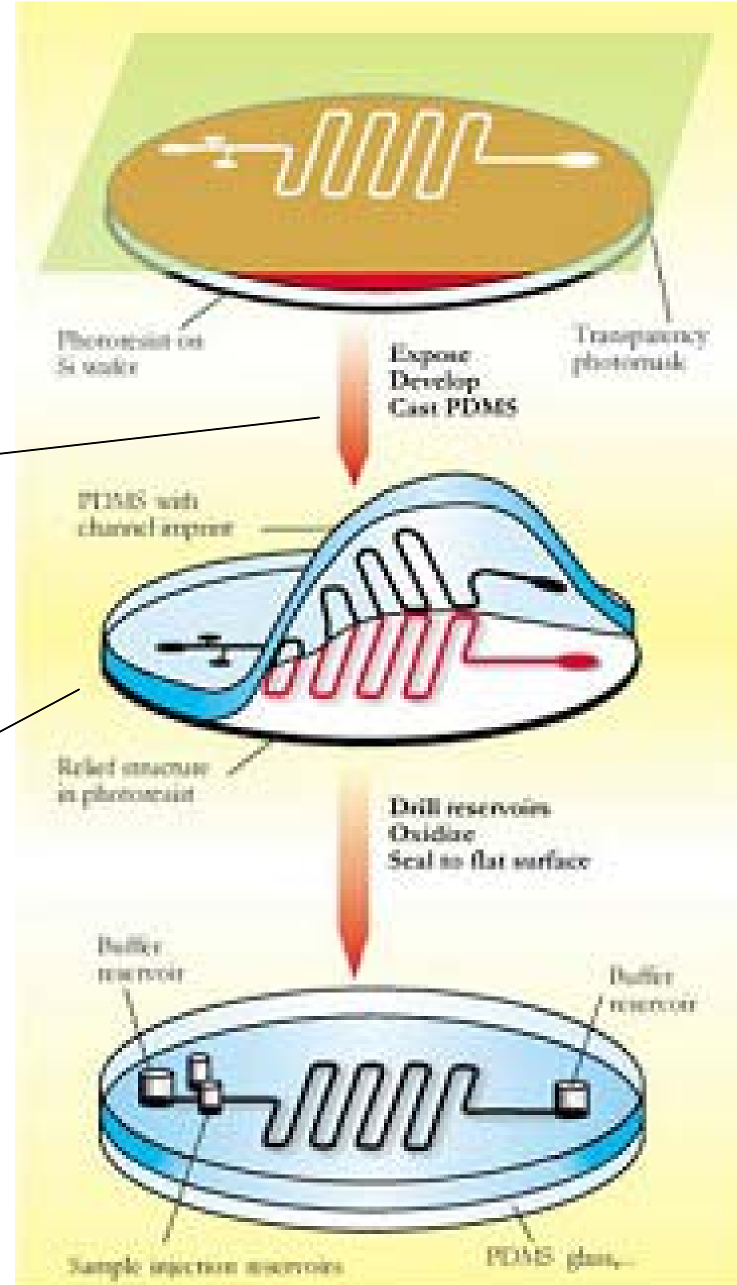


motivated by • **interest**

enabled by • **technology**

enabling technology – – soft lithography and rapid prototyping

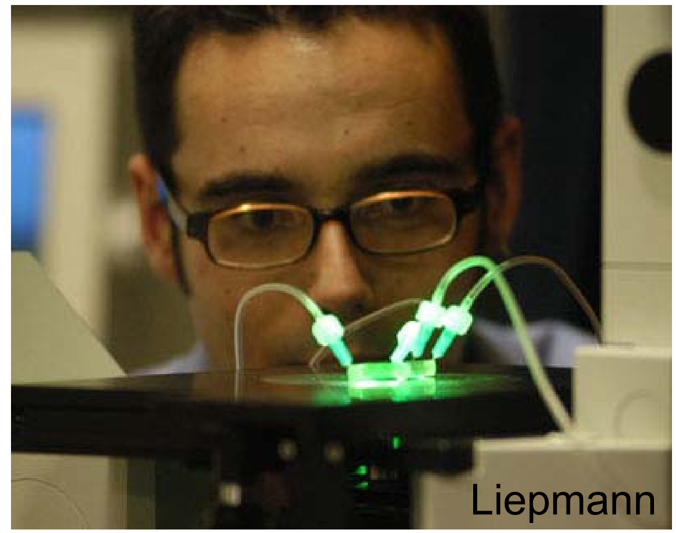




planar geometries

rapid prototyping

→



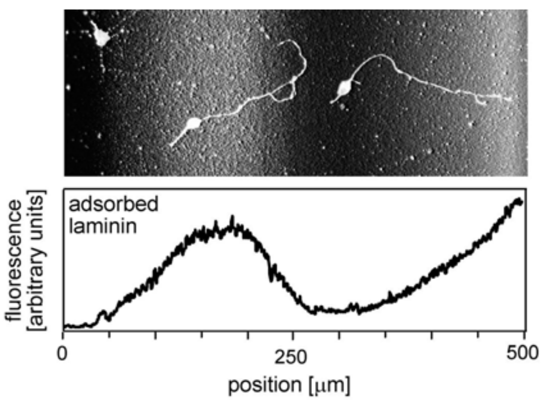
design ~ 1 hour
print out ~ 1 day
fab master ~ 3 hours ~ 2 days

----

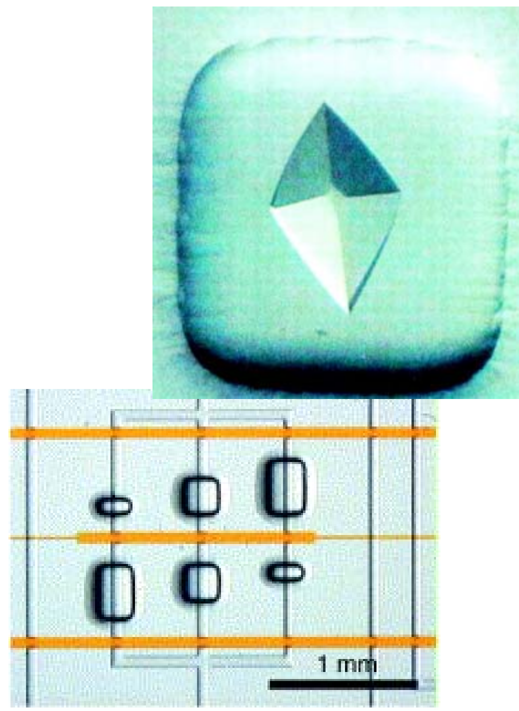
make copies of the device ~ 2 hours each

interest and applications

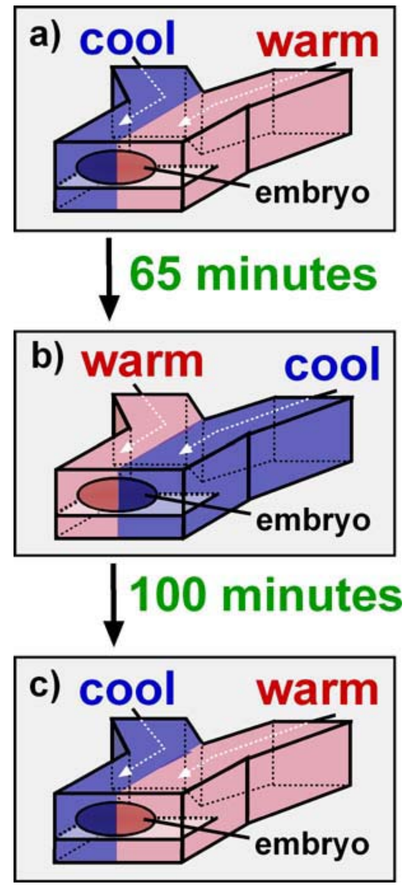
- chemistry (kinetics, organic / inorganic synthesis)
- drug design (hts)
- biotechnology (genomics, protemics …)
- material science
- physics – new flow phenomena
- biology (cell response)
- optics



Whitesides, Harvard

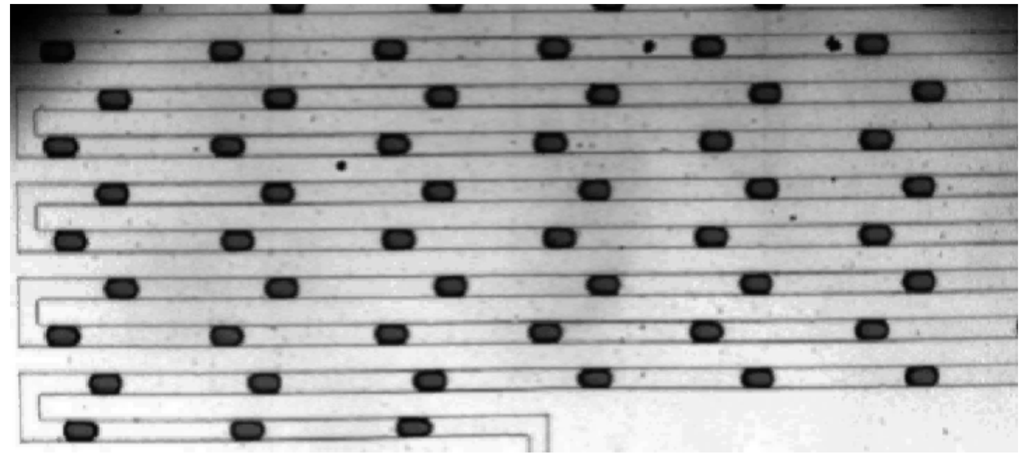


Quake, Caltech



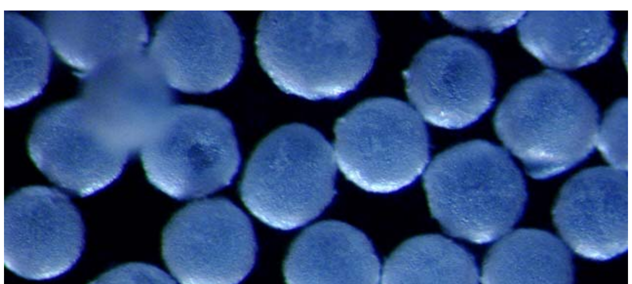
Ismagilov, UChicago

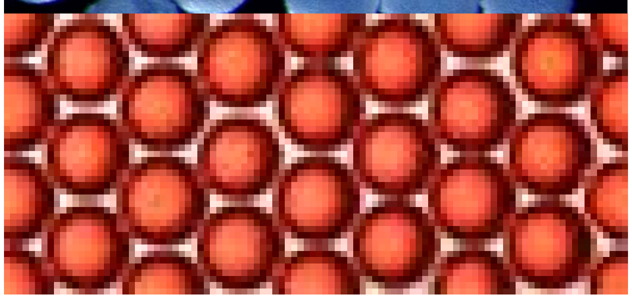
microfluidics with drops

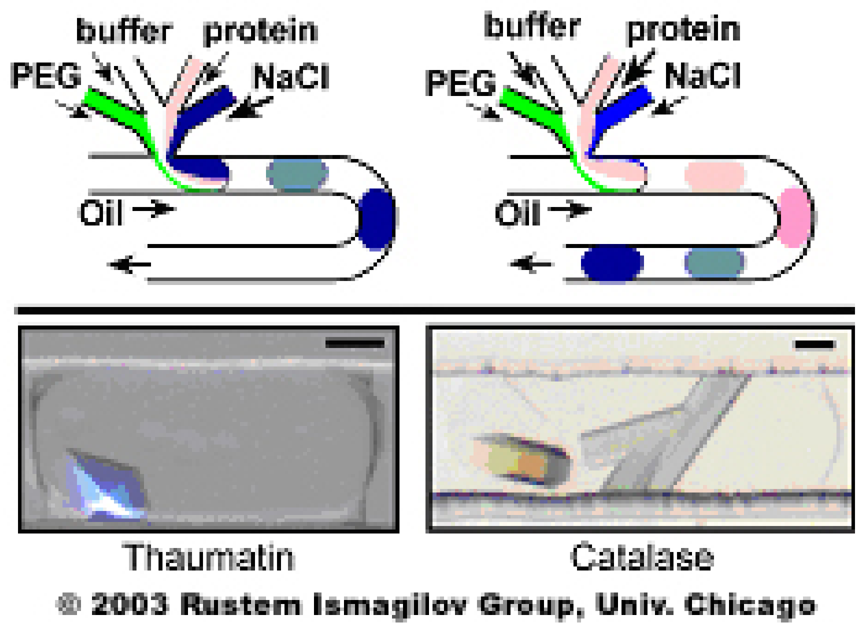


applications

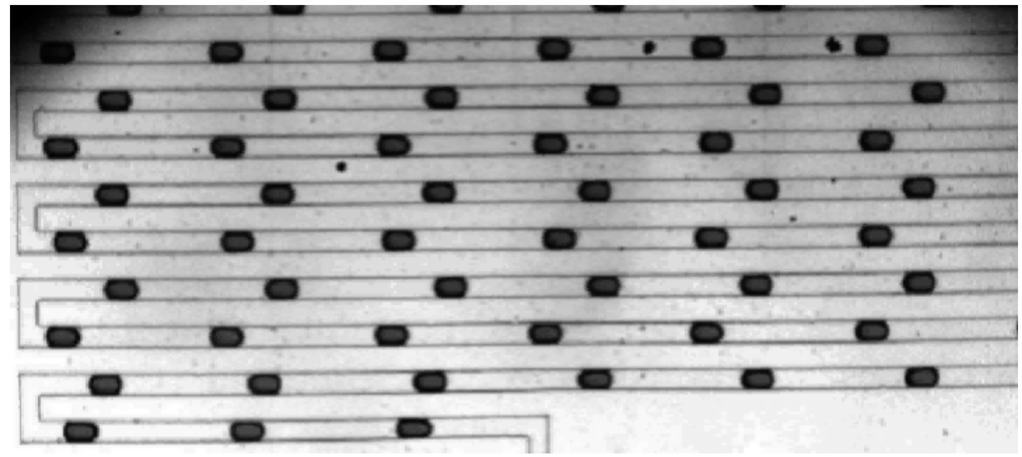
- controlled emulsification
- droplet as a beaker
  - aqueous chemistry
  - biochemistry
  - organic chemistry
- processing / screening / kinetics
- material synthesis







microfluidics with drops

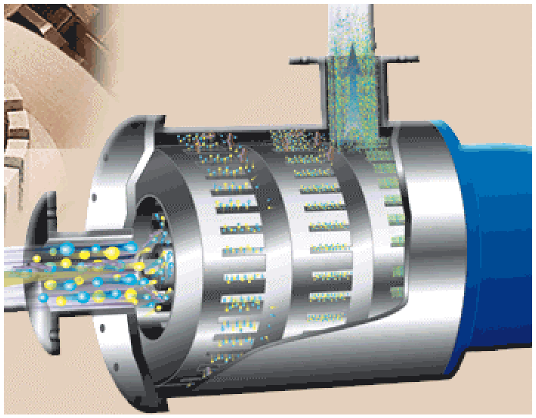


- how do you make drops in a controlled way?
- how do you guide them through networks?

- **microfluidics**
  - simple fluids
  - droplets and bubbles
- **formation of drops and bubbles**
  - flow-focusing
  - T-junction
- **stable oscillations with long periods**
- **time-reversible non-linear dynamics**
- **applications**
  - micromixing, portable assays
  - micro-particles and micro-capsules
  - diffraction gratings

emulsification

Ca >> 1



Fluko

We >> 1

Bo > 1

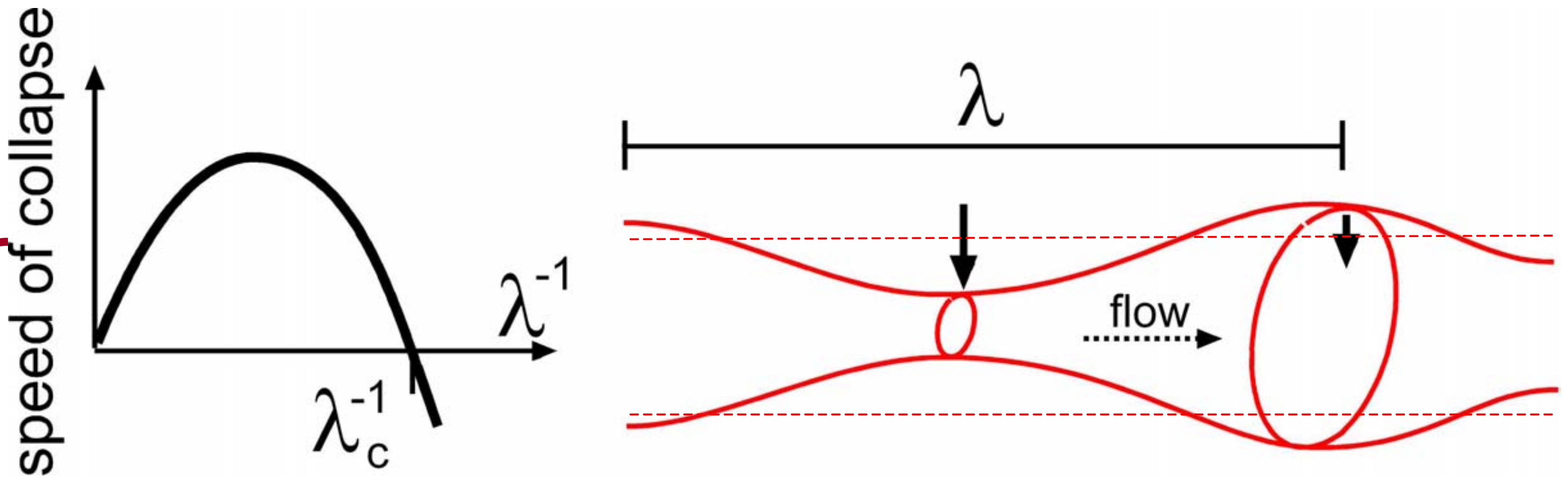
instability

capillary number (Ca) = **viscous / interfacial**

Weber number (We) = **inertial / interfacial**

Bond number (Bo) = **gravitational / interfacial**

Rayleigh-Plateau instability



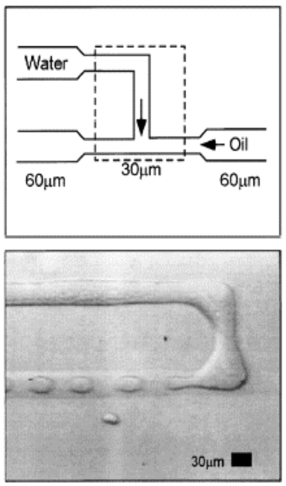
$u \sim \gamma / \mu$ viscous dynamics

$u \sim (\gamma / \rho l)^{1/2}$ inertial dynamics

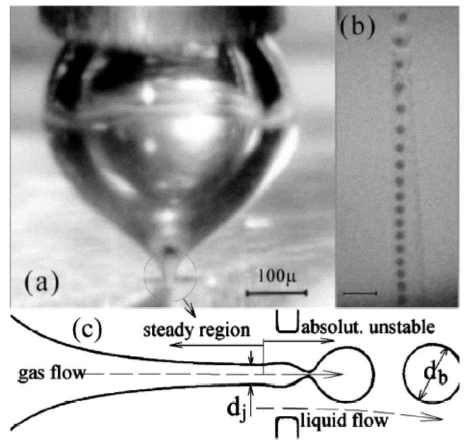
→typical size ~ $1/\lambda$

→typically broad size distribution

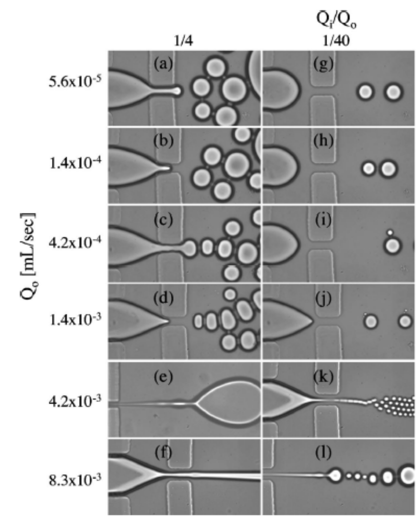
micro emulsification



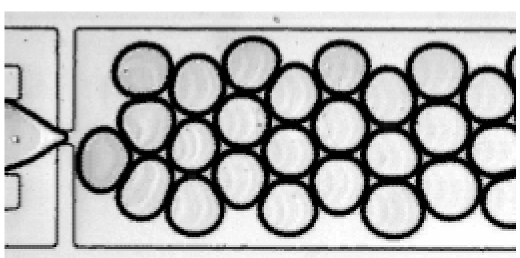
Thorsen (2001)



Ganan-Calvo (2001)



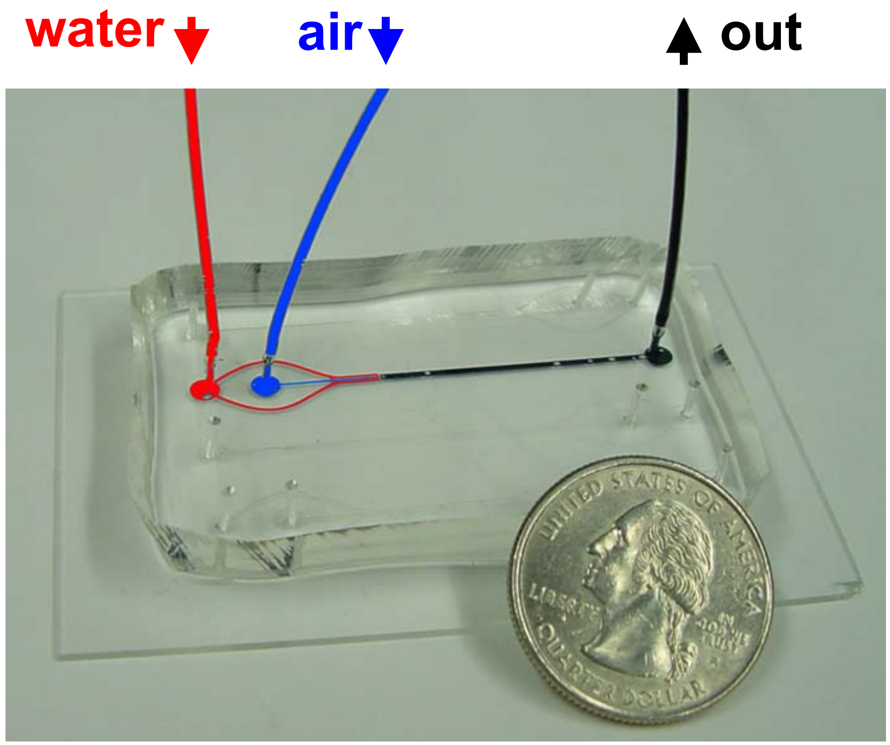
Anna (2003)

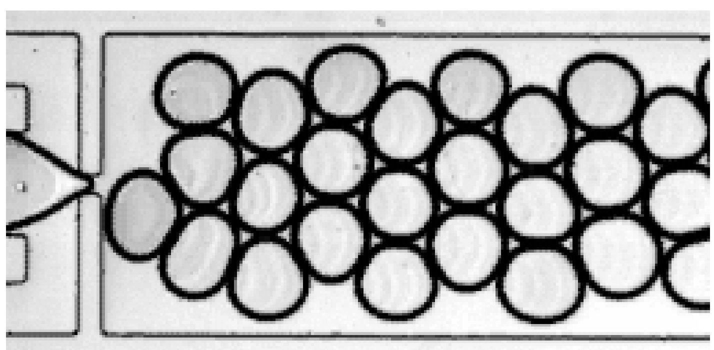


Garstecki (2004)

- liquid/liquid & gas/liquid
- possible to obtain narrow size distributions

flow focusing



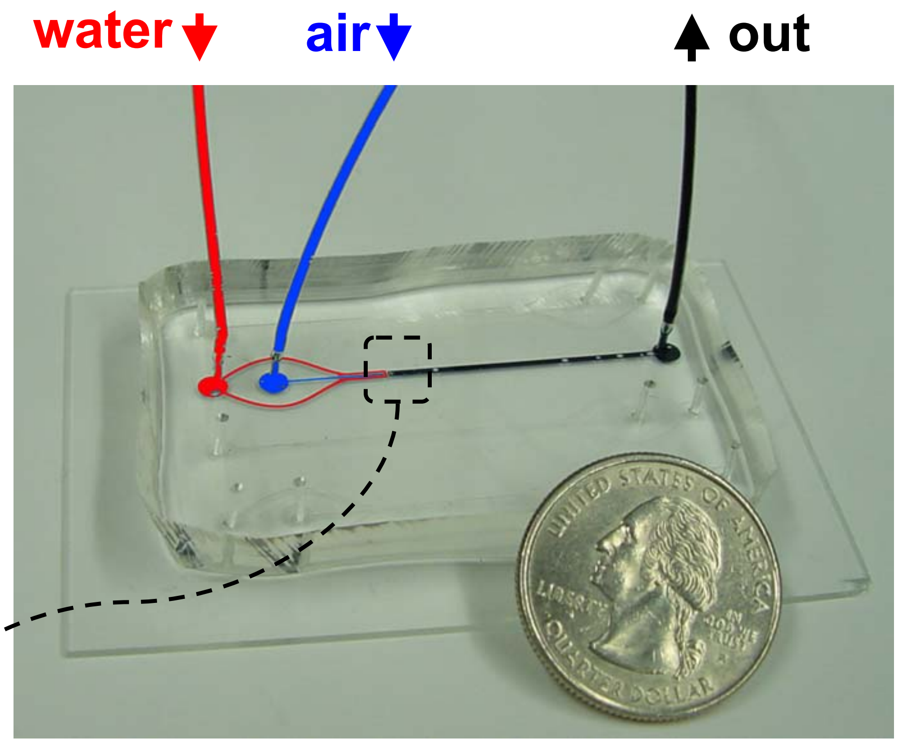


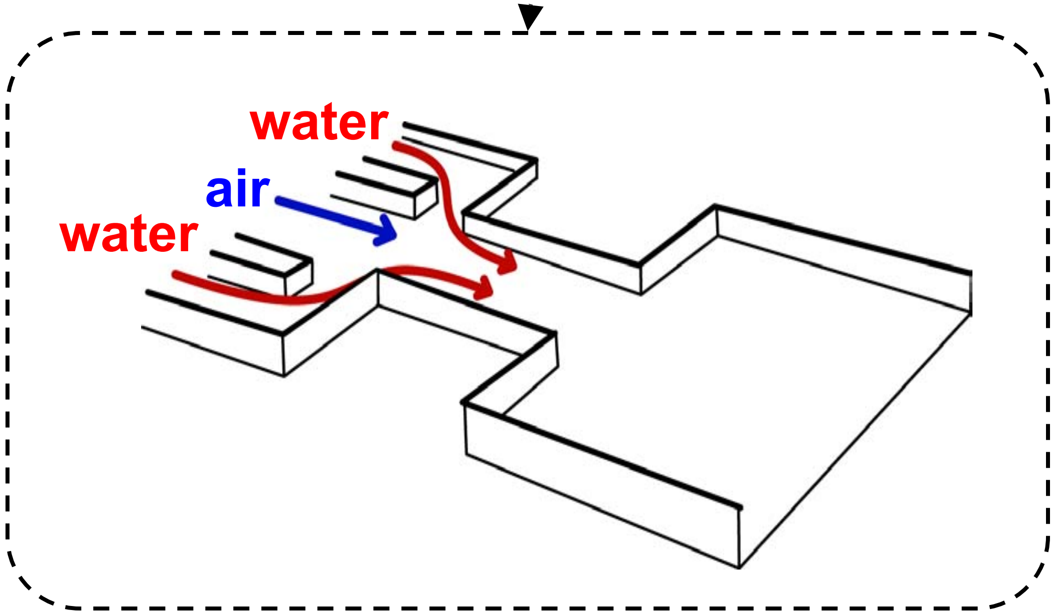
flow focusing

confined (planar) geometry

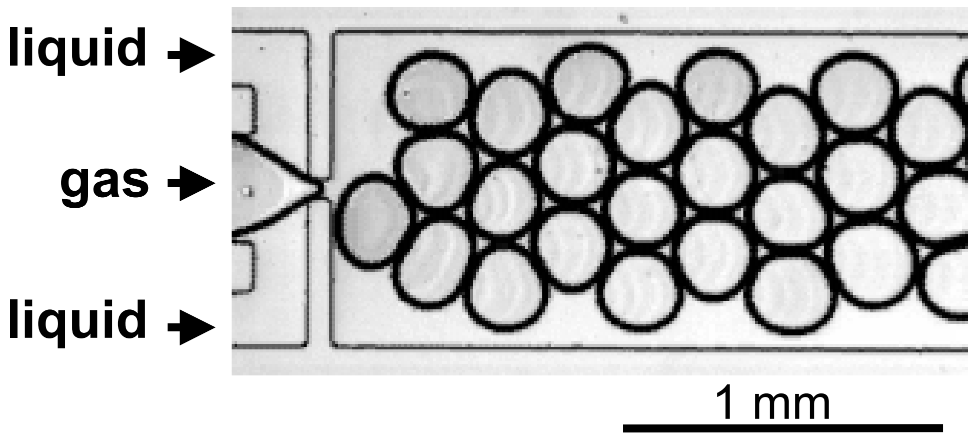
inlets:

- rate of flow of the liquid (**Q**)
- pressure app. to gas stream (**p**)





results



bubbles:

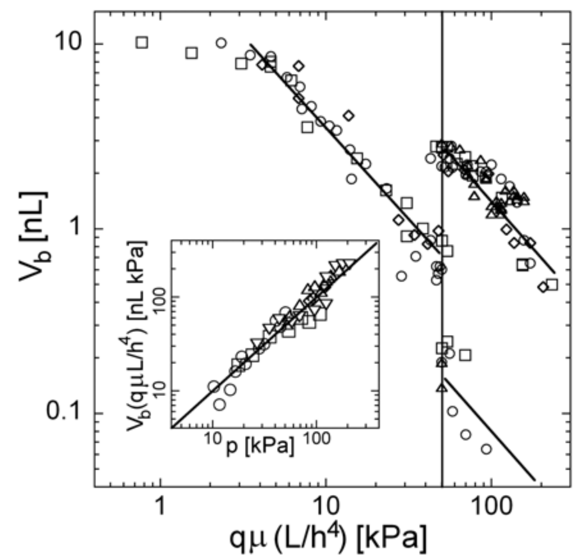
- size: 10 – 1000 μm
- standard deviation < 5 %
- volume fraction: 0 – 100 %

scaling

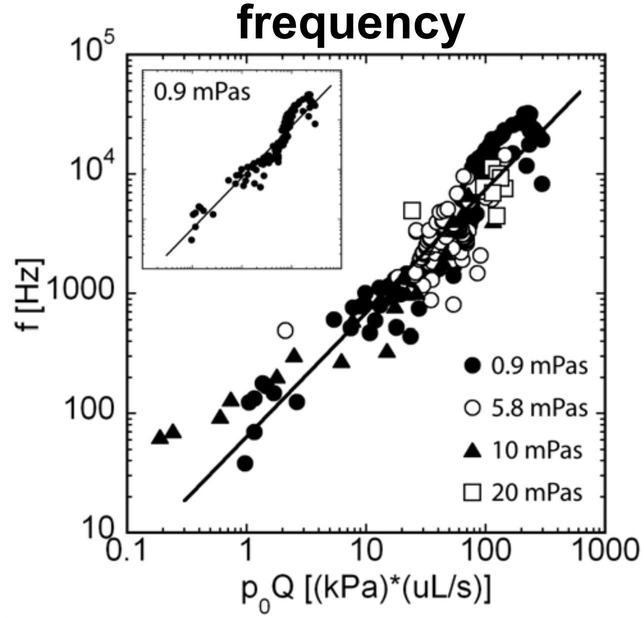
$$V_b \propto p/Q\mu$$
$$f \propto pQ$$

simultaneous,
independent control
of the
size and **volume fraction**

volume of the bubble



frequency



questions

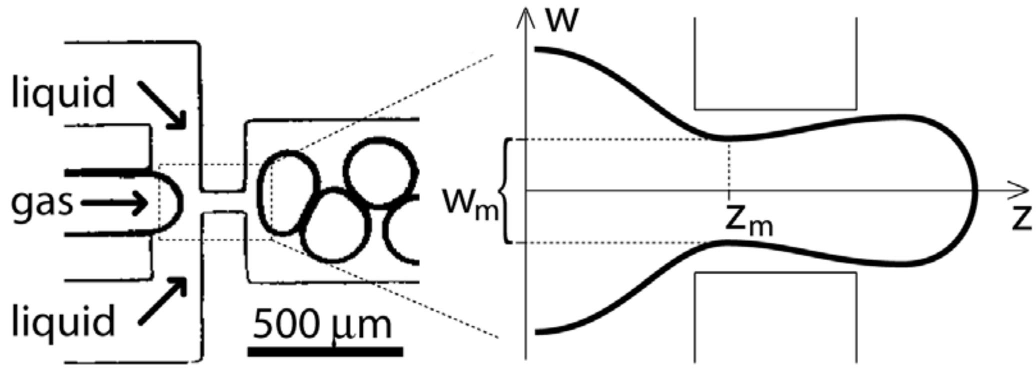
$$V_b \propto p/Q\mu$$
$$f \propto pQ$$

no dependence on surface tension

Ca: 10^{-3} to 10^{-1}

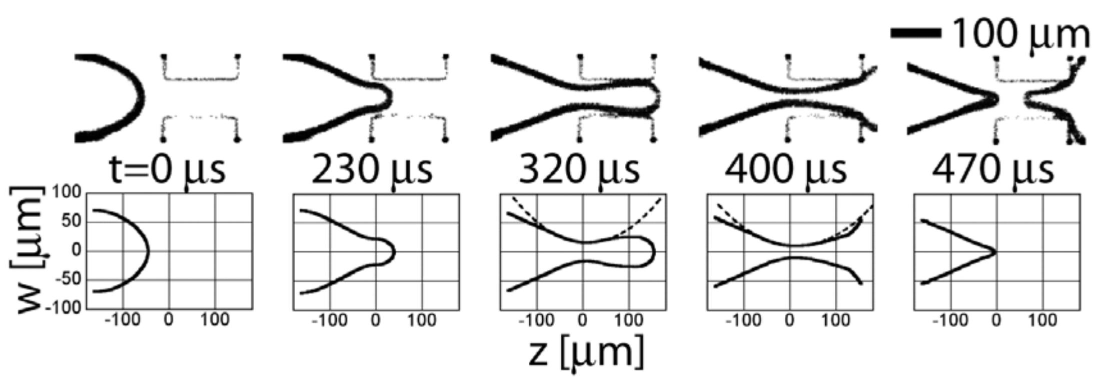
- why doesn't surface tension come into the equations?
- what is the mechanism of break-up?

break-up: evolution of the interface



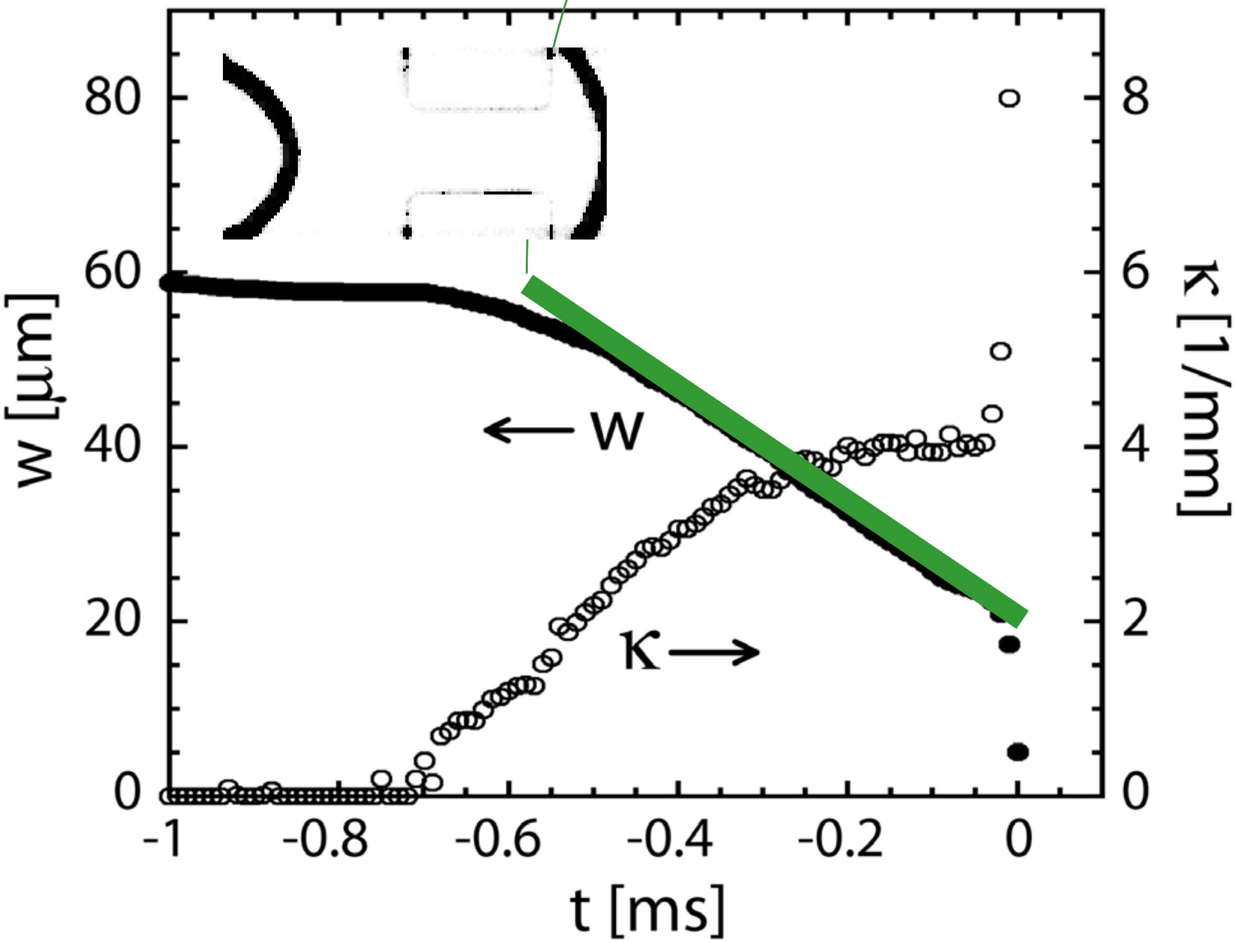
recording and image analysis

100 μm, 3000 times slower

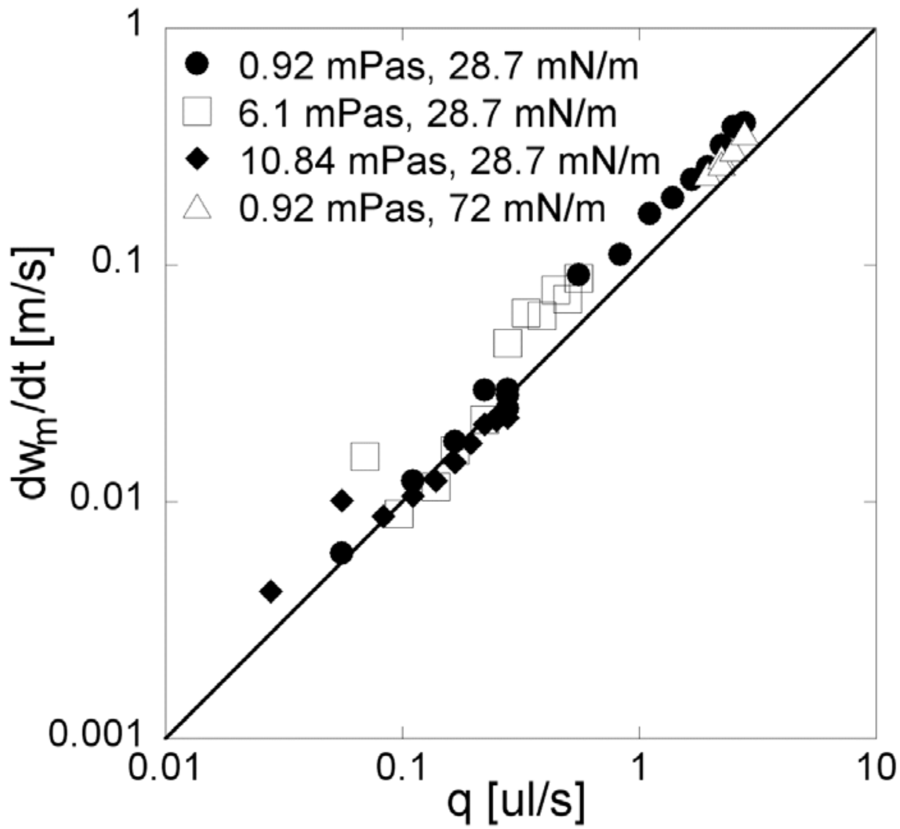


single break-up

"speed of collapse"
$dw/dt = f(Q, \mu, p, \gamma)$



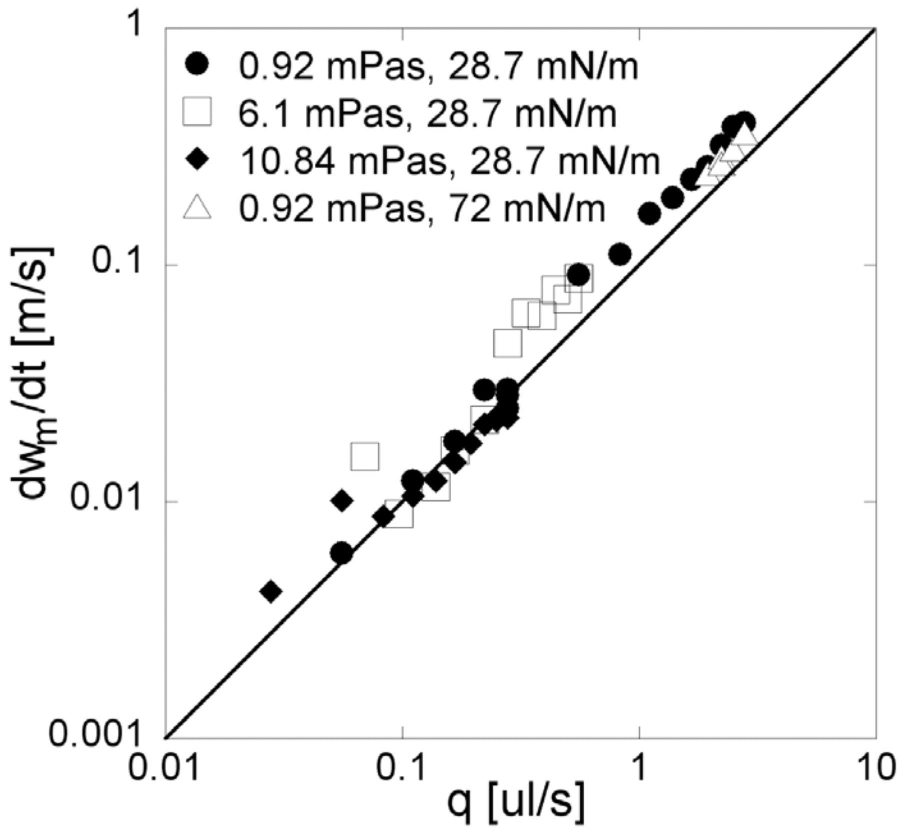
speed of collapse



dw/dt =

f(Q, μ, p, γ) =

speed of collapse



$dw/dt =$

$f(Q, \mu, p, \gamma) = \alpha\, Q$

'interfacial' speeds:

viscous regime

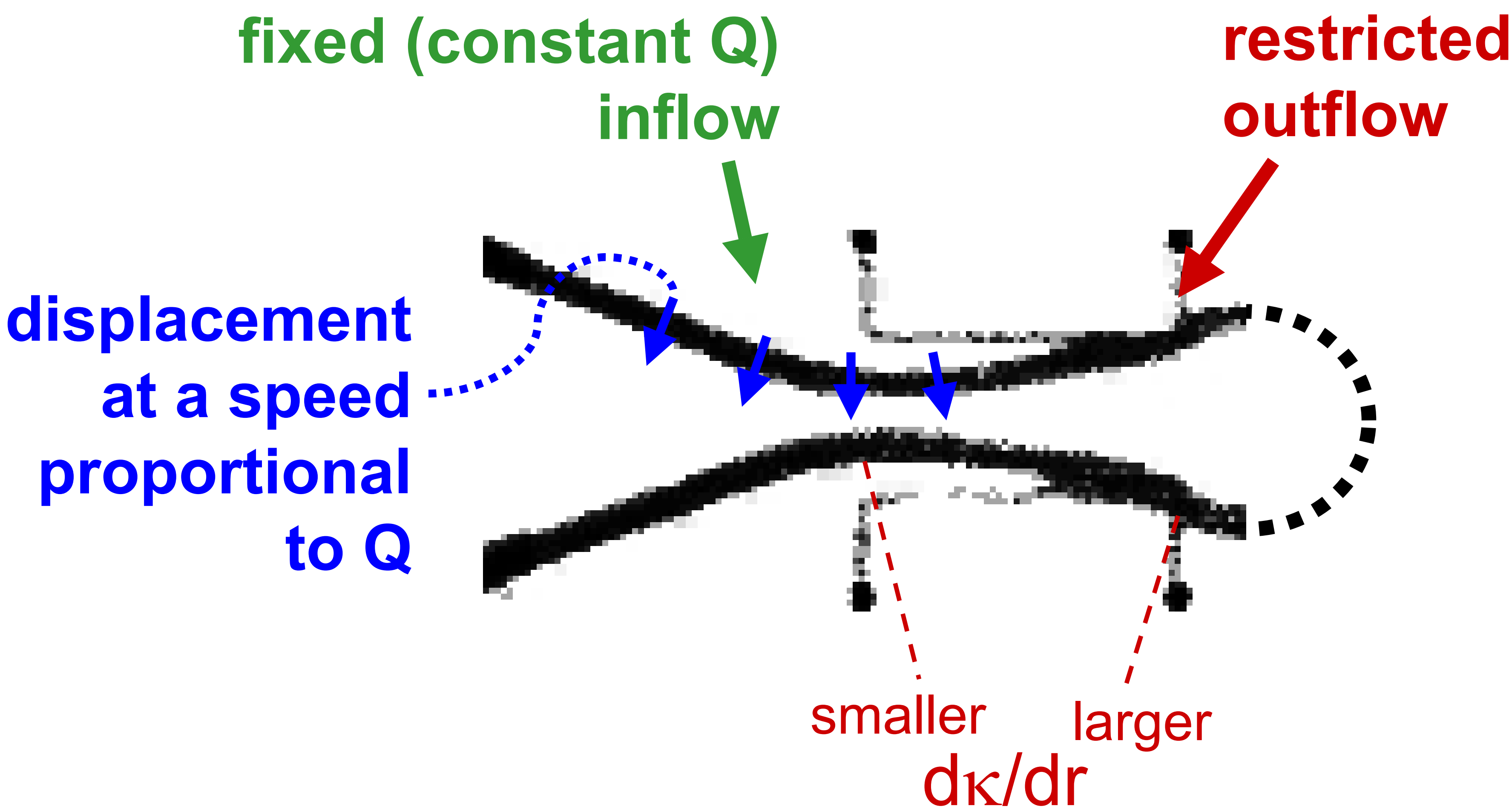
$u \sim \gamma/\mu \sim$ 10-100 m/s

inertial regime

$u \sim (\gamma/\rho l)^{1/2} \sim$ 1-10 m/s

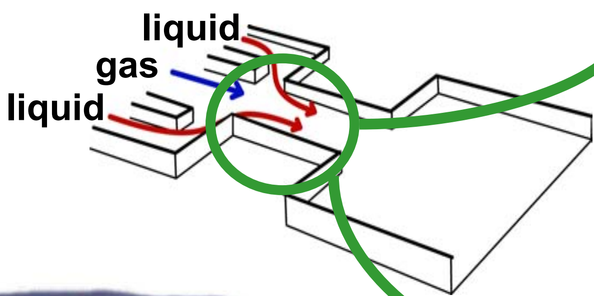
- **the speed depends only on the rate of flow of the continuous fluid**
- **the evolution is much slower than the speed of a capillary wave**

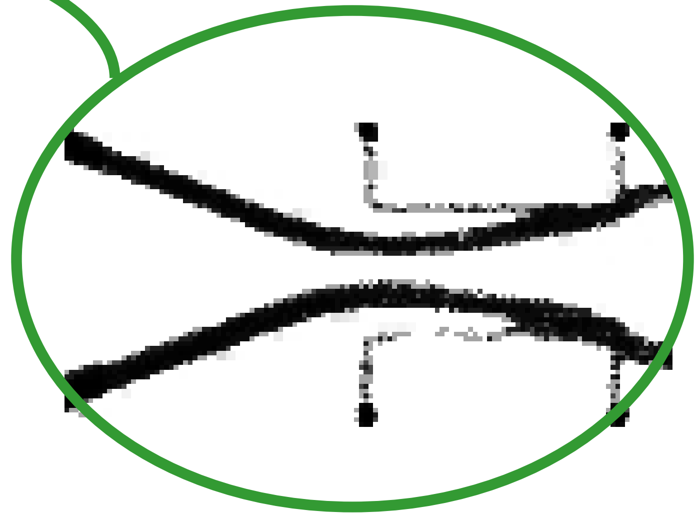
collapse is *not* driven by surface tension ‘squeezing’

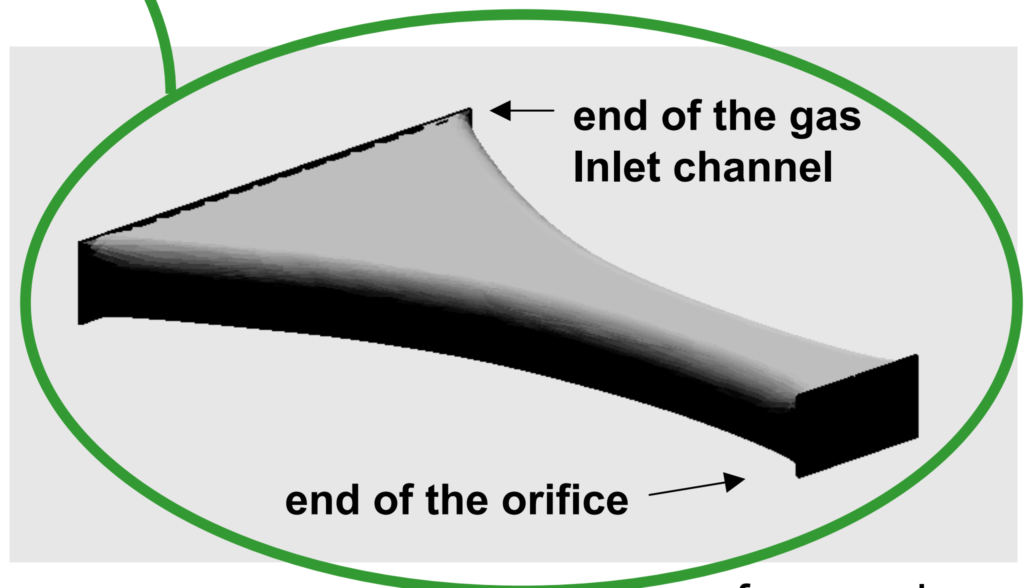


but, is the thread stable?

confinement

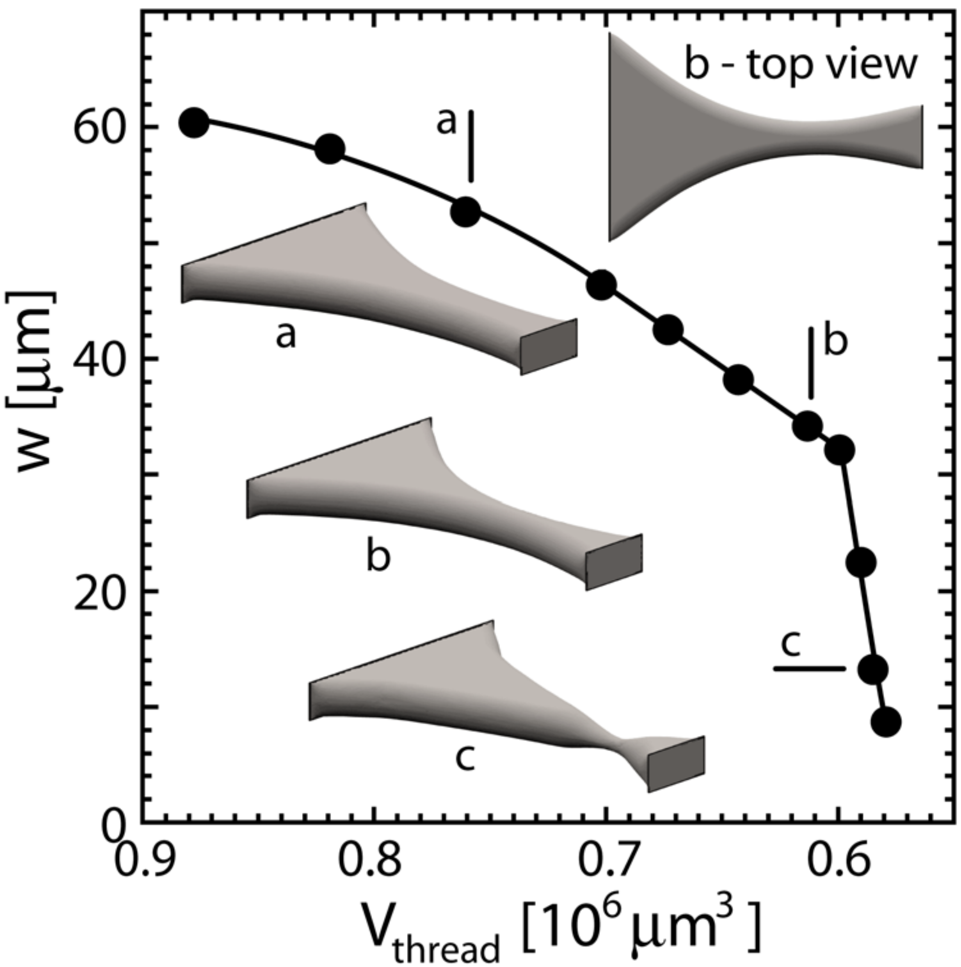






surface evolver

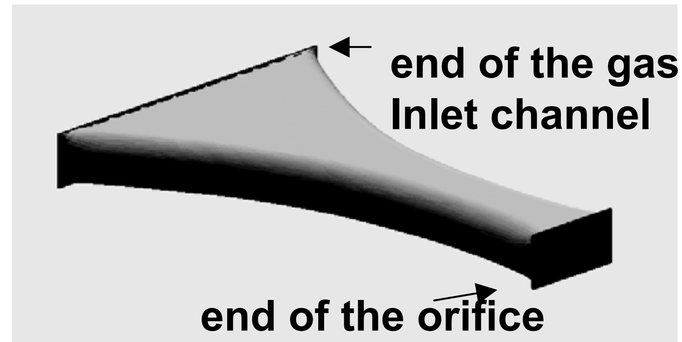
equilibrium *shape for a given volume enclosed by the gas-liquid interface* equilibrium



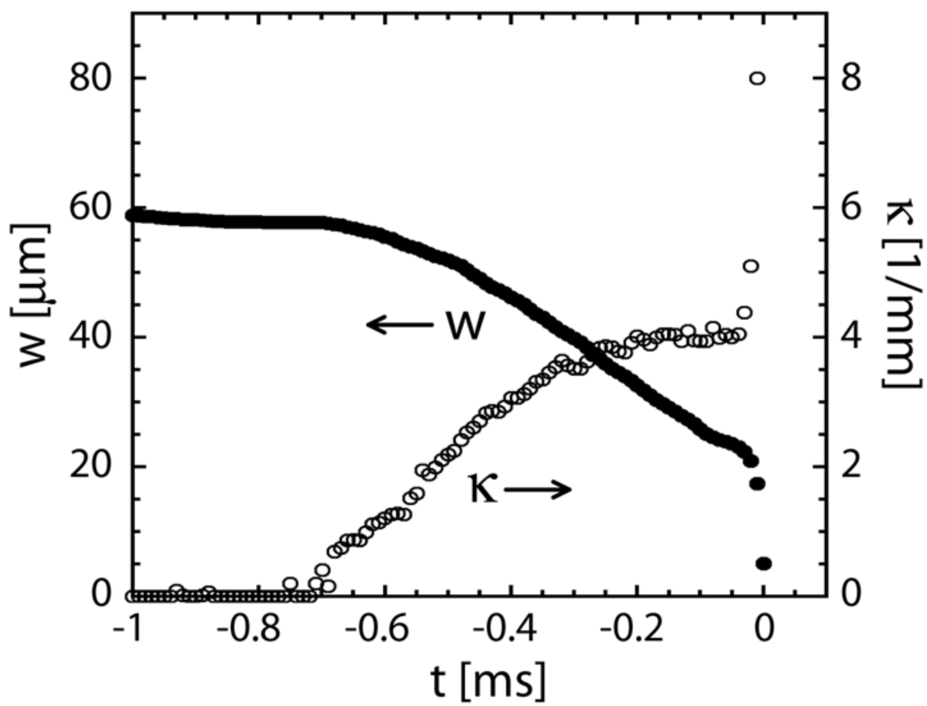
no dynamics here

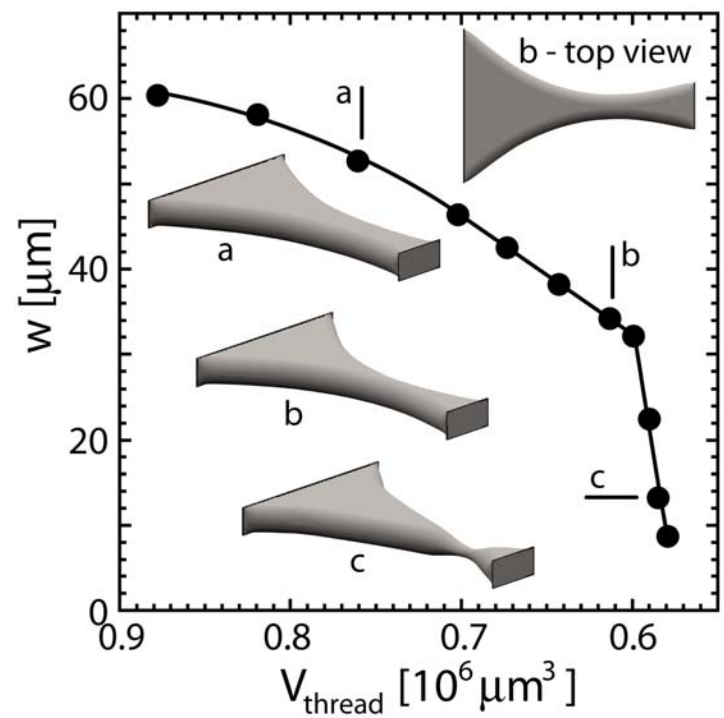
experiment

simulation



surface evolver





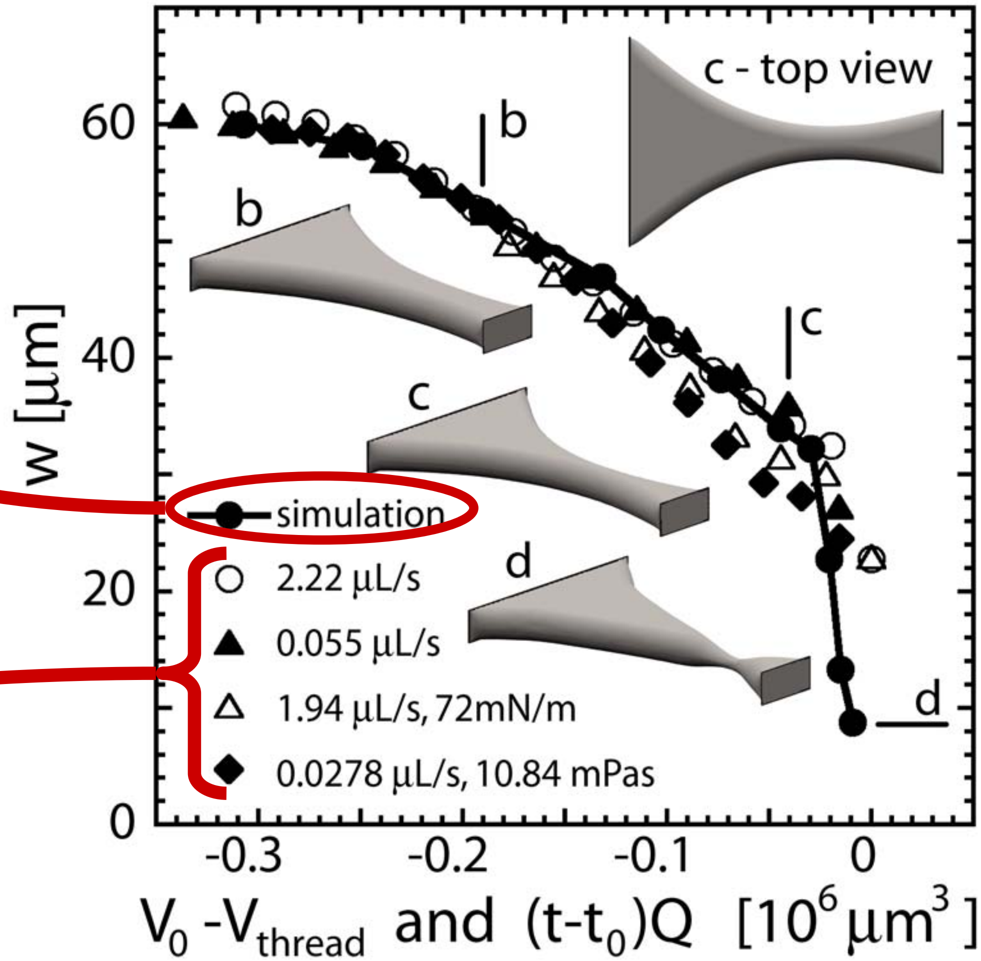
dynamics

equilibrium

quasi-stationary break-up

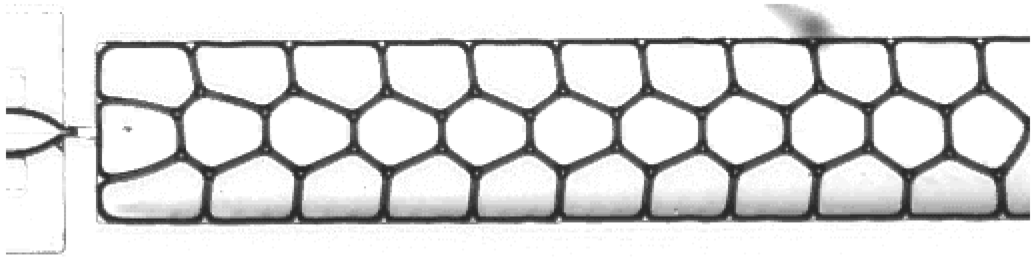
surface evolver

experiment



break-up follows through a series of equilibrium states

bubble growth rate



resistance to flow in the outlet channel: $R \propto \mu$

rate of inflating the bubble: $\mathbf{Q_{gas}} \propto \mathbf{p}/\mu$

volume of the bubble

$$V_b \propto t_{open}\ Q_{gas}$$

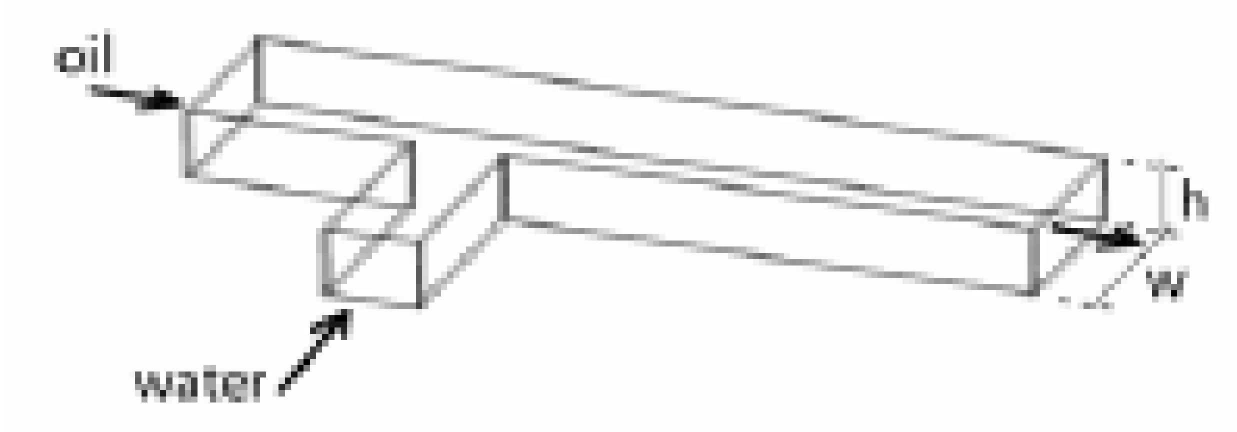
$$V_b \propto (1/Q)\ (p/\mu) = \boxed{p/Q\mu}$$

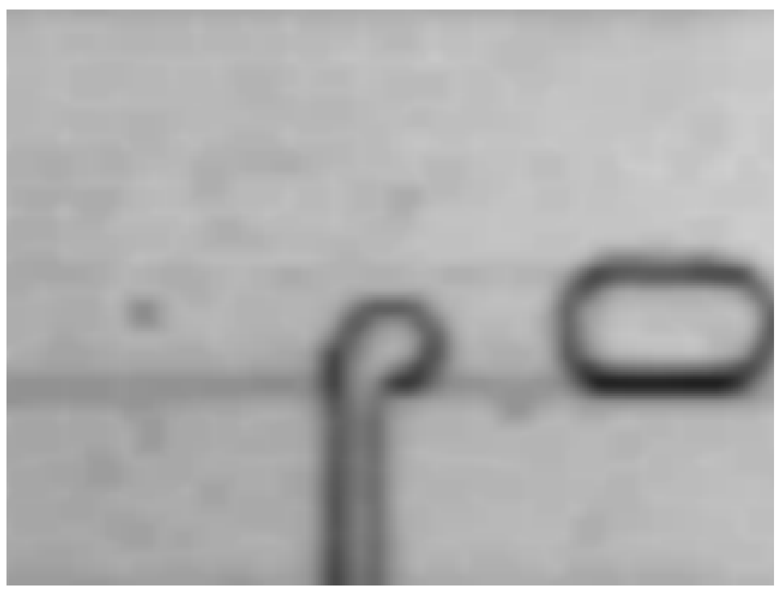
as observed

rate of flow controlled break-up

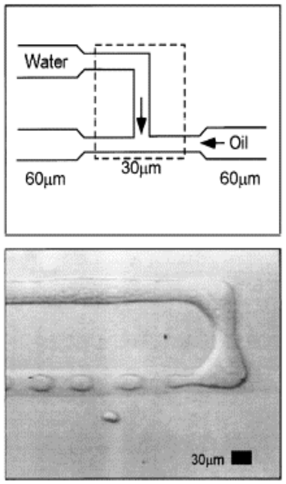
- **quasi-stationary break-up**
  - break-up govered by
    the evolution of pressure
  - strong effects of confinement
  - slow compared to relaxation rates
  - (new) mechanism
    specific to microgeometries and low Ca
- **bubbles**
  - both the size and the volume fraction can be controlled
- **applications**
  - formation of emulsions (*food, cosmetics, ultrasound contrast, artificial blood*)
  - formation of monodisperse droplets
    lab-chip, micro-particles, micro-capsules, lattices

T-junction





mechanism of break-up



Thorsen (2001)

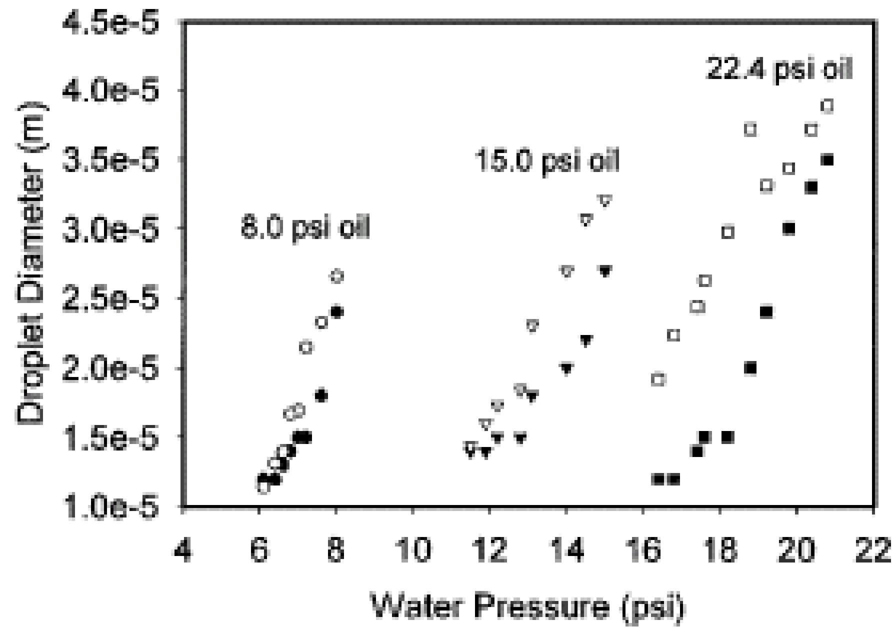


FIG. 4. Predicted vs actual drop size at different water and oil/surfactant pressures. The predicted sizes were calculated using Eq. (1). Open symbols, predicted size; solid symbols, experimental.

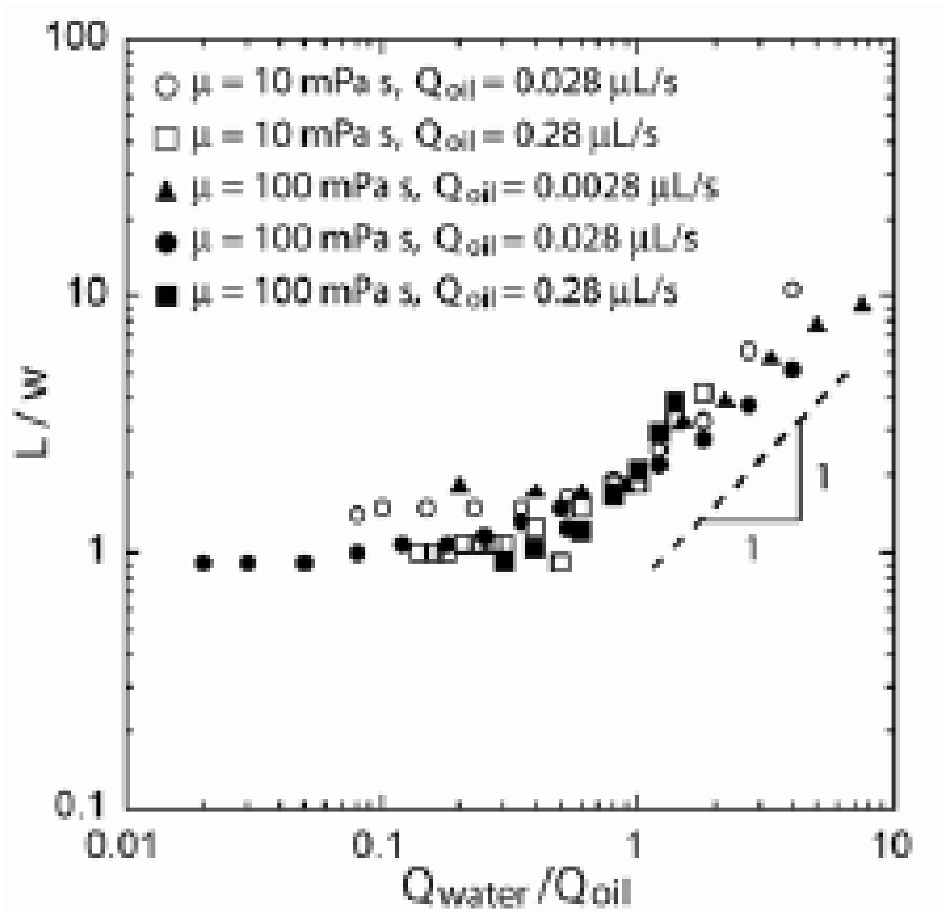
Thorsen (2001)

shear vs interfacial forces

linear size ~ Ca^{-1}

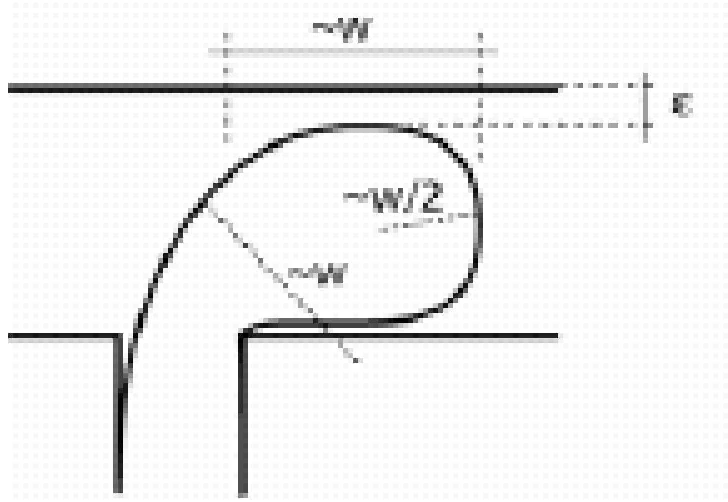
not checked rigorously

mechanism of break-up



100-fold change in shear stress
no change in size

forces



- interfacial stresses (stabilizing)

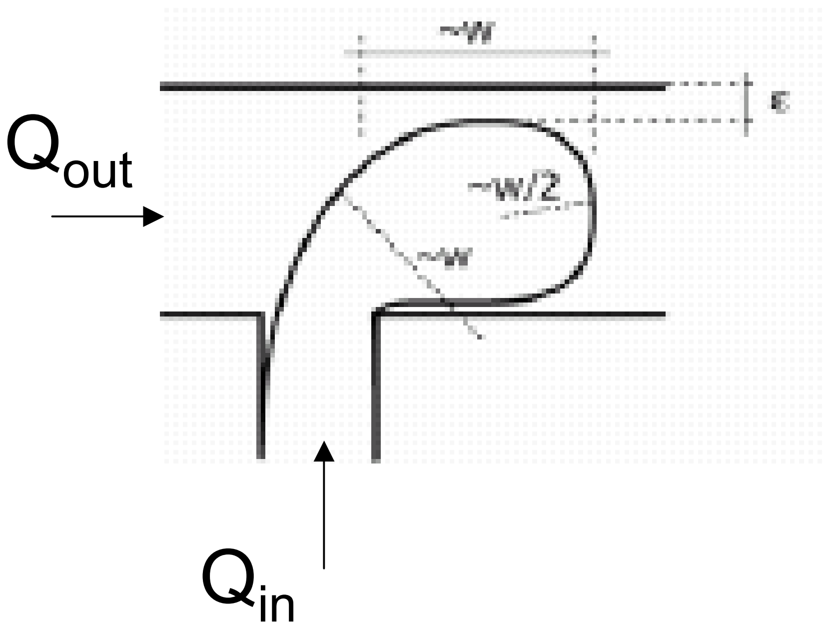
- shear stresses (destabilizing)

  overestimate scaling as ε^{-2}

- pressure drop (destabilizing)

  scaling as ε^{-n} with n>2

‘squeezing’ –
– rate of flow controlled break-up



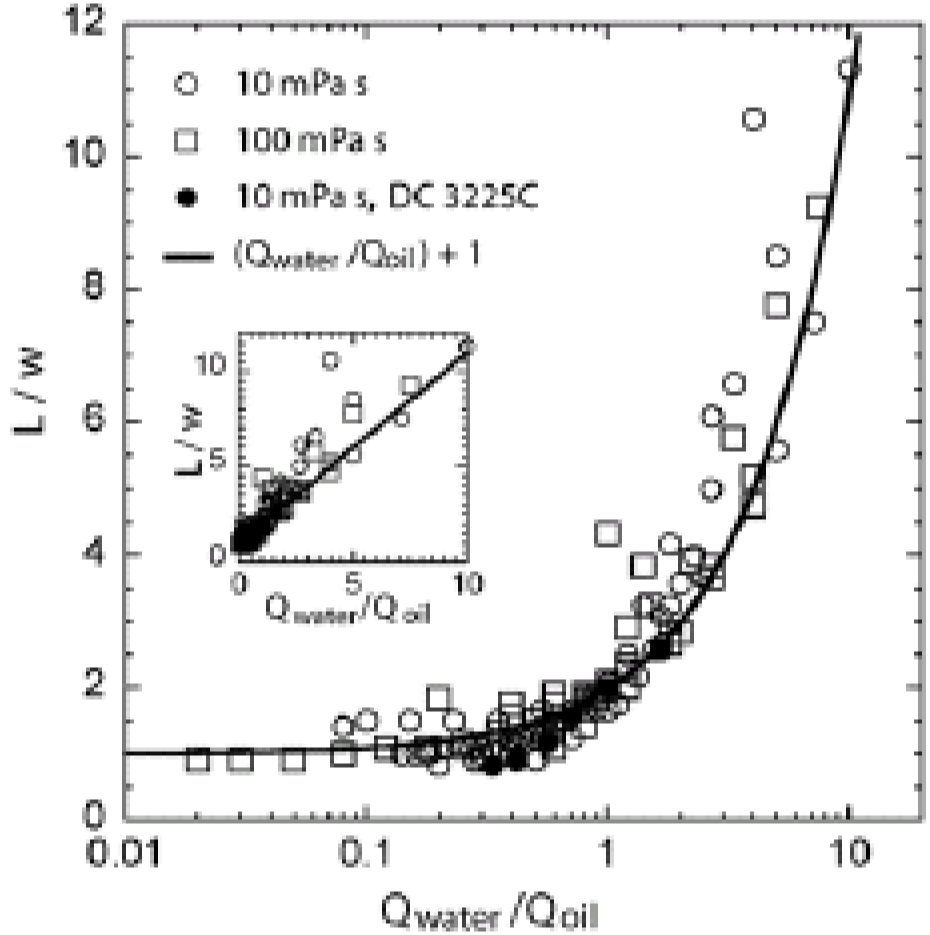
- blocking the channel
  $t_{block} \propto 1/Q_{in}$

- squeezing
  $t_{squeeze} \propto 1/Q_{out}$

$$\text{size} \sim (t_{block} + t_{squeeze})\, Q_{in}$$

$$\text{size} \sim 1 + Q_{in}/Q_{out}$$

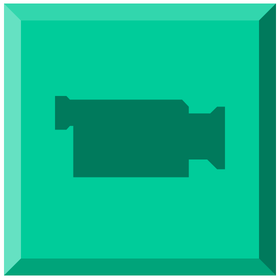
scaling



$L/w \sim 1 + Q_{in}/Q_{out}$

T-junction: simulations

simulations confirm both the details of the dynamics of break-up and the scaling

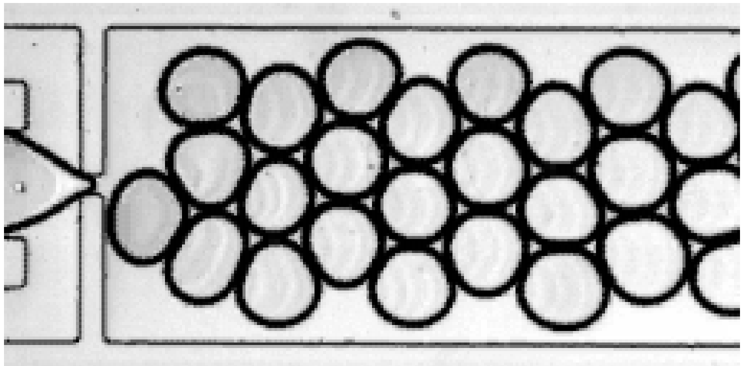


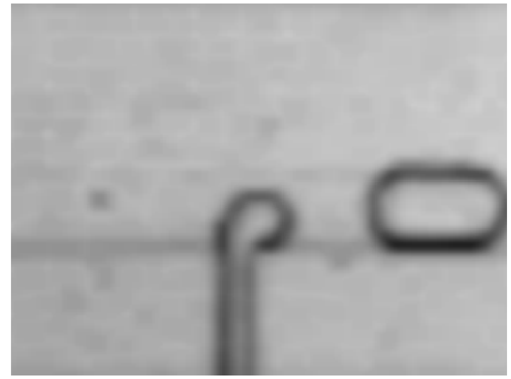
runs over a wide range of values of Ca show three distinct regimes:

squeezing – dripping – jetting

with **squeezing** being a new break-up mode, specific to microgeometries

M. De Menech, P. Garstecki, F. Jousse, H. A. Stone, *in preparation*





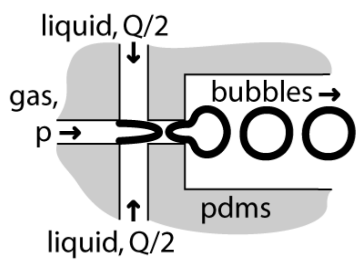
- **quasi-stationary break-up**
    - break-up govered by

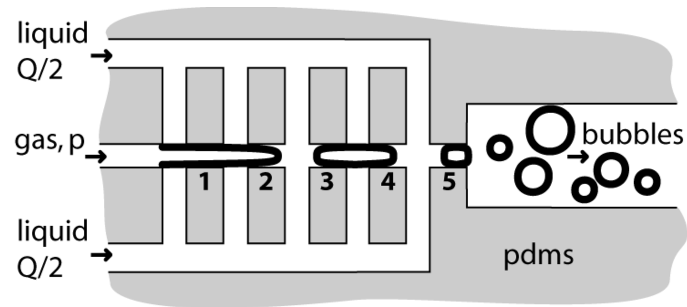
      the evolution of pressure
    - strong effects of confinement
    - slow compared to relaxation rates
    - (new) mechanism

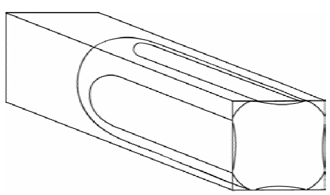
      specific to microgeometries and low Ca

- **microfluidics**
    - simple fluids
    - droplets and bubbles
- **formation of drops and bubbles**
    - flow-focusing
    - T-junction
- **stable oscillations with long periods**
- **time-reversible non-linear dynamics**
- **applications**
    - micromixing, portable assays
    - micro-particles and micro-capsules
    - diffraction gratings

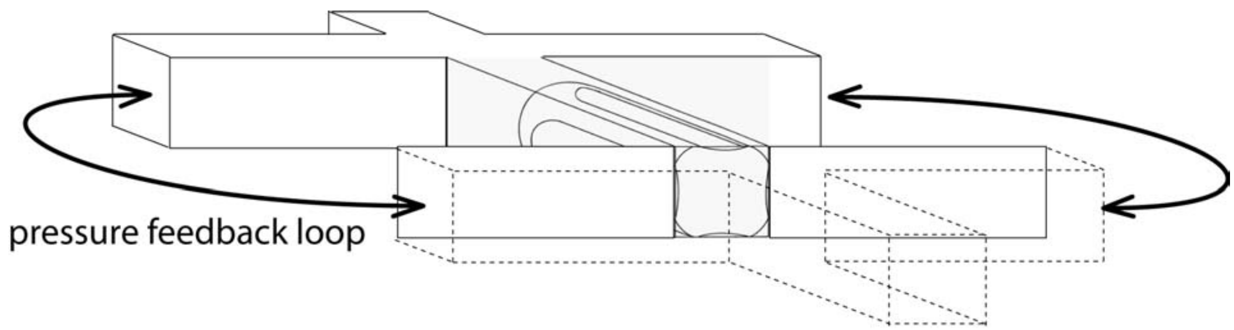
coupled flow-focusing oscillators







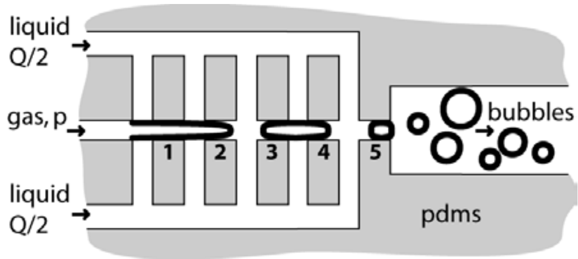
a plug
'blocks' the channel

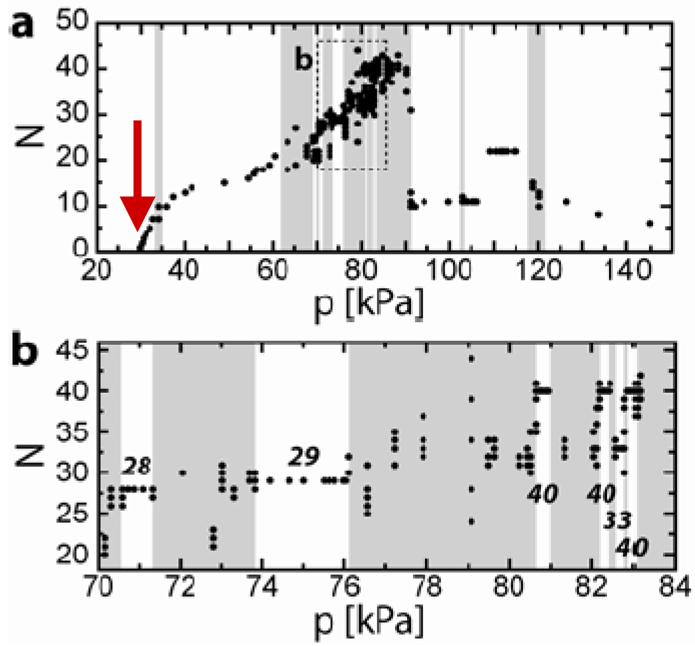


1. ***the rate of collapse of the thread at each orifice depends on what happens everywhere else***

2. ***the exchange of information (via pressure waves) is much faster than the evolution of the thread***

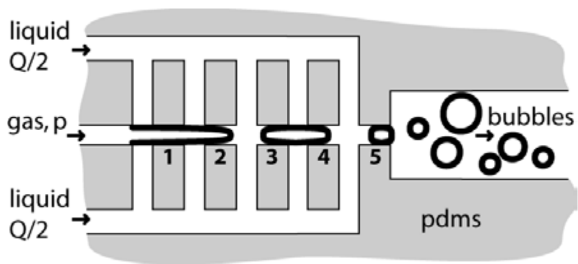
multi-orifice: **operation**

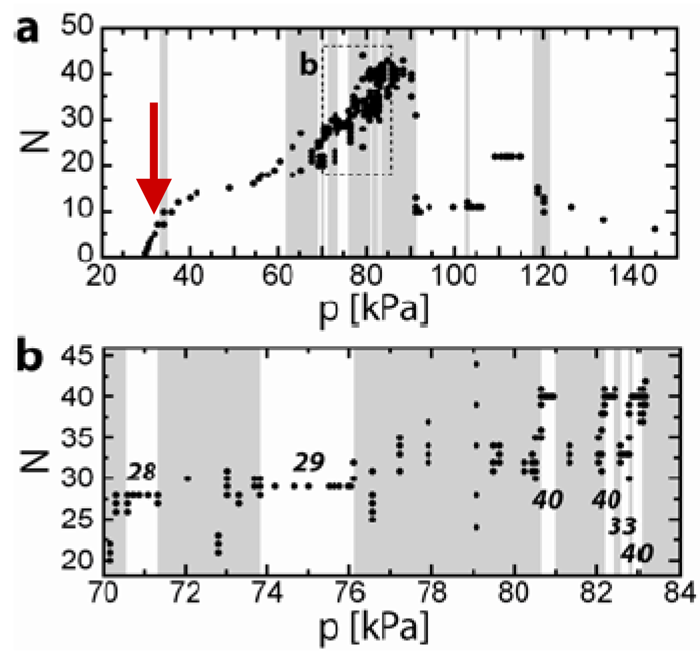




period-1

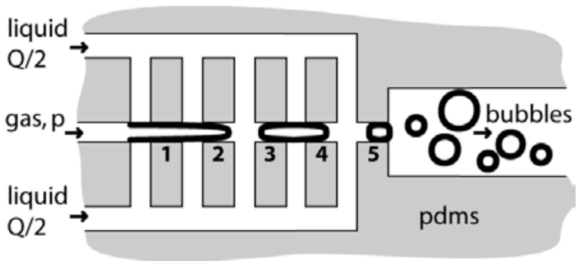
multi-orifice: **operation**

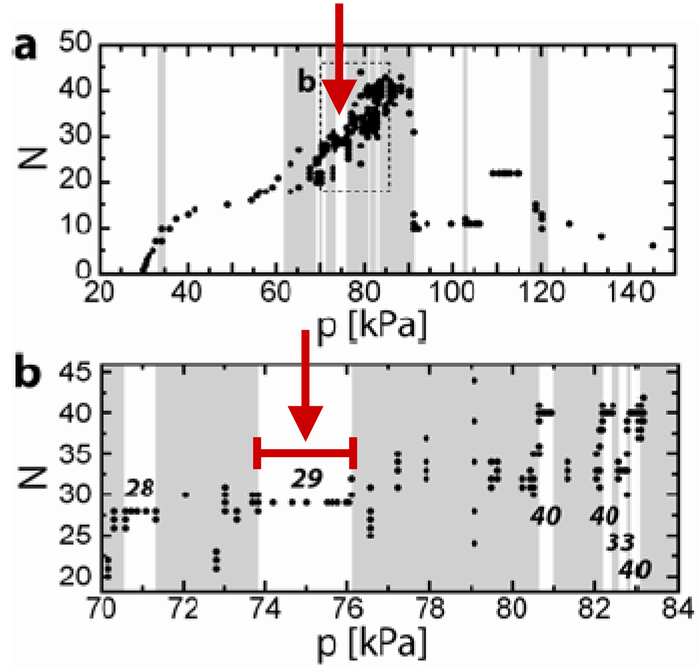




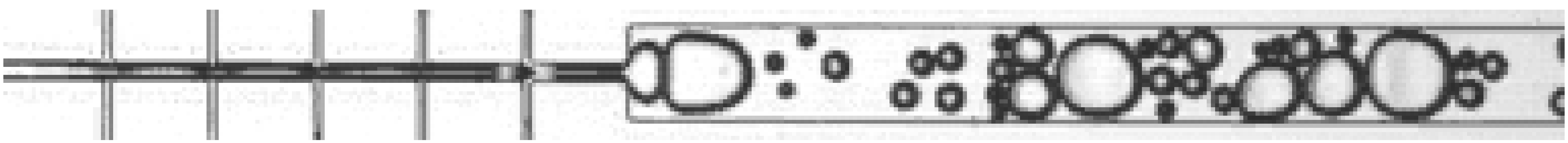
period-7

multi-orifice: **operation**

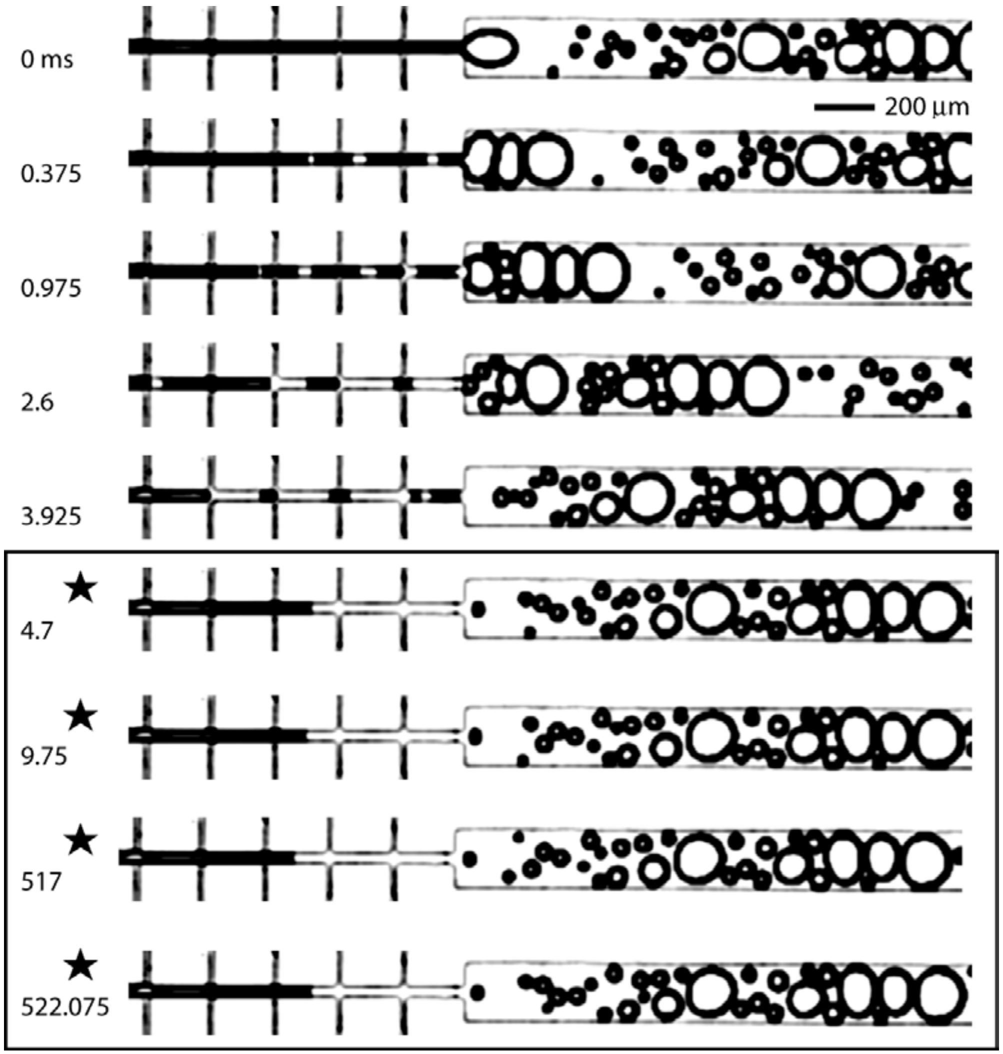




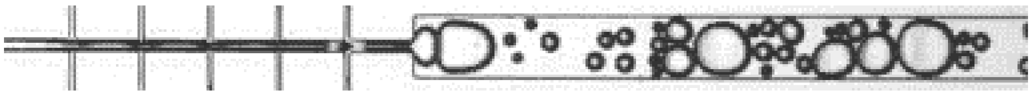
period-29

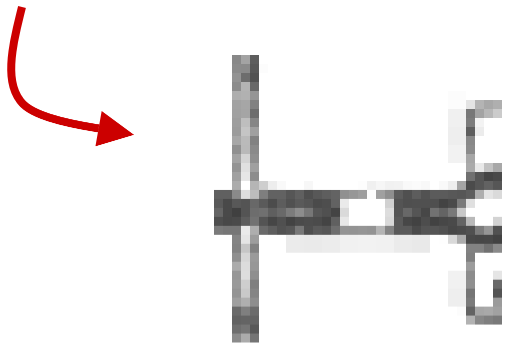


multi-orifice: **period 29**

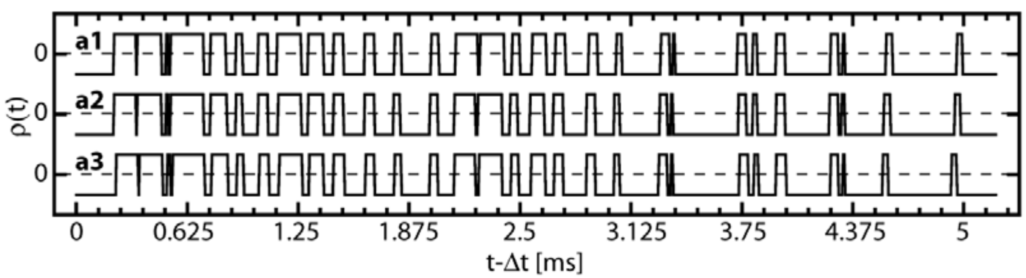


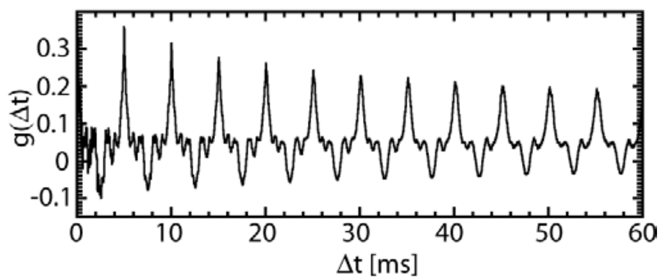
multi-orifice: period 29 – **analysis**

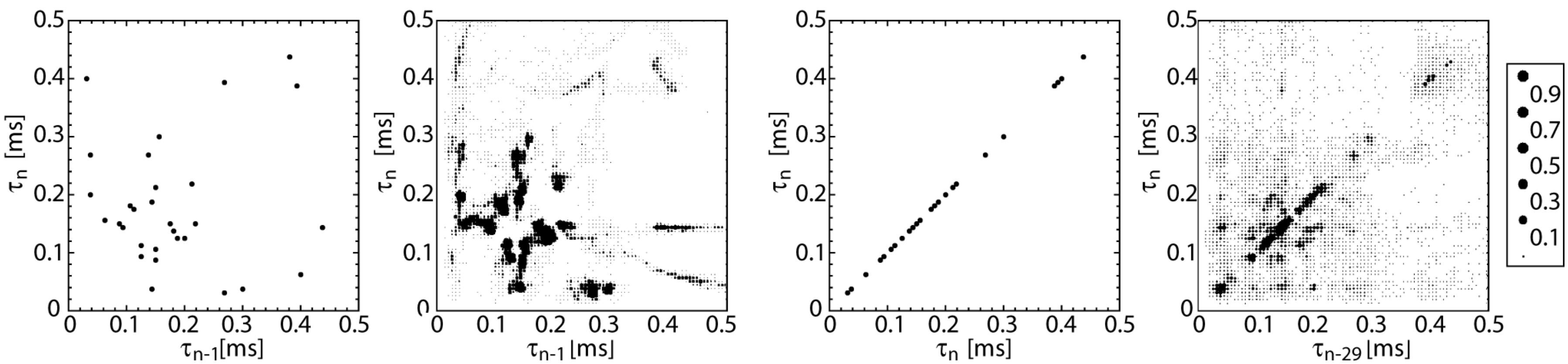




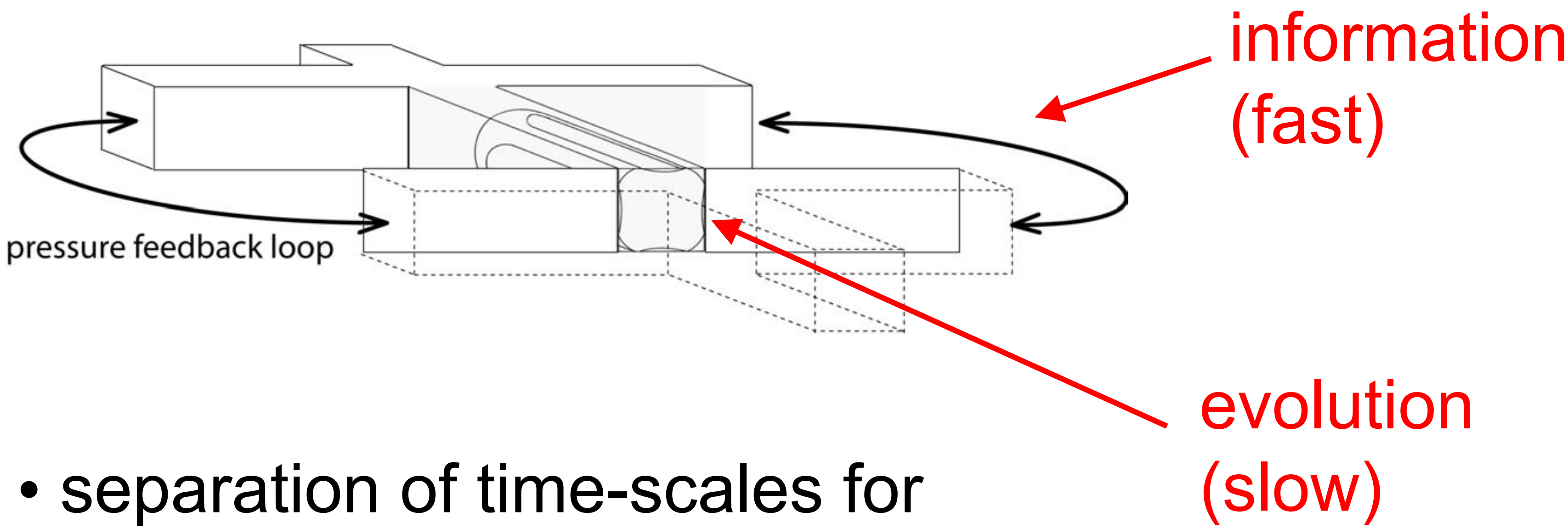
160 kfps –
– 6.25 μs







multi-orifice

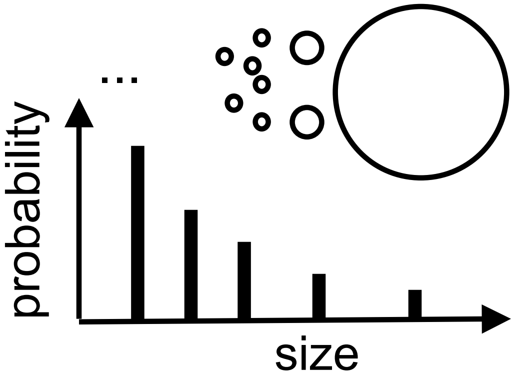


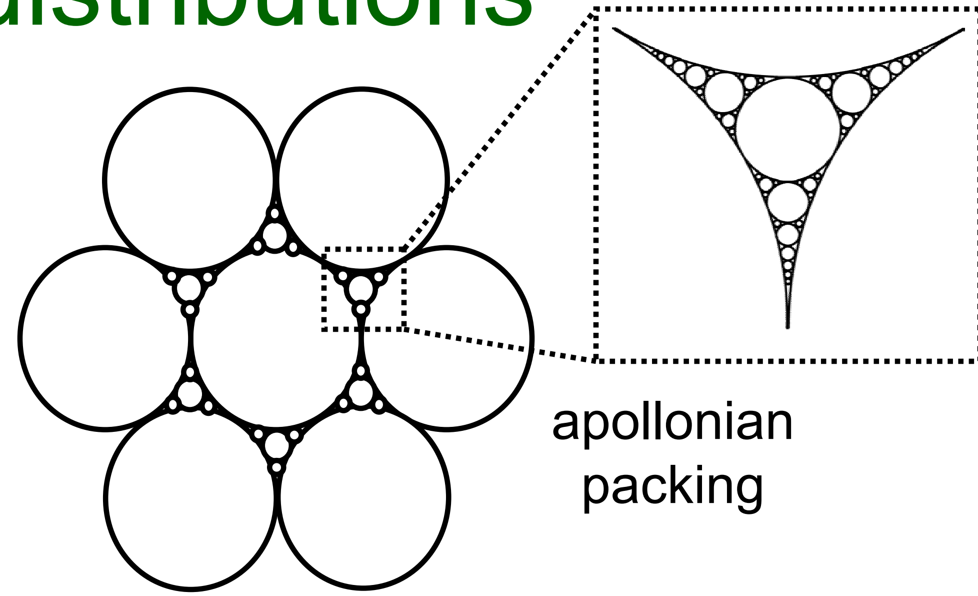
- separation of time-scales for
  - (slow) break-up, and
  - (fast) exchange of information

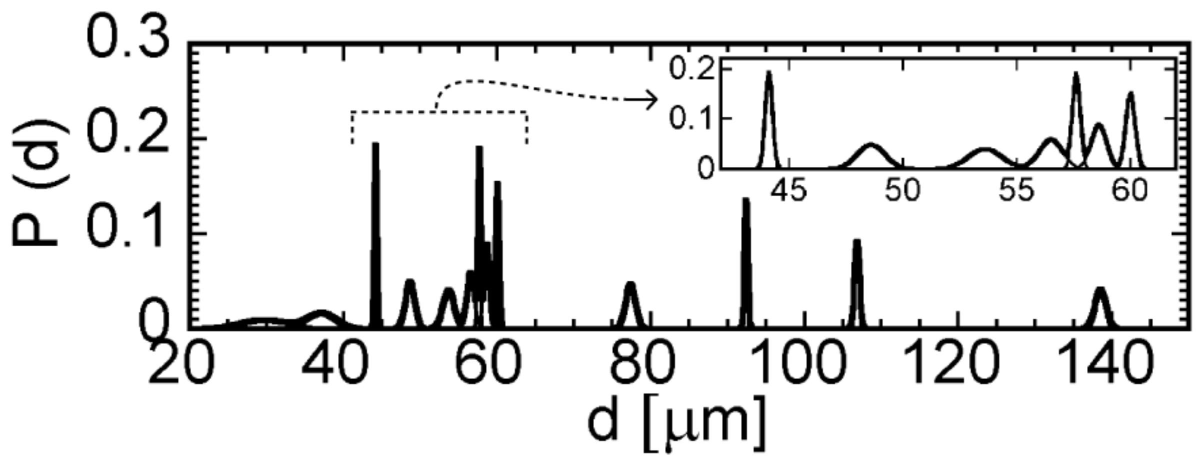
  + dissipative dynamics (low to mod Re)

    → effective isolation of the system
- applications – Apollonian packings?

engineering size distributions



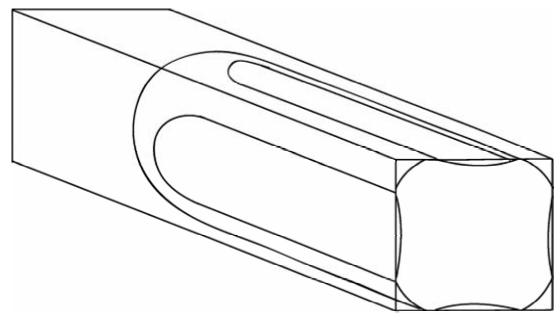




- **microfluidics**
  - simple fluids
  - droplets and bubbles
- **formation of drops and bubbles**
  - flow-focusing
  - T-junction
- **stable oscillations with long periods**
- **time-reversible non-linear dynamics**
- **applications**
  - micromixing, portable assays
  - micro-particles and micro-capsules
  - diffraction gratings

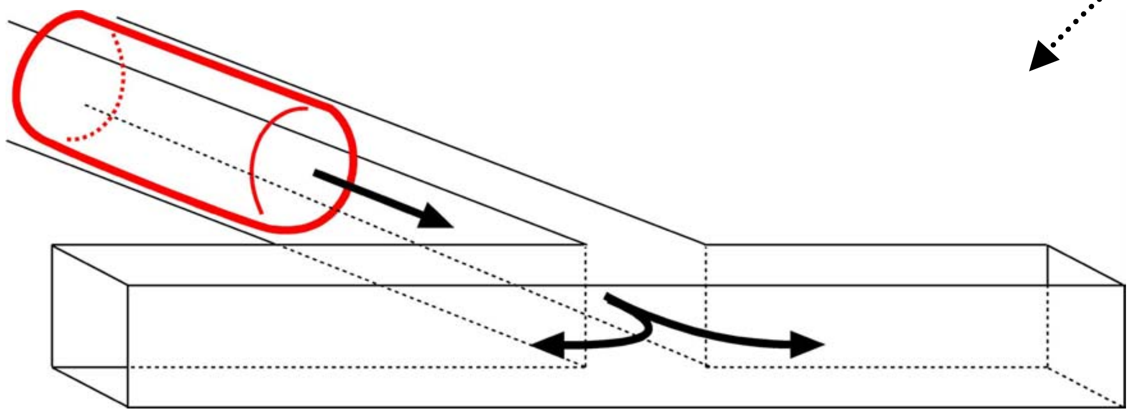
plug flow

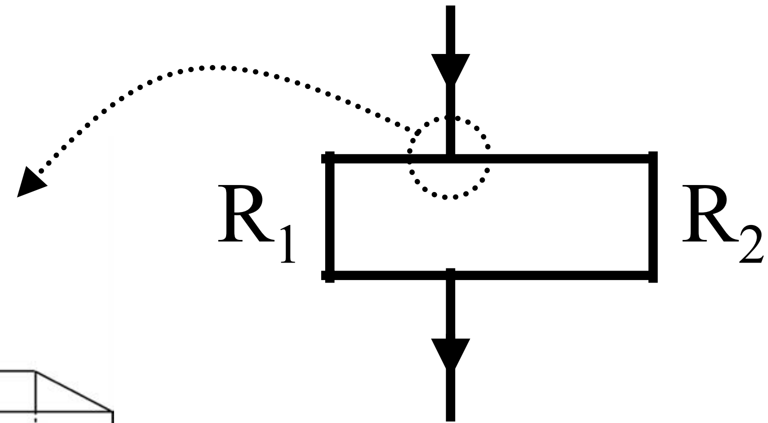
increased resistance to flow, $\Delta p \propto u^{2/3}$



Taylor
Bretherton
Wong

plug flow – decisions



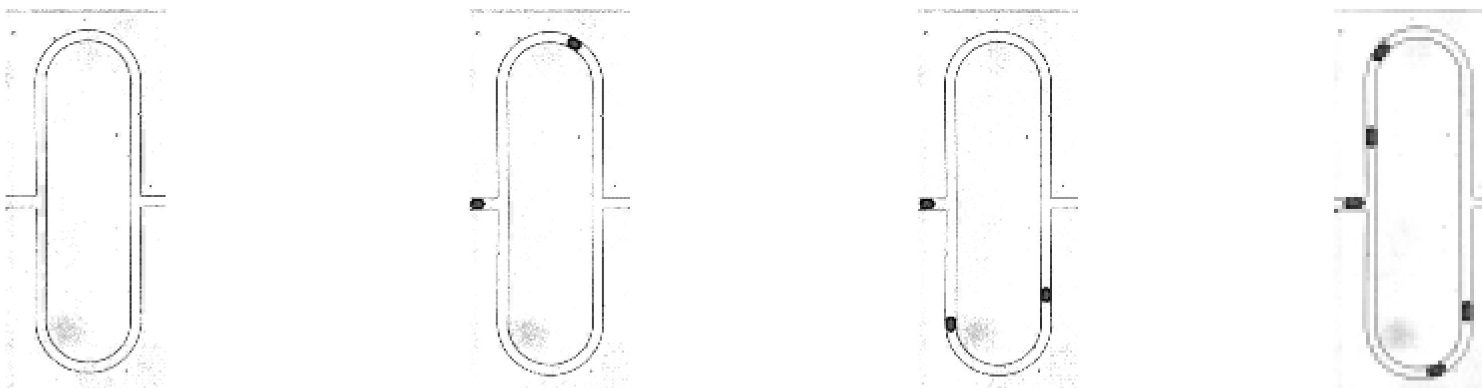


- simple fluid will split as $q_1/q_2=R_2/R_1$
- a bubble has to make a decision
- once it enters a channel it changes (increases) its resistance

a dynamic system with feedback (or memory)

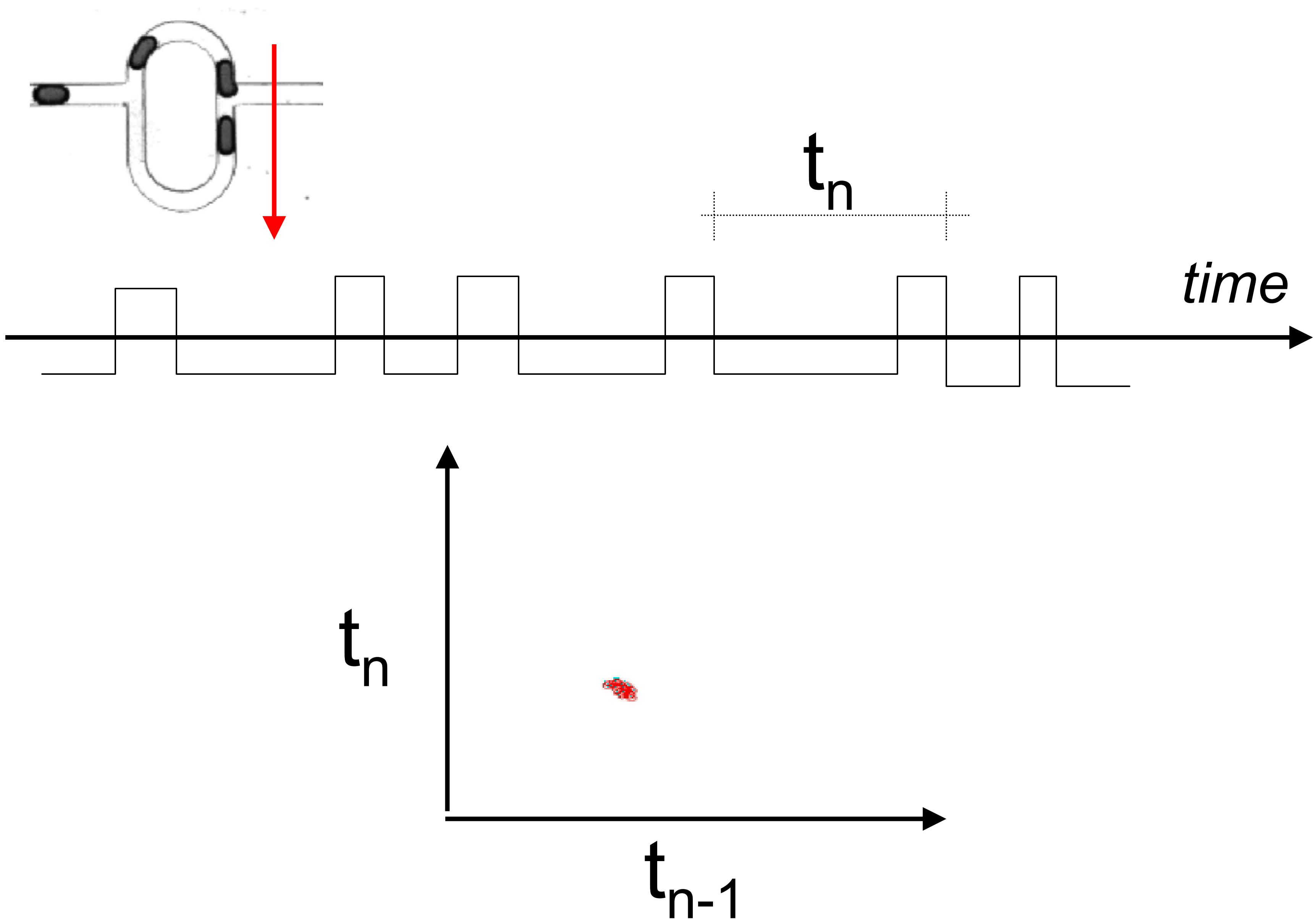
One Loop

Period-1 **Period-2** **Period-3** **irregular**

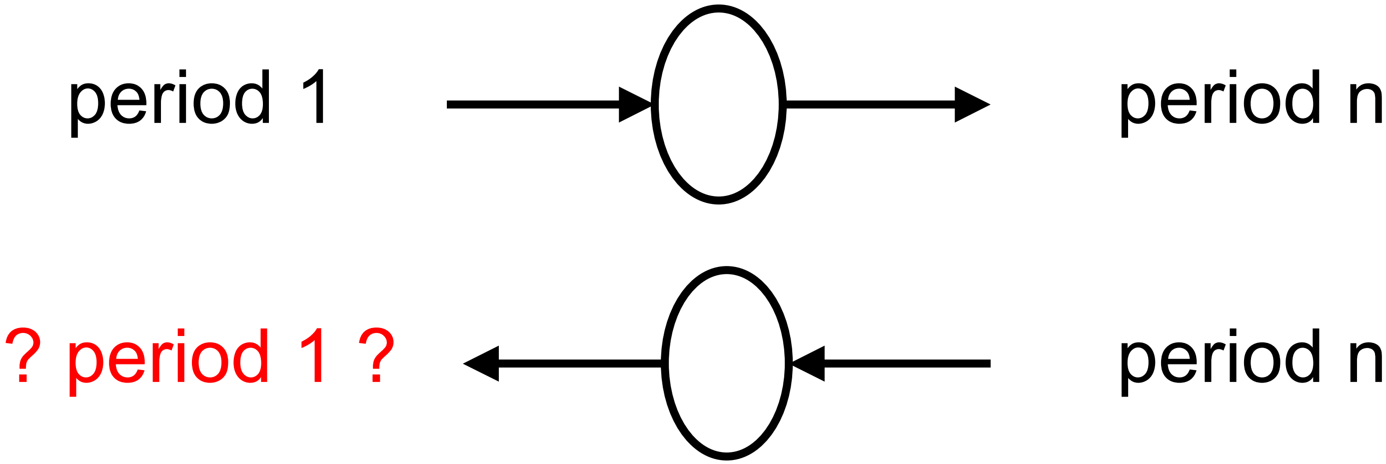


frequency of feeding

One Loop



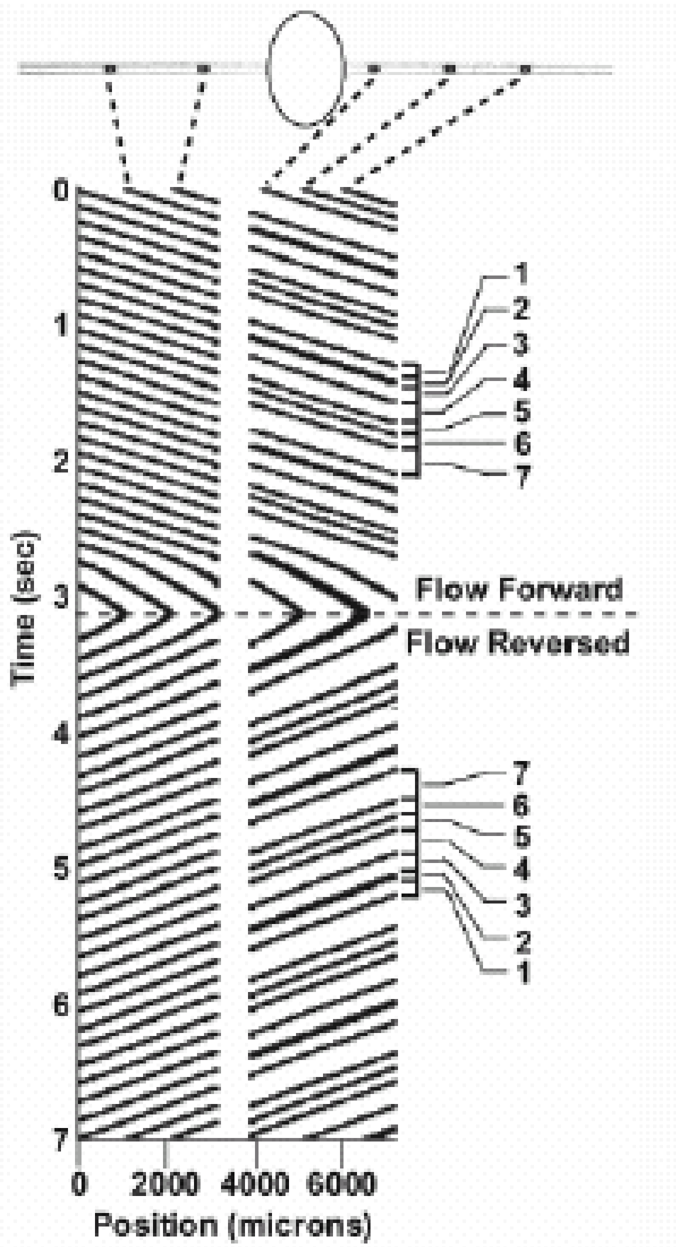
reversibility

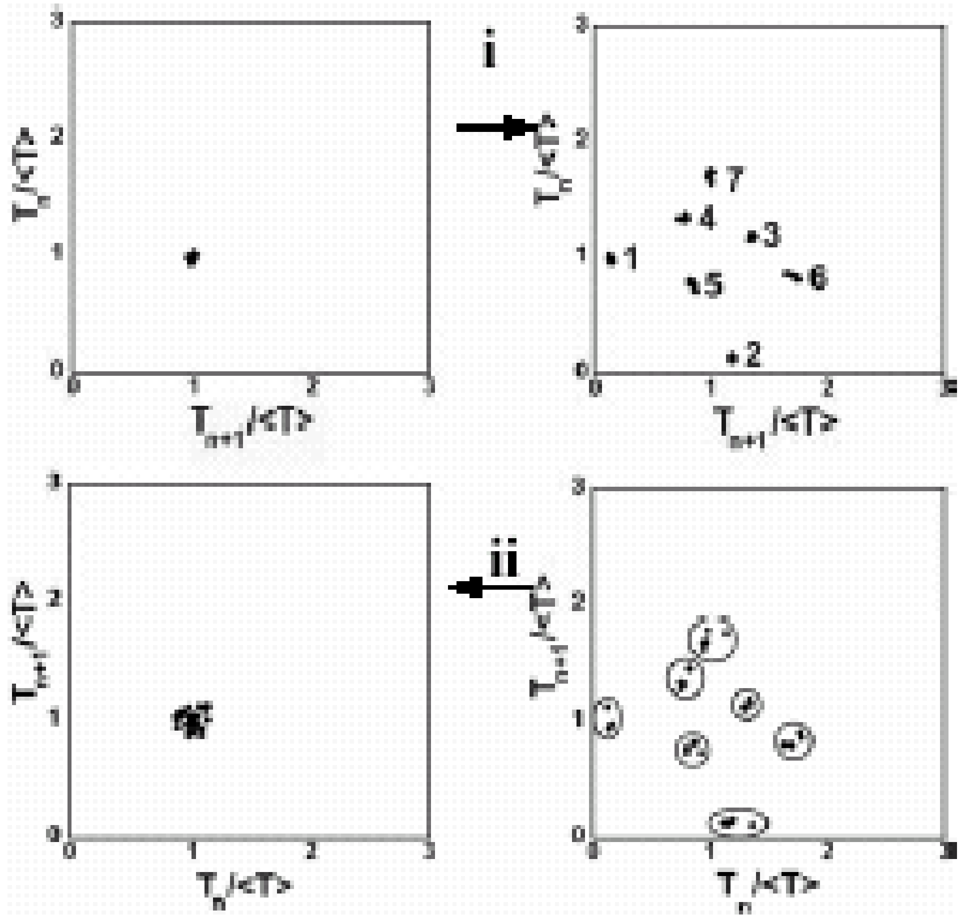


$$\eta \Delta \vec{V} - \vec{\nabla} P = 0$$

invariant under: $V \longrightarrow -V, \;\; P \longrightarrow -P$

period 1 ⟷ period 7

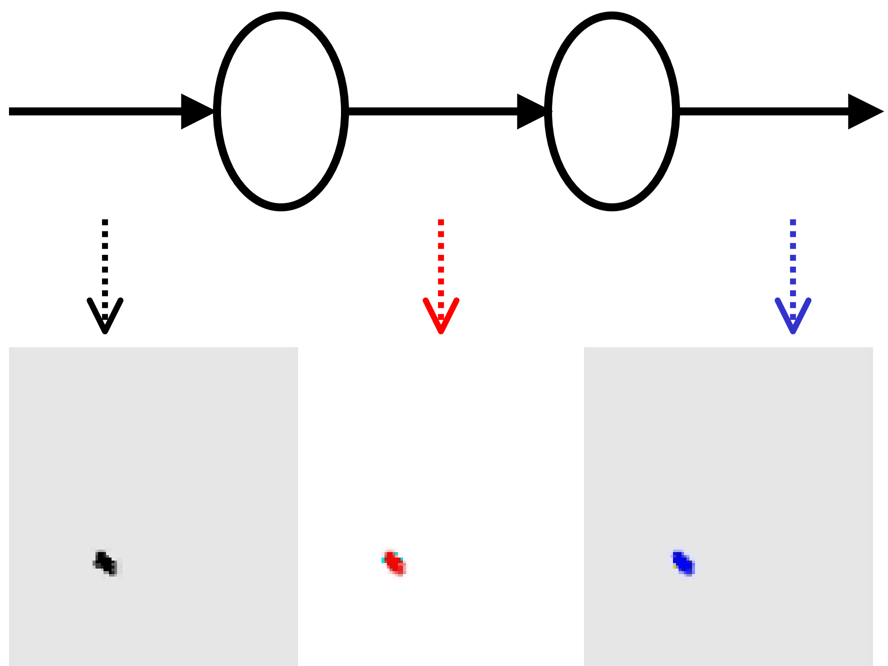




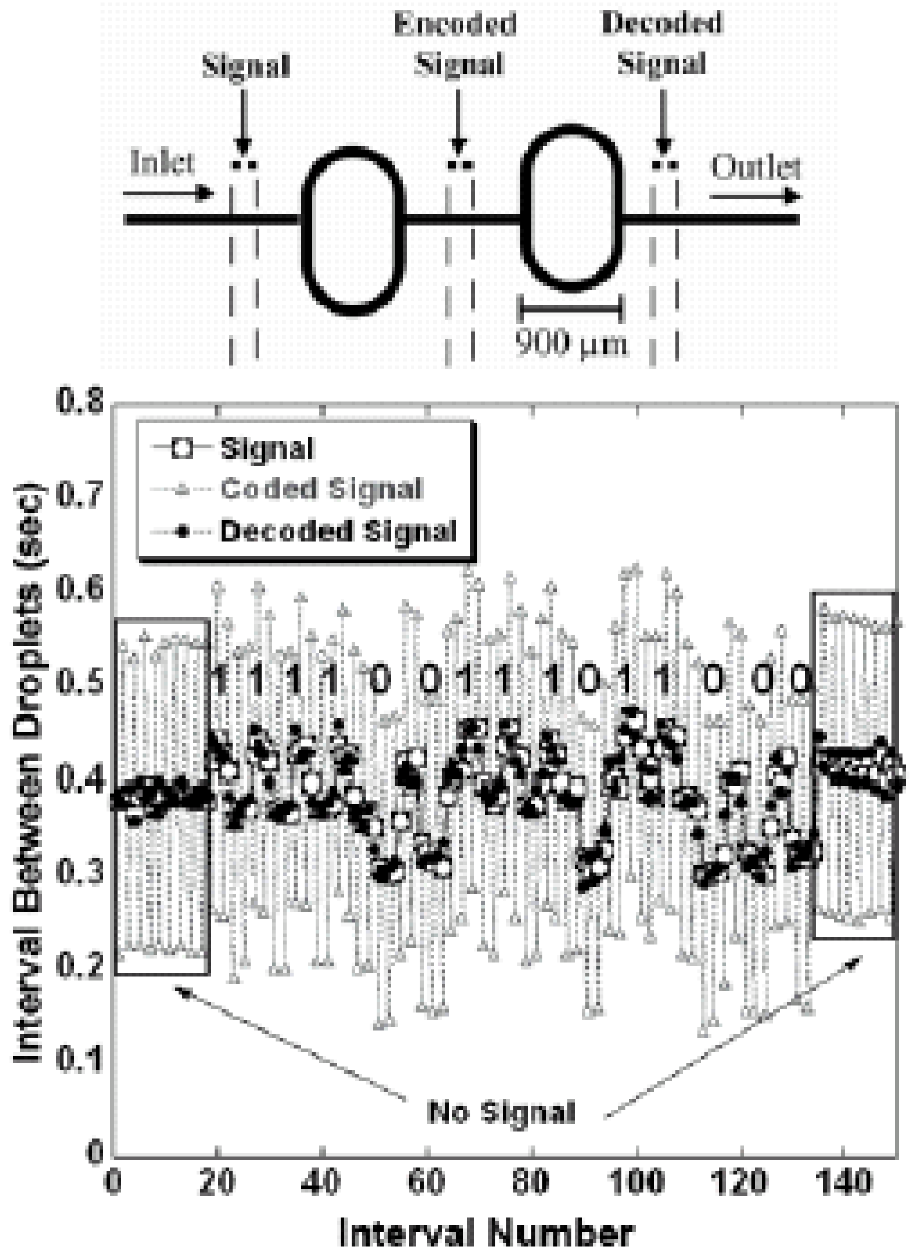
symmetric singals

period 1 → period 2 → period 1

AAAAA → BCBCBC → AAAAAA



coding – decoding



reversible flows

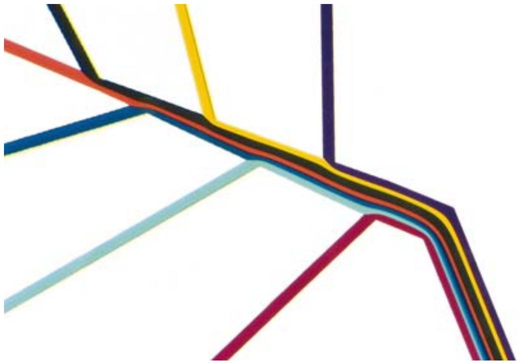
isolated events of amplification
embeded in linear, reversible dynamics of flow

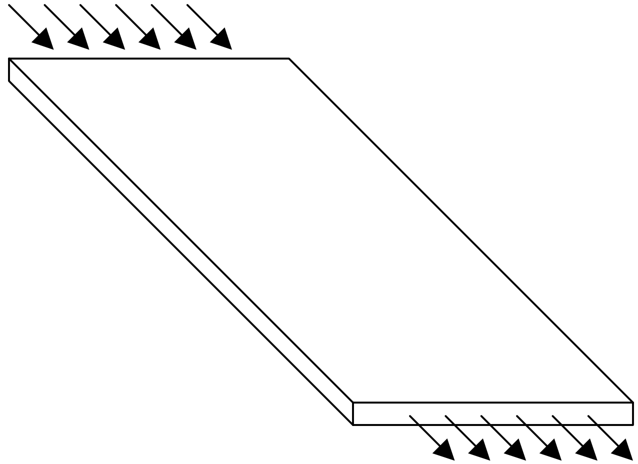
→ probing the fine line between non-linearity and reversibility

→ potential for automated and robust processing of signals on chip (potentially useful in lab-on-chip applications)

- **microfluidics**
    - simple fluids
    - droplets and bubbles
- **formation of drops and bubbles**
    - flow-focusing
    - T-junction
- **stable oscillations with long periods**
- **time-reversible non-linear dynamics**
- **applications**
    - micromixing, portable assays
    - micro-particles and micro-capsules
    - diffraction gratings

mixing





2D, steady, incompressible flow: $u = \dfrac{\partial \psi}{\partial y}, \quad v = -\dfrac{\partial \psi}{\partial x}.$

integrable,
no chaotic advection $\dfrac{dx}{dt} = \dfrac{\partial \psi}{\partial y}, \quad \dfrac{dy}{dt} = -\dfrac{\partial \psi}{\partial x}.$

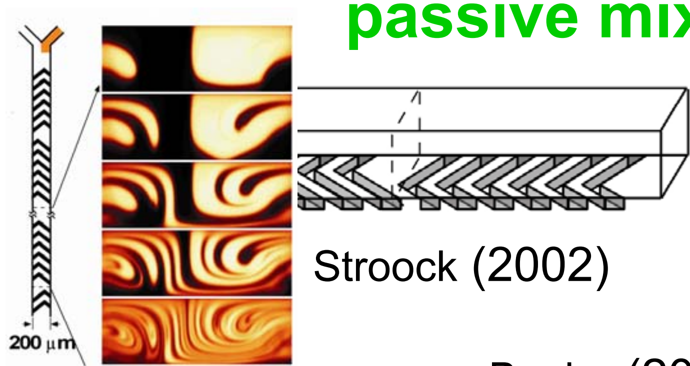
it is difficult to mix fluids in microchannels

mixing – solutions

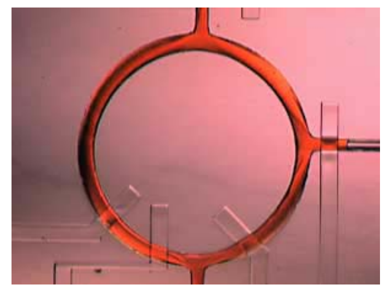
two-dimensional, steady flows

passive mixers

active mixers

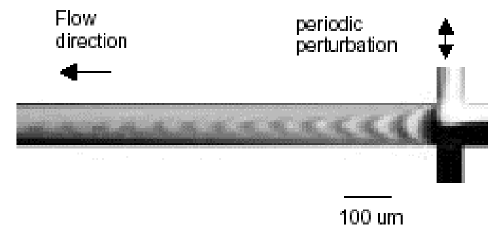


Stroock (2002)

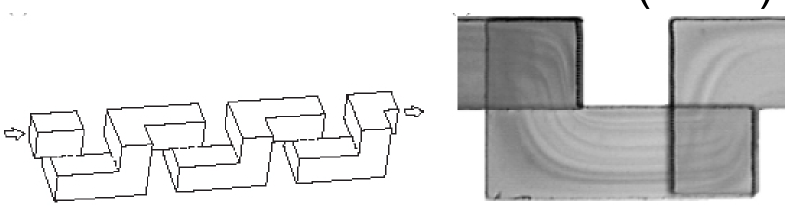


S. Quake

Okkels (2004)



Beebe (2001)

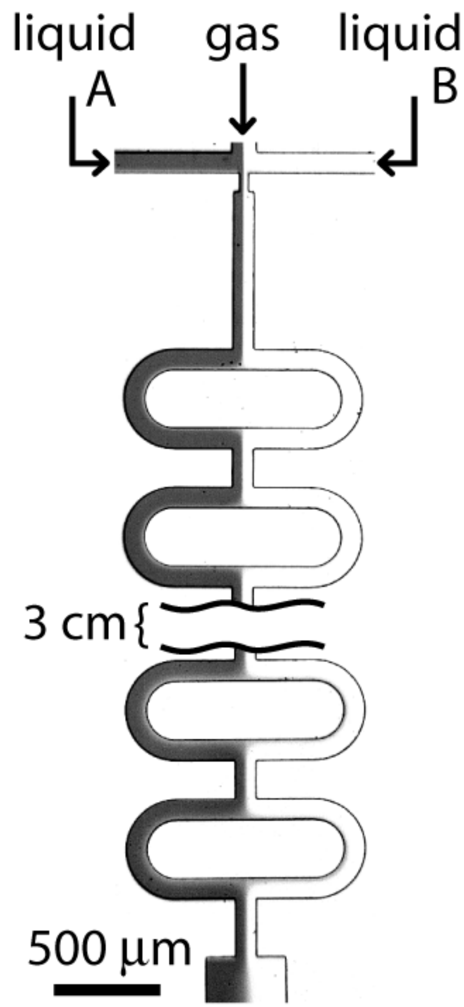


difficult fabrication
always ‘on’

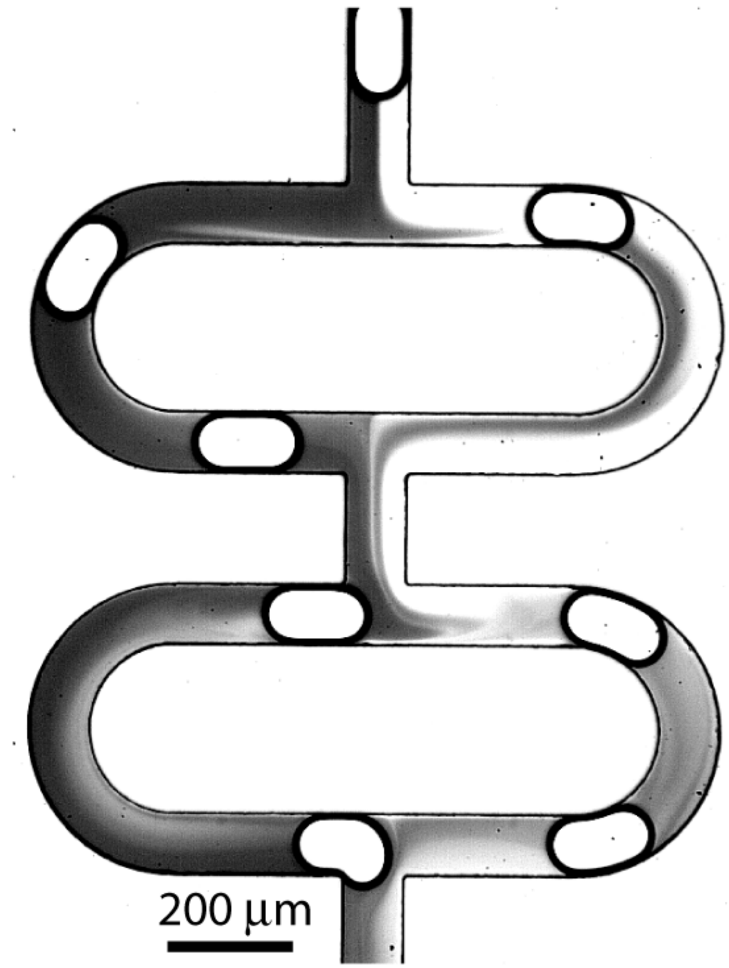
moving parts
external control / agitation

can we achieve exponential folding
in a **planar** device and **steady-state** input?

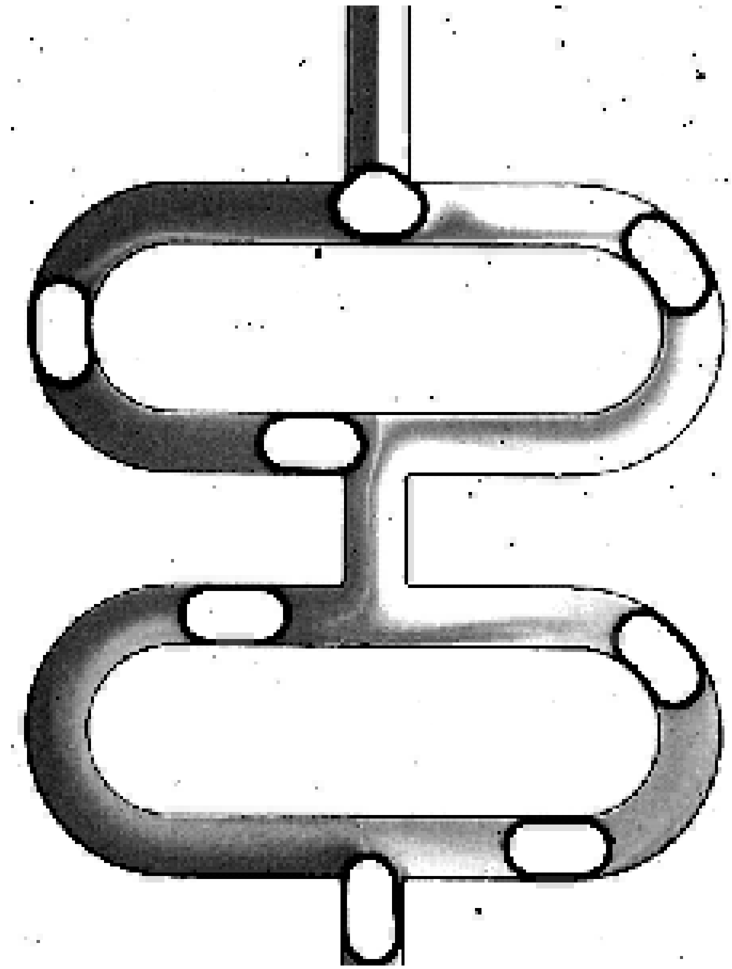
mixer



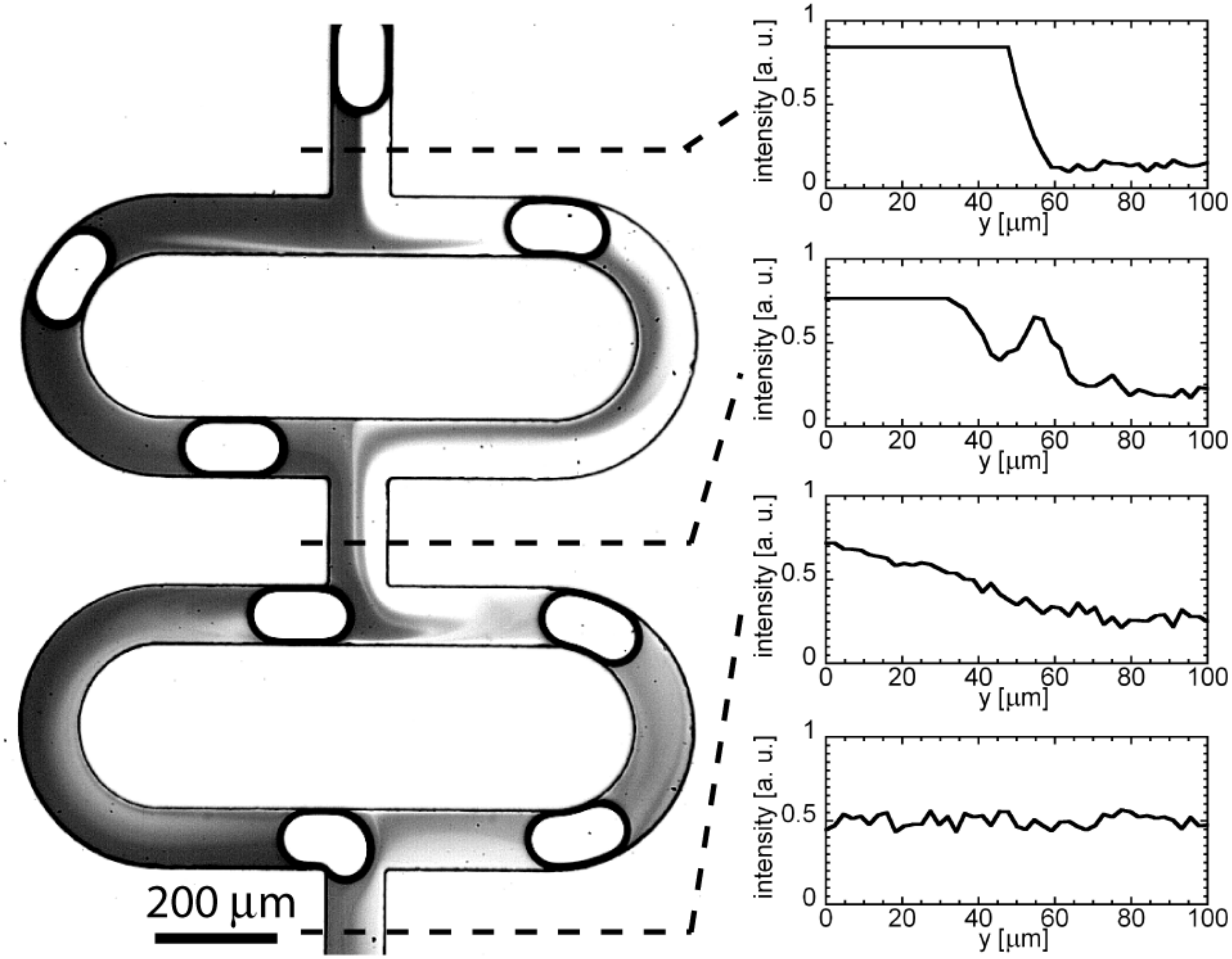
alternating flow



alternating flow



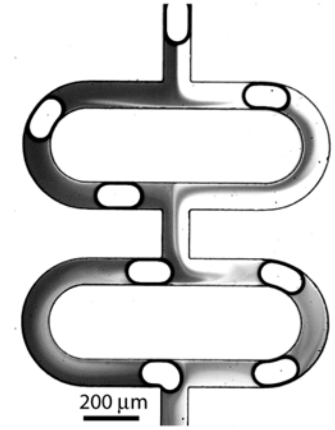
crossing streamlines



folding of the interface

$$d_{inter} \sim w\,(2^{-L/a})$$

$$d_{diff} = (tD)^{1/2}$$

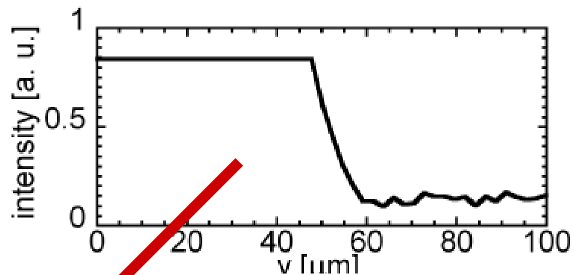


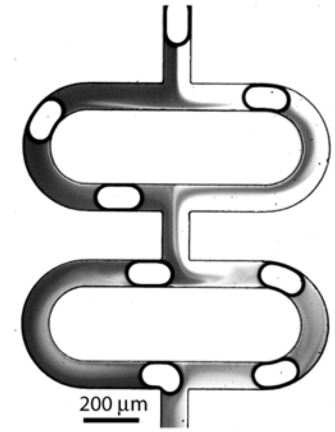
$$(L/a) = (2 \ln 2)^{-1} (\ln Pe - \ln (L/w))$$

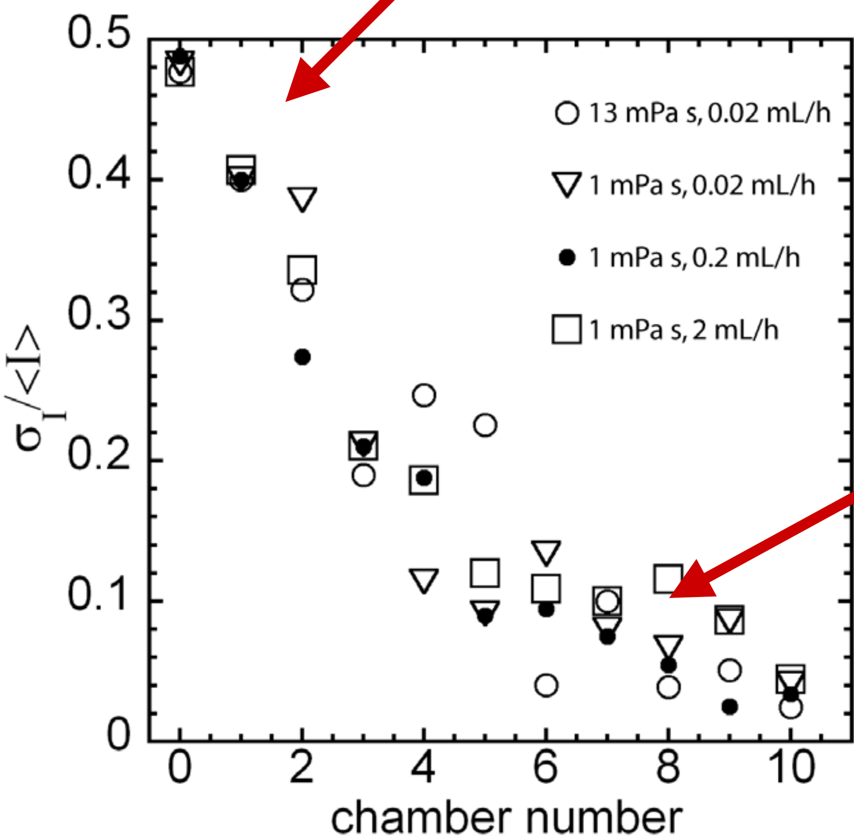
$Pe = Q/Dw = 10^5$ for $Q = 1$ µL/s, $D = 10^{-6}$ cm^2/s and $w = 100$ µm

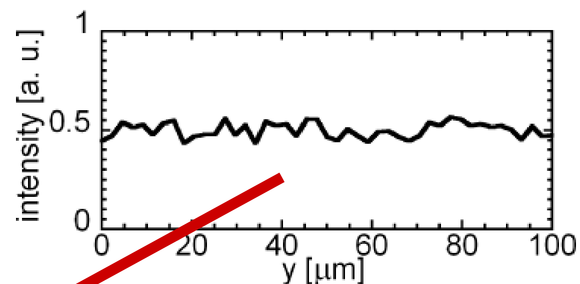
number of chambers to mix the two liquid streams: $(L/a) \sim 8$

mixing









Re $\in (10^{-2}, 10)$

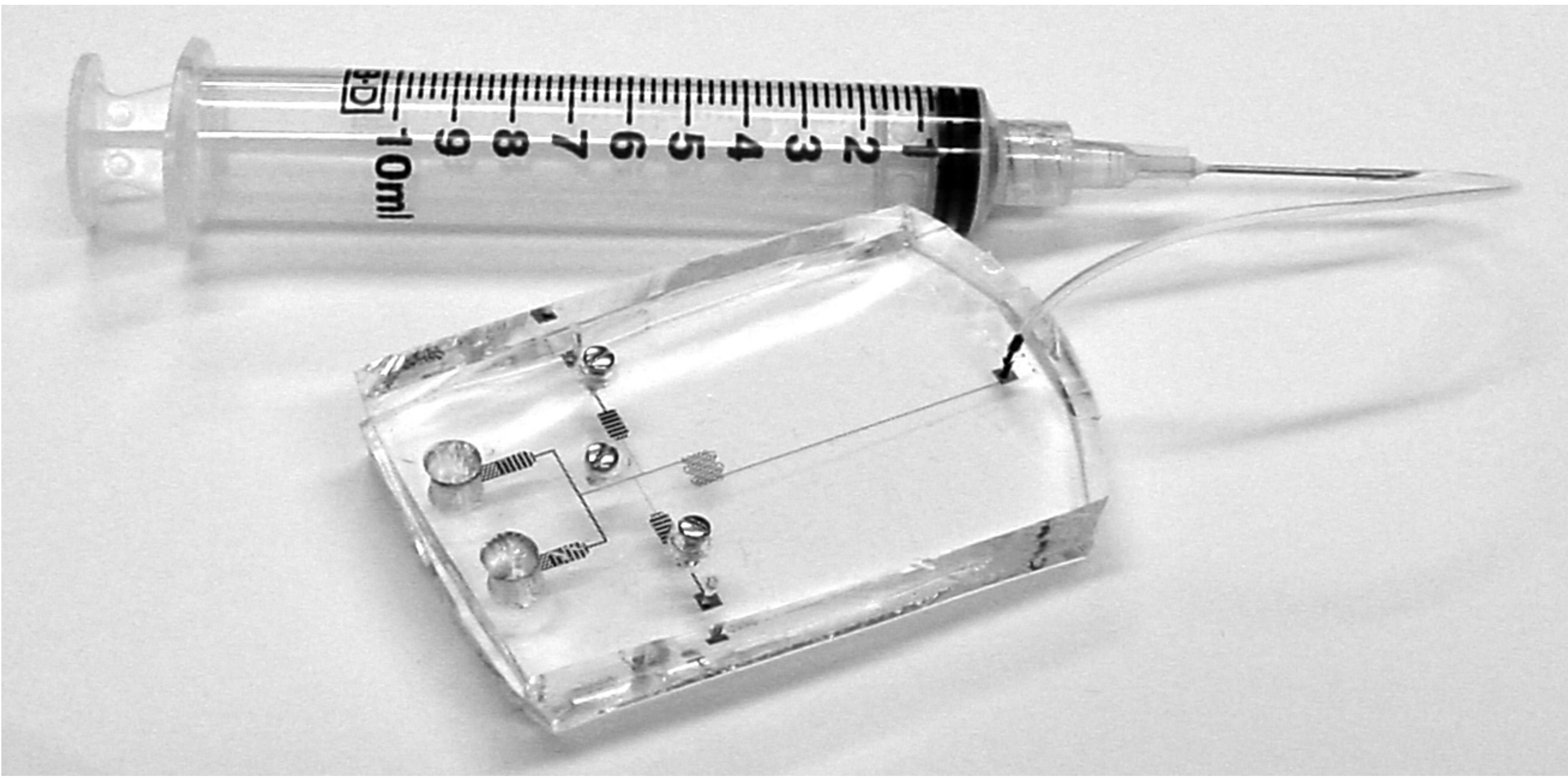
initial Pe $\in (10^3, 10^5)$

reduced to Pe < 100

portability

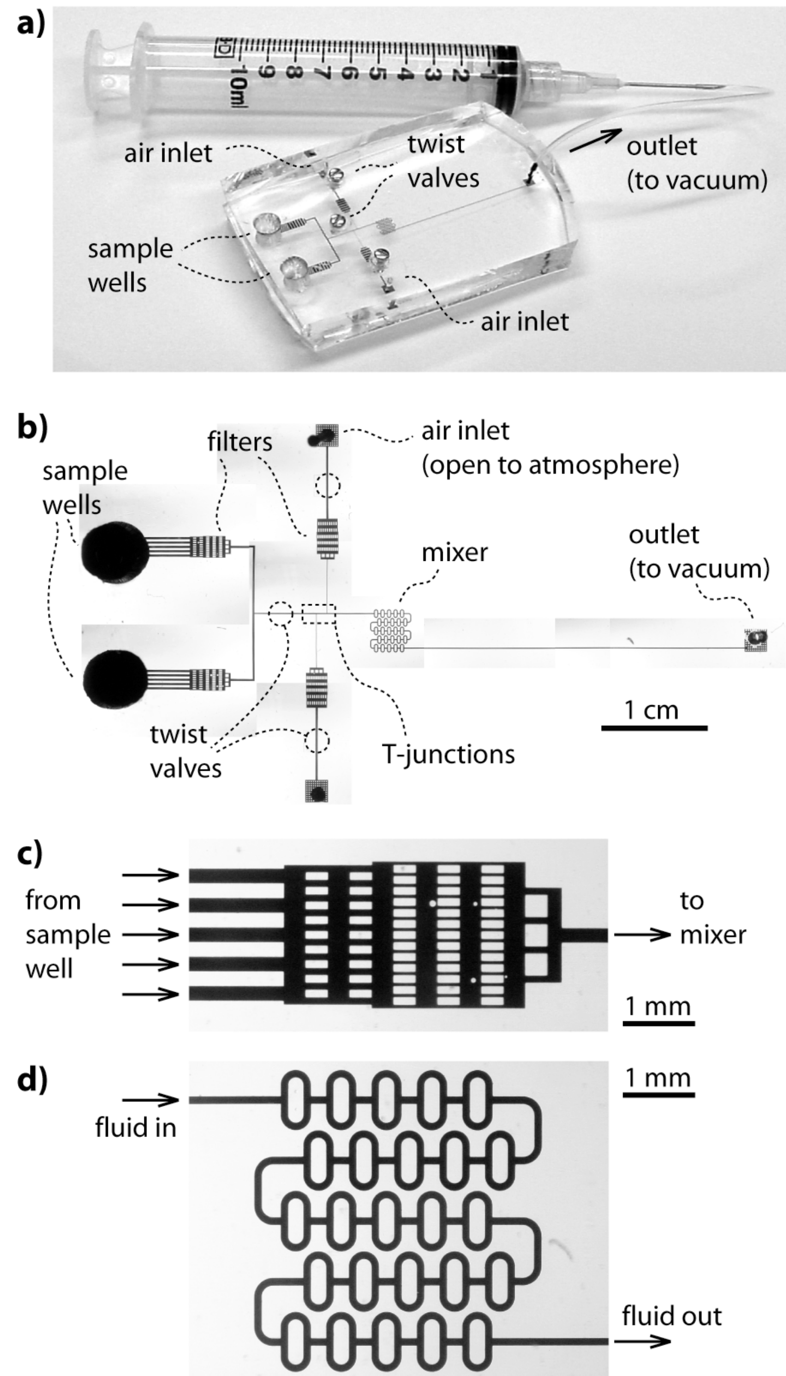
vaxer

A portable platform
solution based micro assays

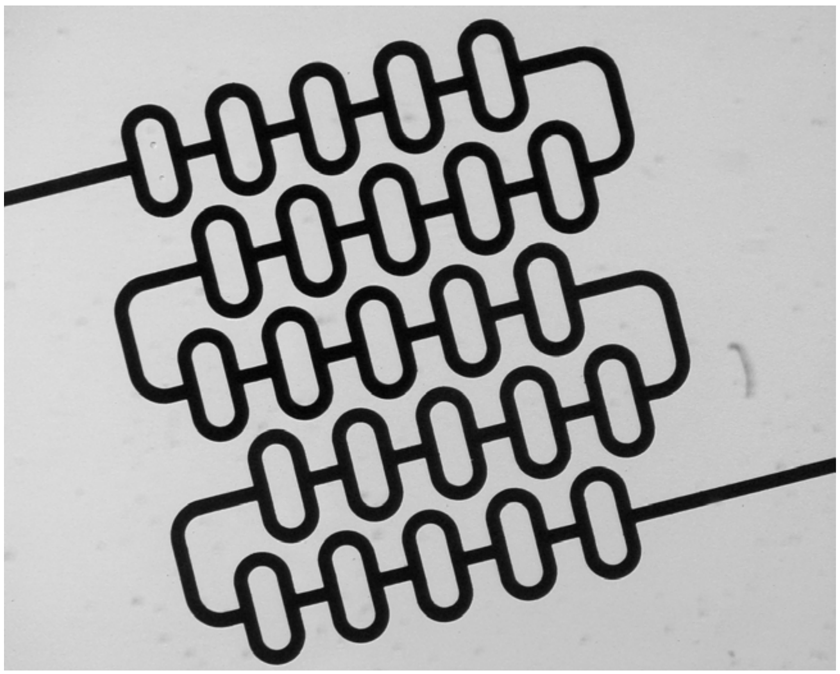


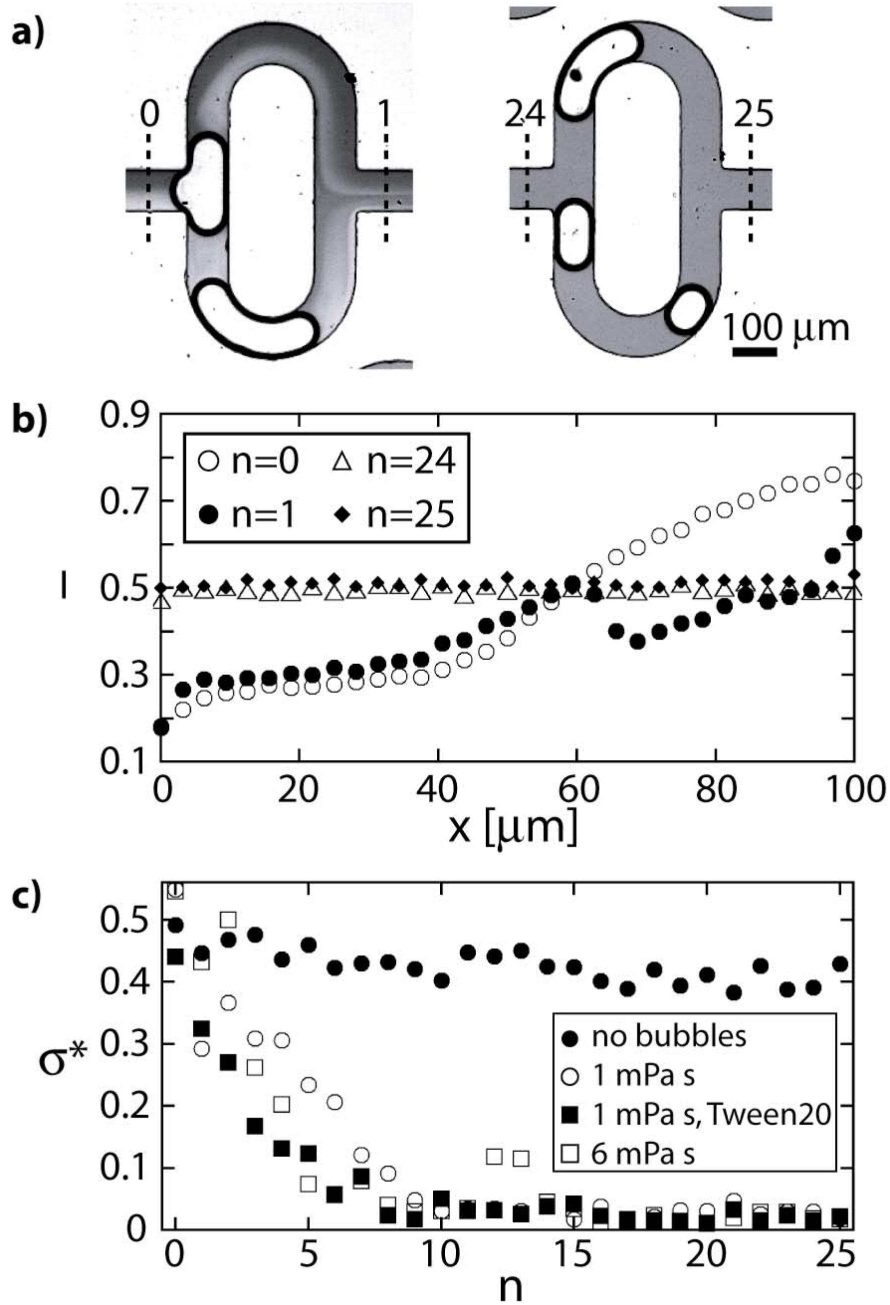
vaxer

A portable platform
solution based micro assays

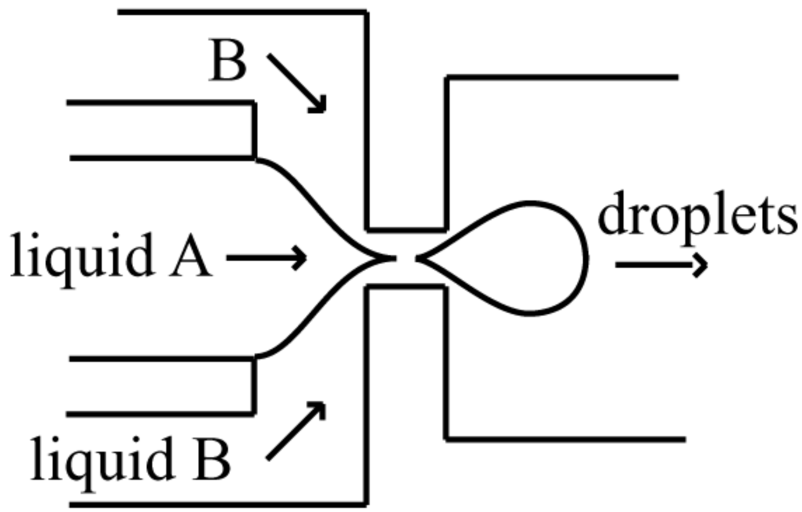


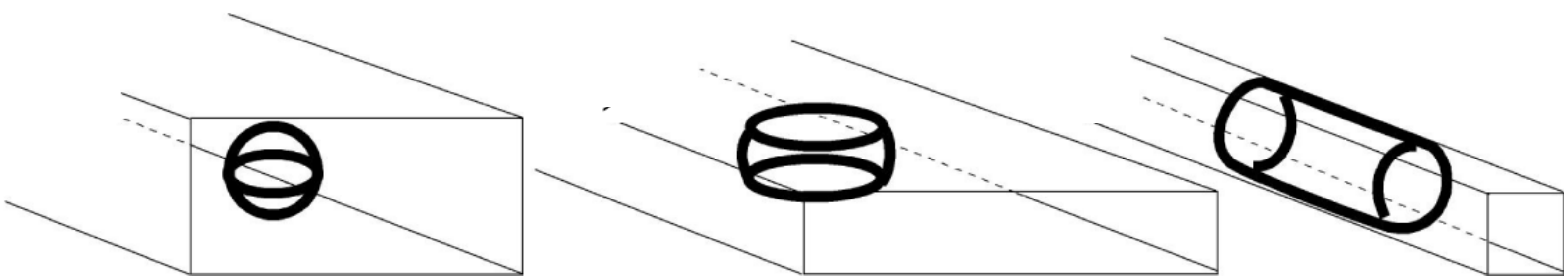
vaxer



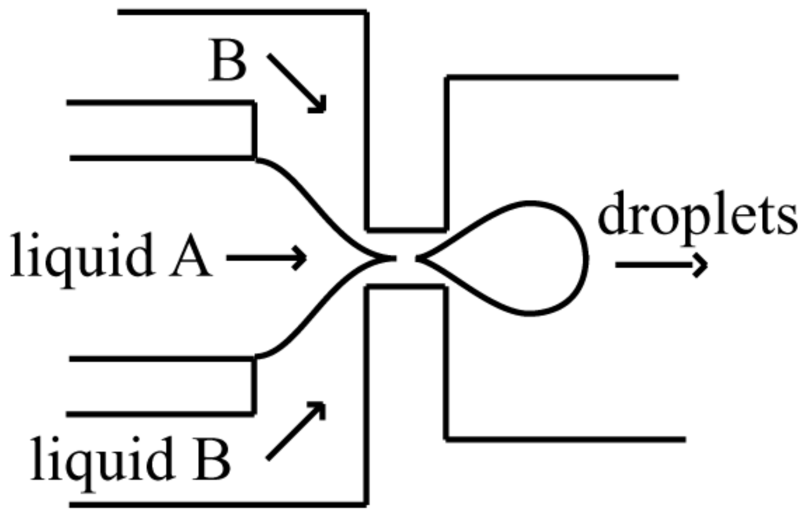

a)
0
1
24
25
100 μm
b)
n=0
n=24
n=1
n=25
I
x [μm]
c)
σ*
no bubbles
1 mPa s
1 mPa s, Tween20
6 mPa s
n

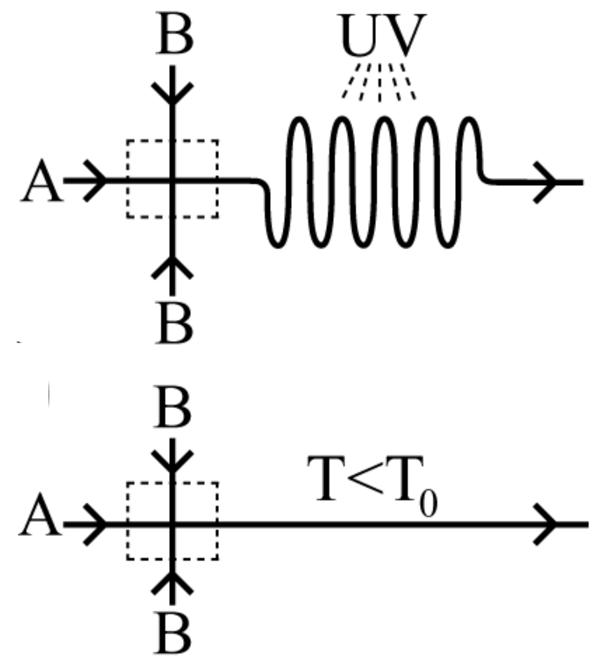
non-spherical particles

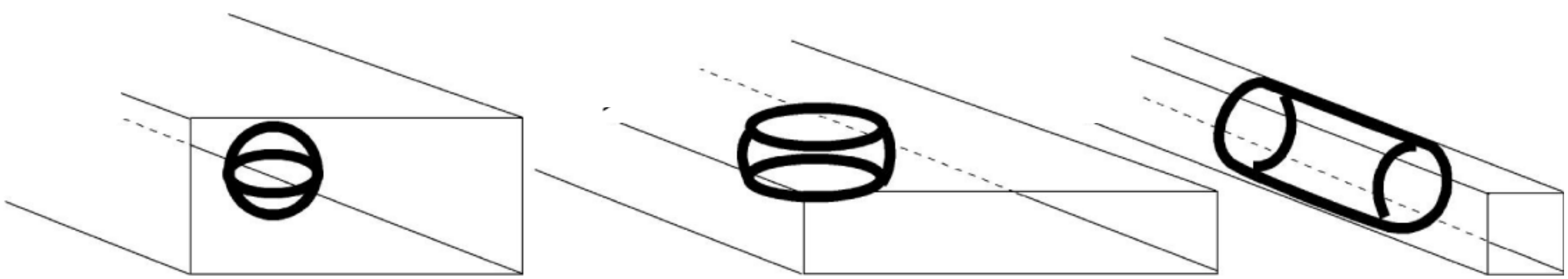




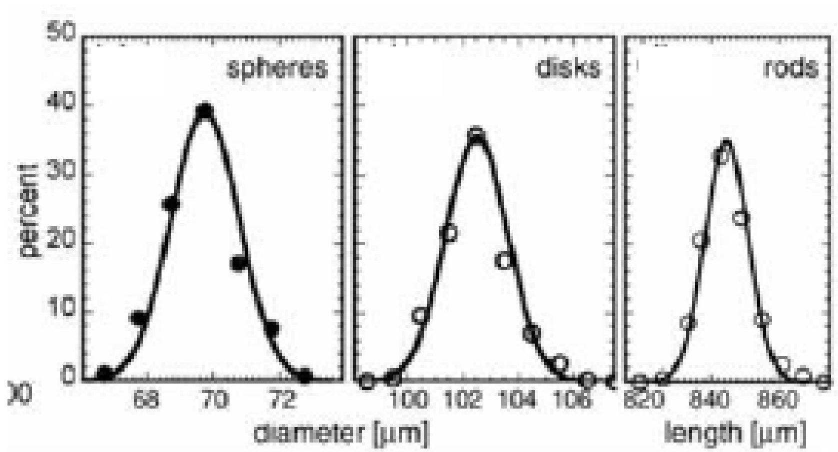
non-spherical particles

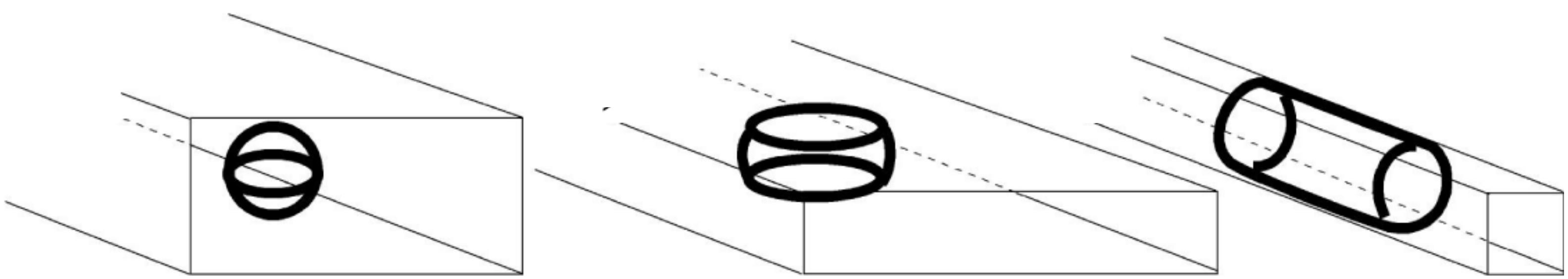




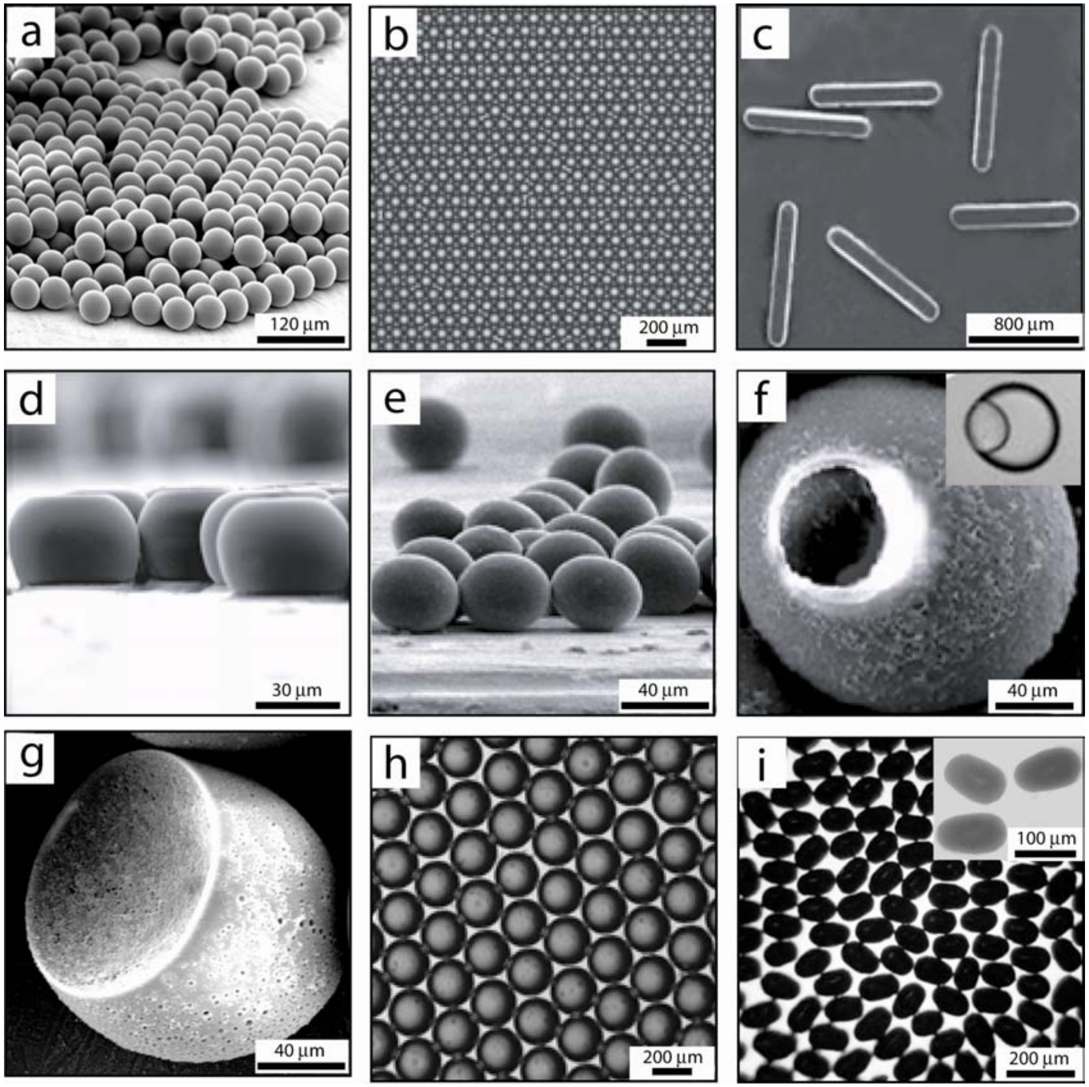


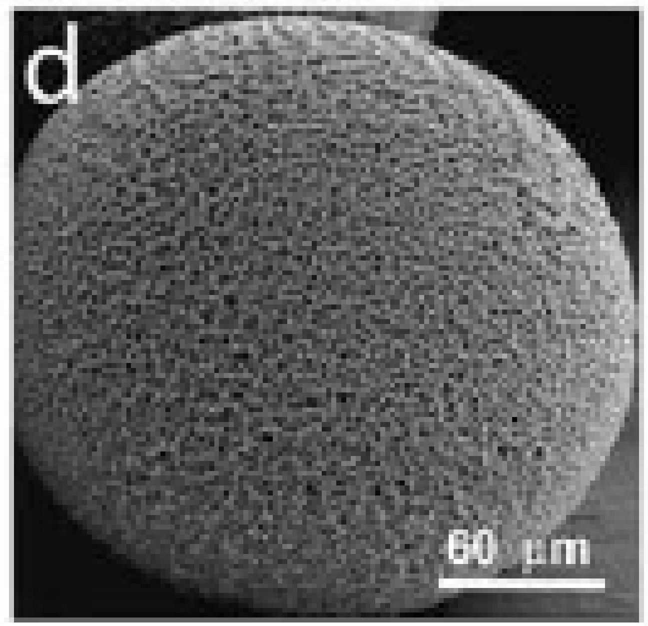
non-spherical particles





spheres, disks, rods, ellipsoids

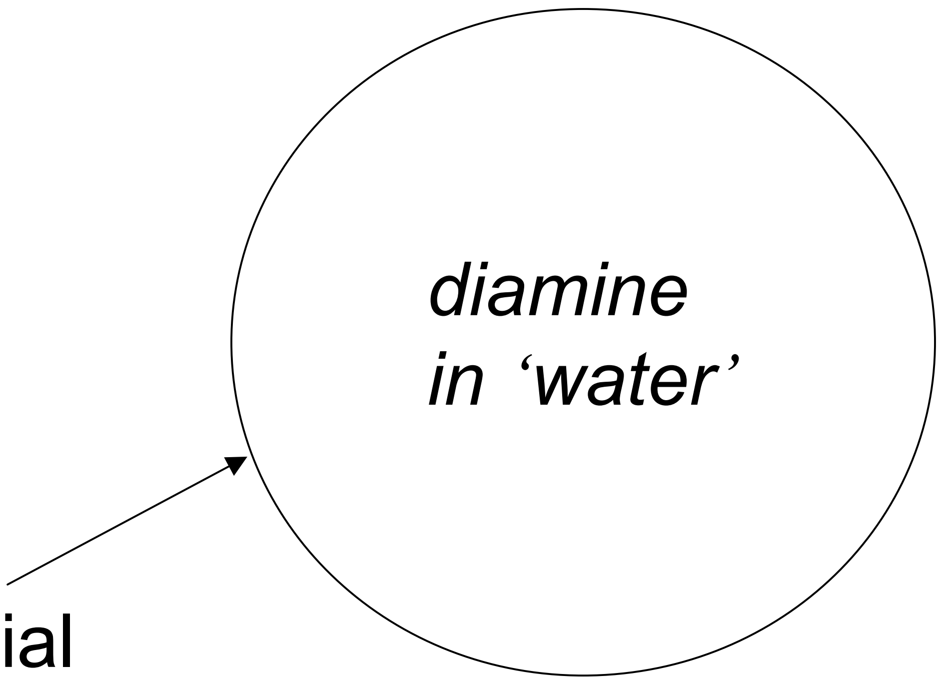




polyTPGDA: (a) microspheres, (b) a colloidal crystal of microspheres (c) rods, (d) disks, (e) ellipsoids, (f) spherical capsules, and (g) truncated microspheres.
(h) agarose disks and (i) bismuth alloy ellipsoids

interfacial polymerization

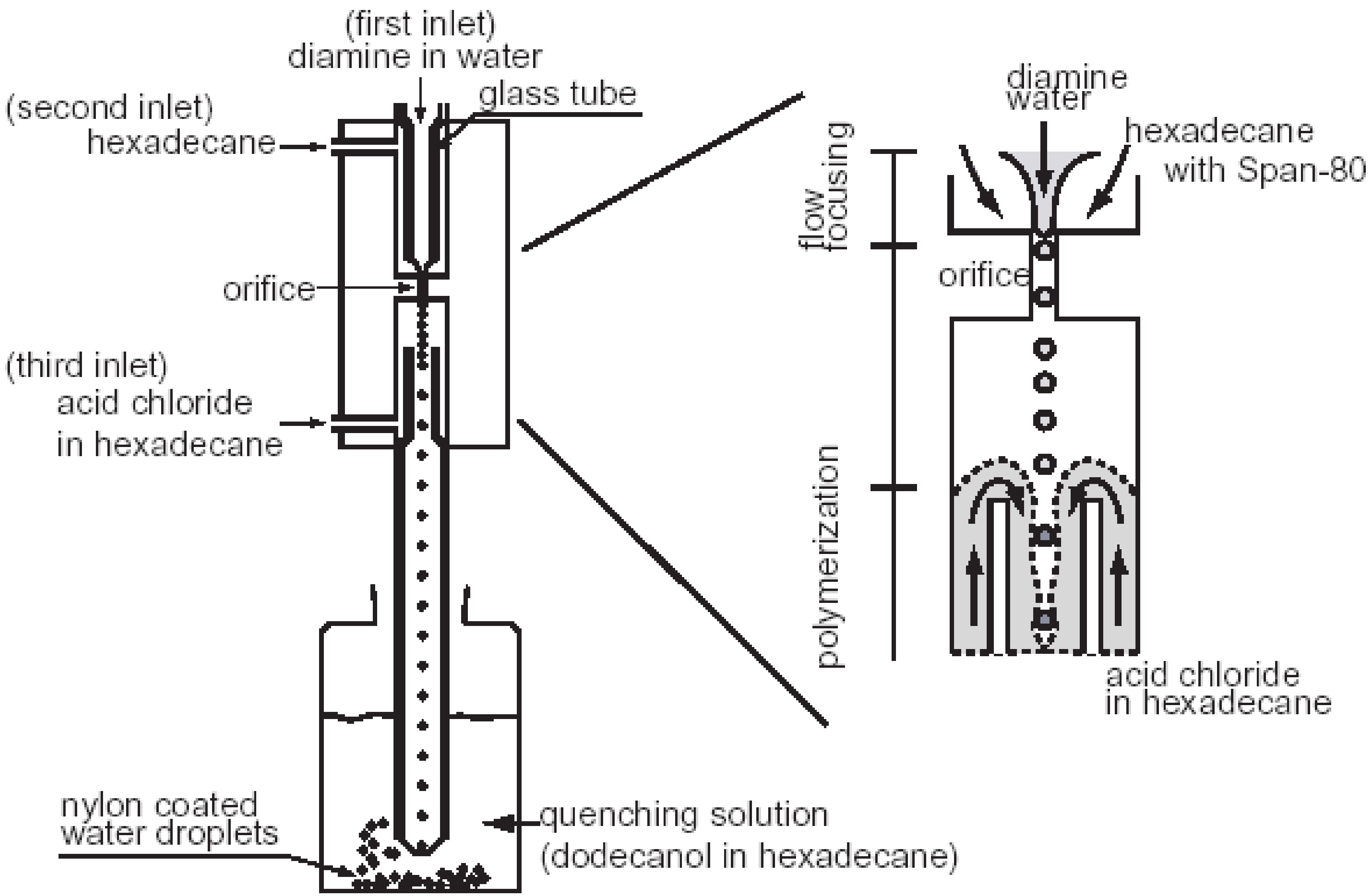
acid chloride in 'oil'



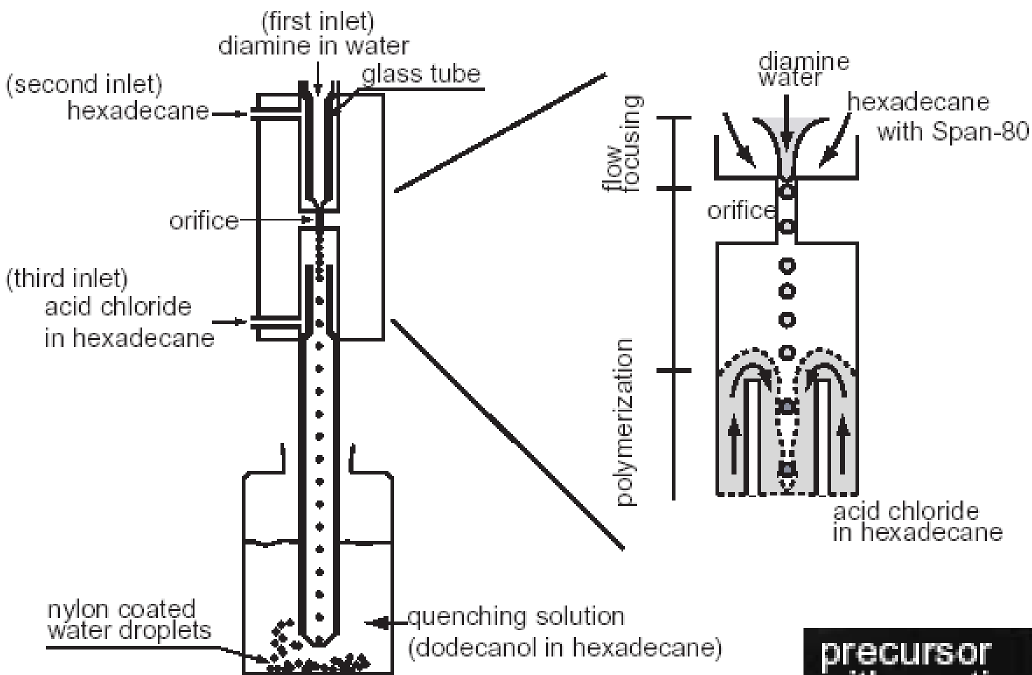
interfacial
polymerization

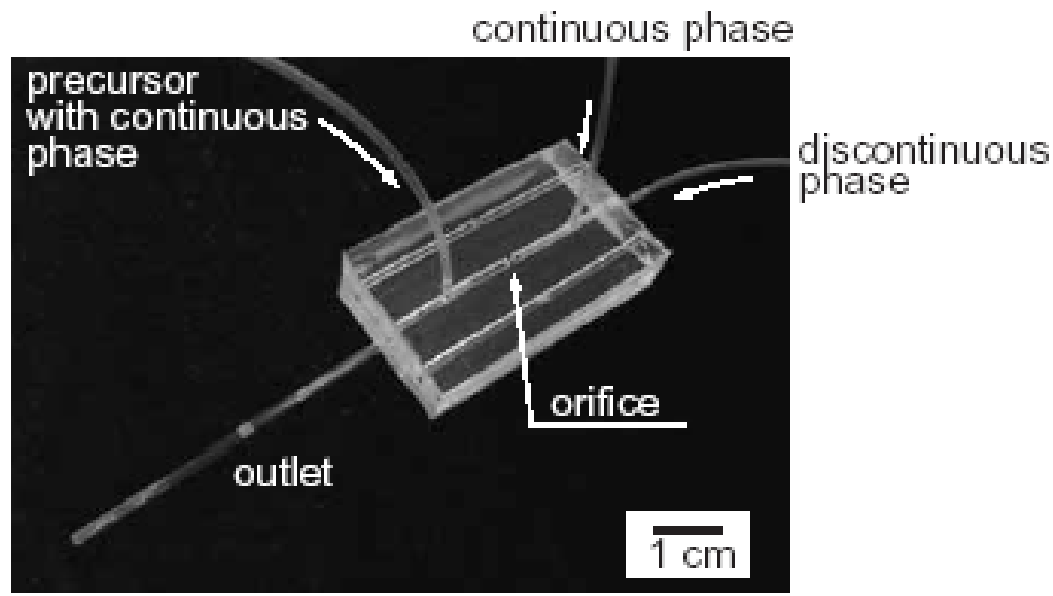
→ semi-permeable microcapsules

in-situ interfacial polymerization

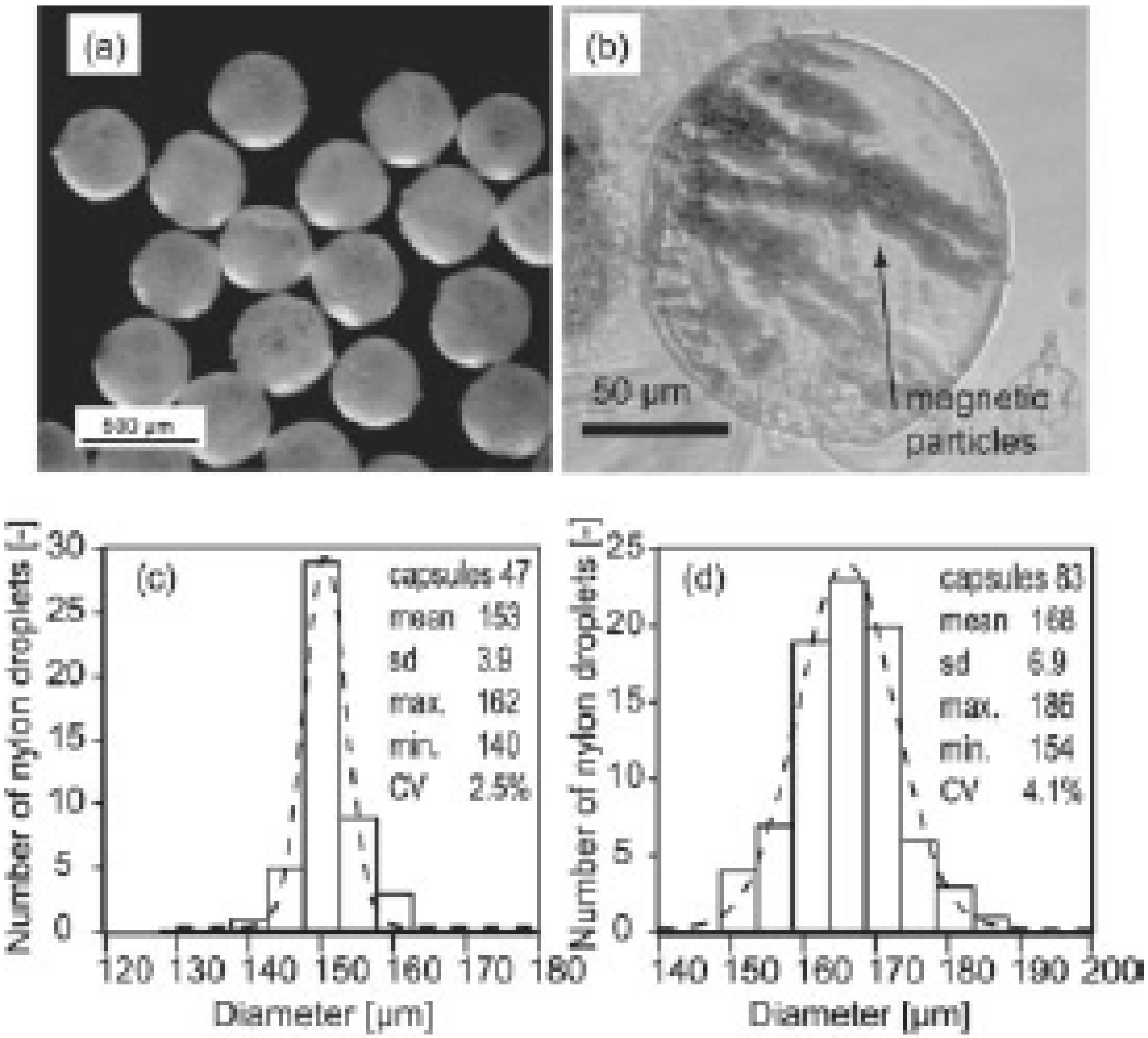


micro-encapsulation

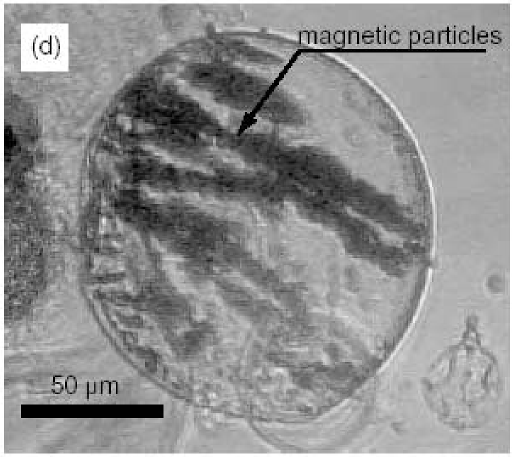


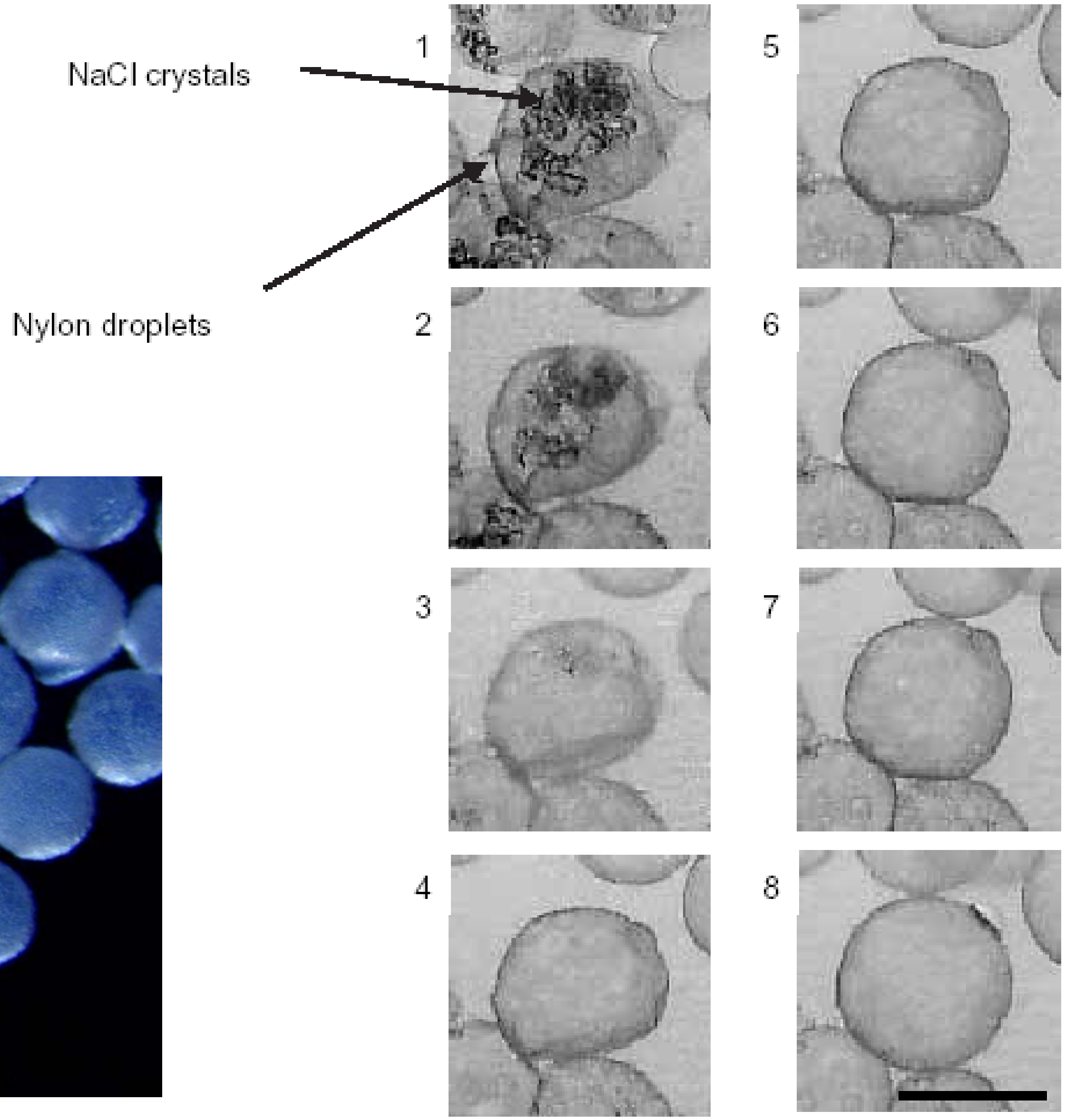


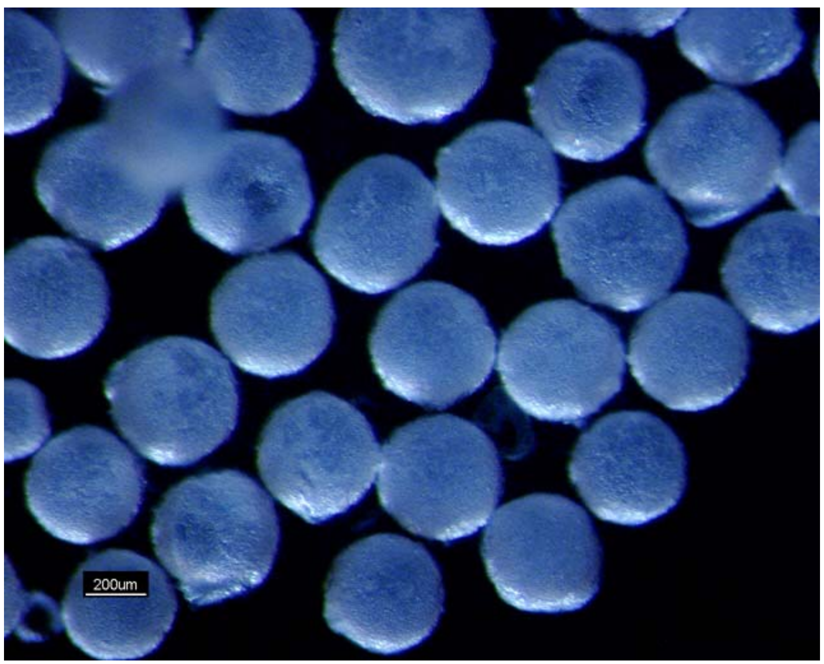
nylon capsules



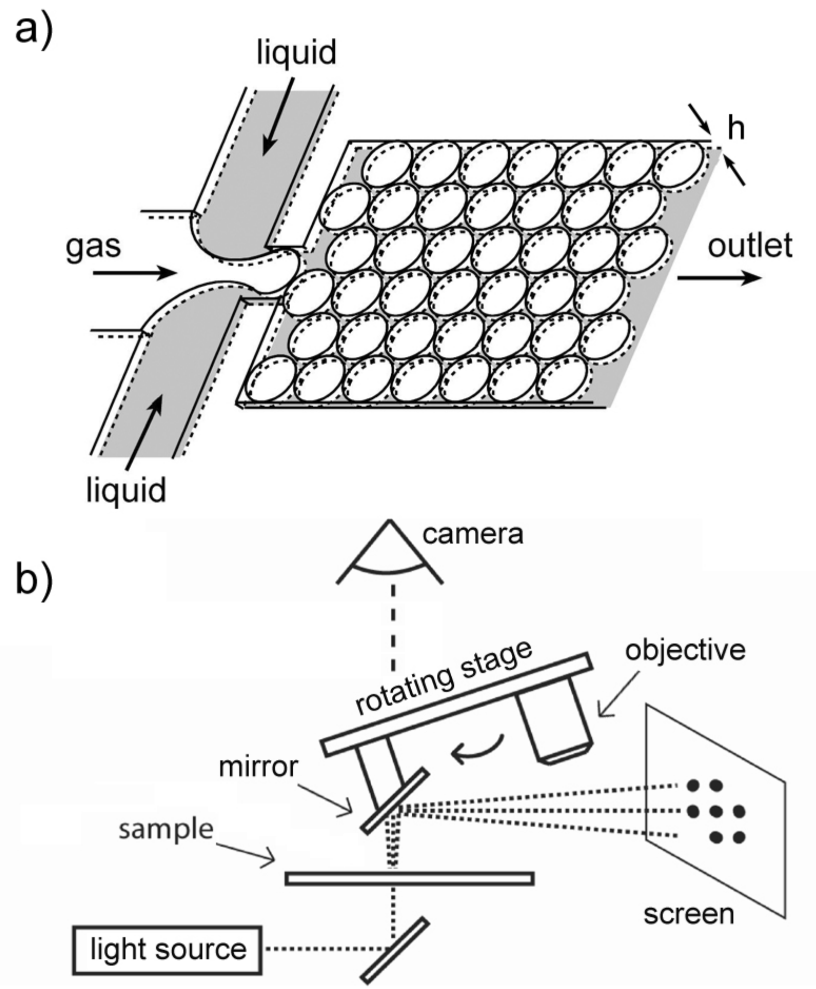
nylon capsules



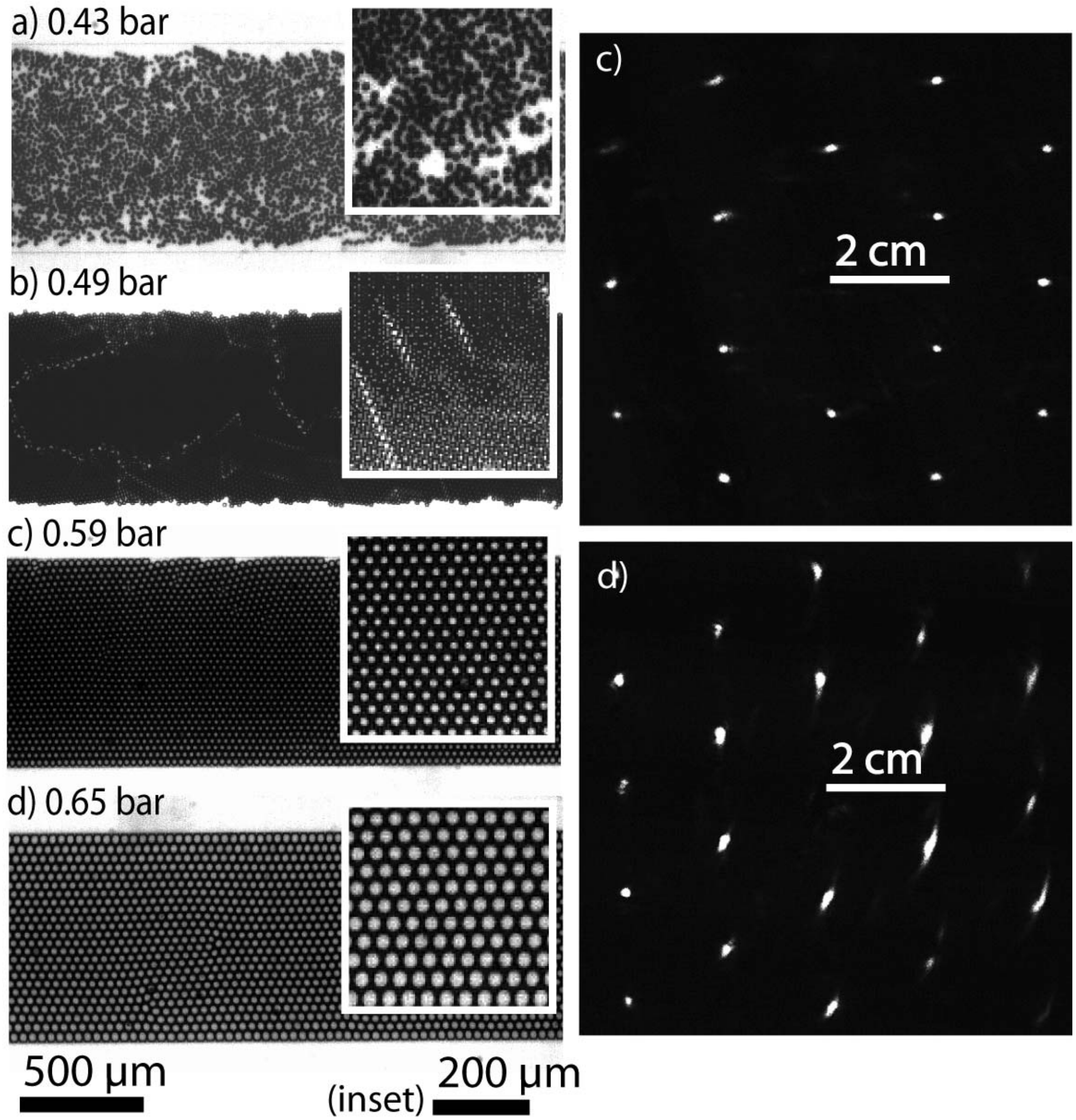




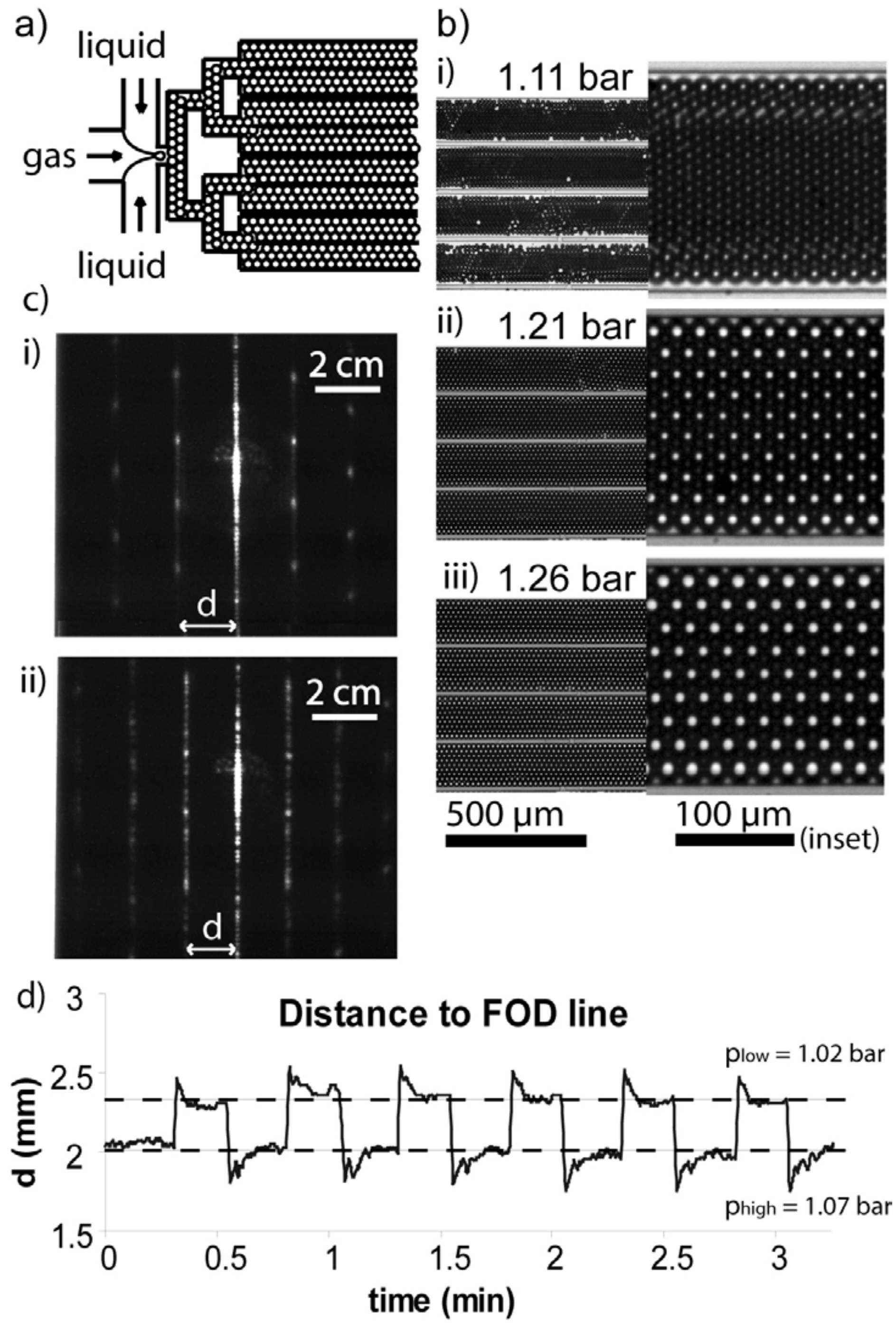
tunable diffraction gratings



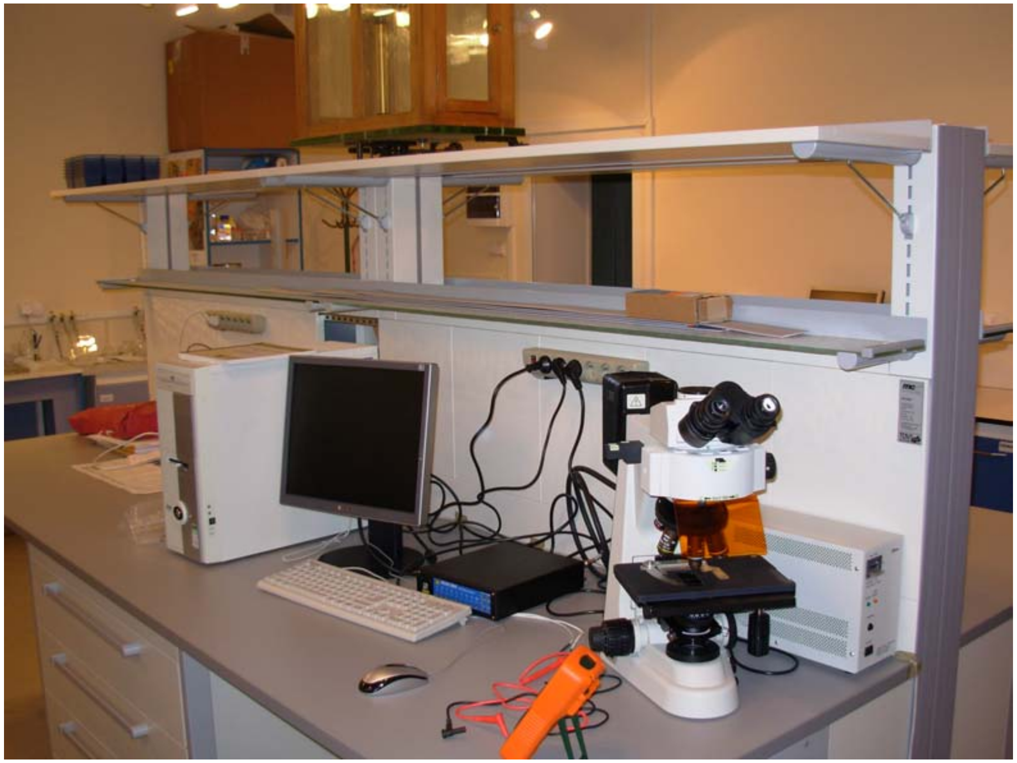
tunable diffraction gratings



tunable diffraction gratings



- **microfluidics**
    - simple fluids
    - droplets and bubbles
- **formation of drops and bubbles**
    - flow-focusing
    - T-junction
- **stable oscillations with long periods**
- **time-reversible non-linear dynamics**
- **applications**
    - micromixing, portable assays
    - micro-particles and micro-capsules
    - diffraction gratings



garst@ichf.edu.pl

acknowledgement

Prof. George Whitesides

- controlled formation of bubbles and droplets

  Irina Gitlin, Willow DiLuzio, Michael Furstman, Prof. Eugenia Kumacheva, Prof. Howard Stone, M. De Menech, F. Jousse & Unilever
- periodic bubbling

  Michael Furstman, Michinao Hashimoto, Prof. Mahadevan
- stability

  Prof. A. M. Ganan-Calvo & Sevilla
- mixing and simple solutions

  Michael Fuerstman, Michael Fishbach, Sam Sia
- particles and capsules

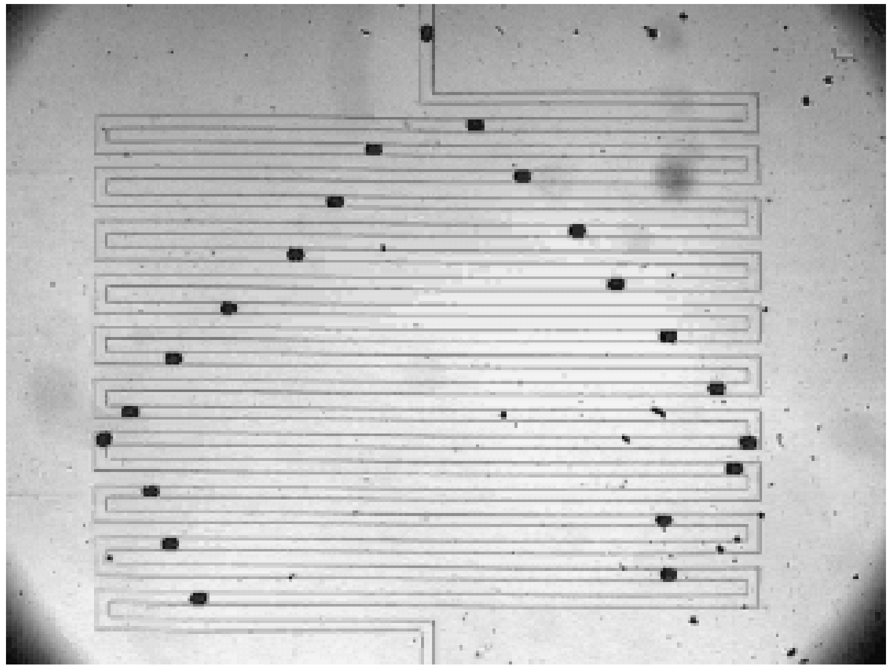
  Doug Weibel, Prof. Shoji Takeuchi, Irina Gitlin, Prof. Kumacheva & Toronto
- digital microfluidics

  Adam Siegel, Derek Bruzewicz
- interfacial instabilities in a HeleShaw

  Michinao Hashimoto, Prof. Howard Stone
- fluidic optics

  Brian Mayer, Michinao Hashimoto

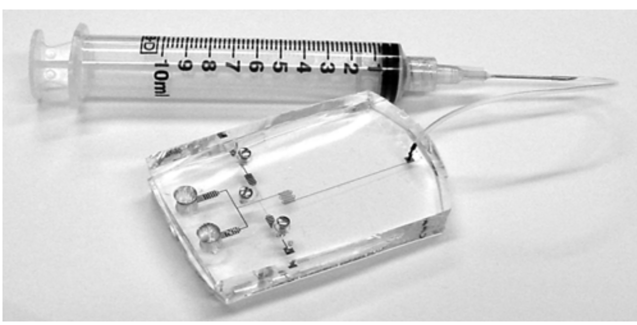
- discussions **Weitz and Stone Groups, A. Ganan-Calvo**
- funding **Foundation for Polish Science, U.S. Department of Energy**

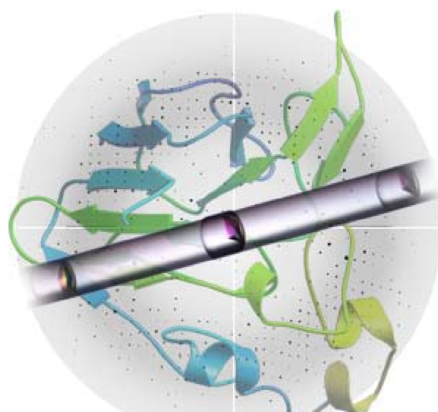


thank you

drops and bubbles in microfluidics

- control, reproducibility
- size, size distribution
- preparation of emulsions
- phenomena
- chemical kinetics, synthesis, materials
- analytical and portable systems





© 2004 Rustem Ismagilov Group, Univ. Chicago