Local control of periodic pattern formation in driven binary immiscible fluid

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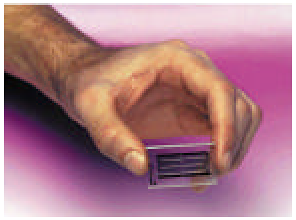
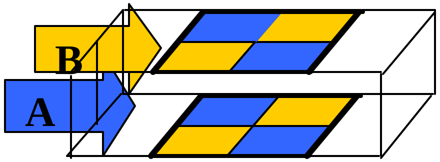
Binary fluids within microchannels

- **Microfluidic devices: fluid flow in micron-wide channels: Motivations**

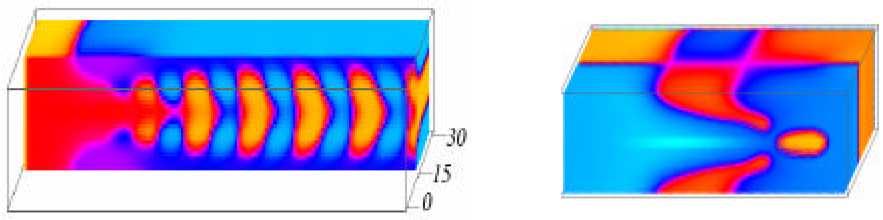


  - "Lab-on-a-chip": hand held device
  - Controlling fluid streams, mixing different fluids in microchambers

- **Control fluid streams within the microchannels**

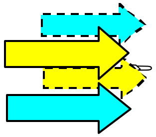


  - Use chemically distinct patterned substrates

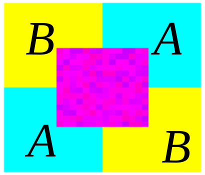


O. Kuksenok et al, Phys. Rev. Lett. 91, 108303 (2003);

O. Kuksenok et al, Phys. Rev. E 68, 051505 (2003), Physica D (2004)

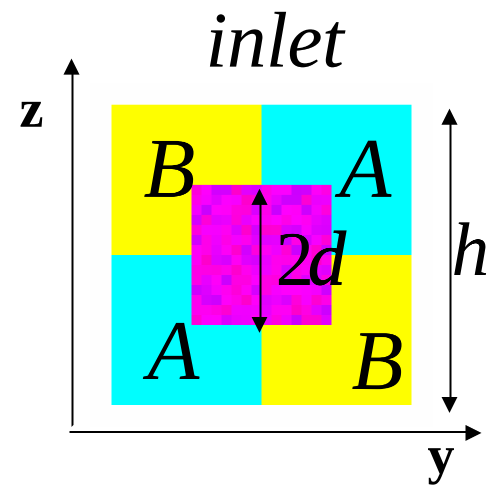


  - Aim: use local perturbation in inlet to control fluid streams

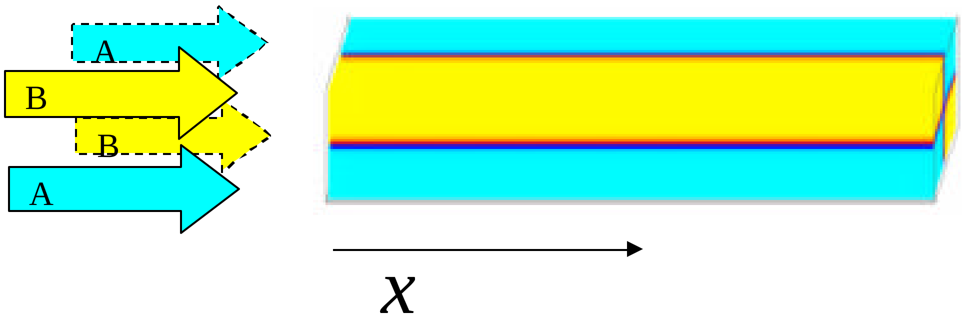


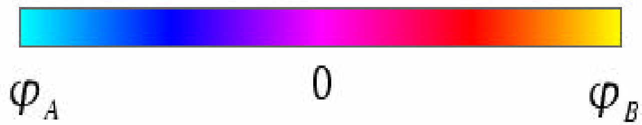
Pattern formation on interface between 4 streams

- **Motivation: create & control periodic structures by local perturbation**
  - “Hot spot” at inlet
  - Neutral walls



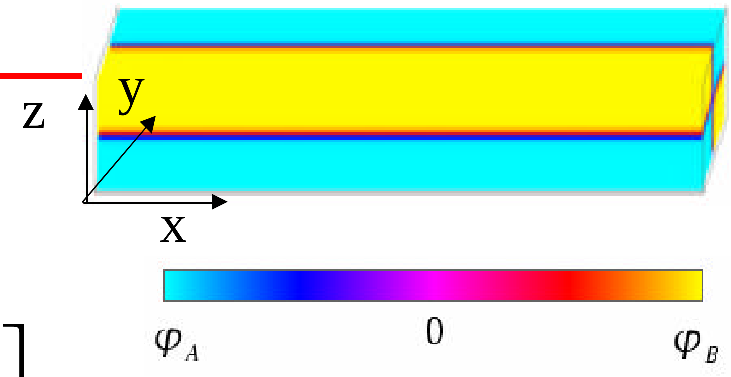
- **Schematic of the channel:**





  - “Hot spot”: fluid is mixed
  - Creating controlled gradient, periodic structures

Oscillatory pattern formation in a binary immiscible fluid: the model



- **Order parameter** $\varphi = \rho_B - \rho_A$
- **Ginzburg-Landau FE:**

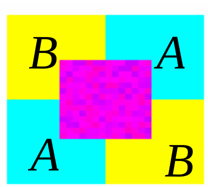
$$F = \int d\mathbf{r}\left[-\frac{1}{2}j^{2} + \frac{1}{4}j^{4} + \frac{k}{2}|\nabla j|^{2}\right]$$

- **Evolution: Cahn-Hilliard eq. (use CDS to simulate)**

$$\frac{\partial j}{\partial t} + u(y,z)\cdot\frac{\partial j}{\partial x} = \nabla^{2} m; \qquad m = \frac{dF}{dj};$$

  - u(y,z) is Poiseuille flow, $\nabla^{2} u(y,z) + H = 0$
  - **H** is const. pressure grad; no-slip on walls.

- **Boundary conditions:**
  - Inlet:

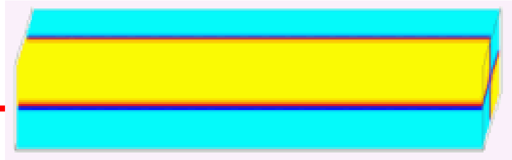


Neutral walls: $(\mathbf{i}\cdot\nabla j)\big|_{wall} = 0; \ (\mathbf{i}\cdot\nabla m)\big|_{wall} = 0;$

Outlet: free draining flow

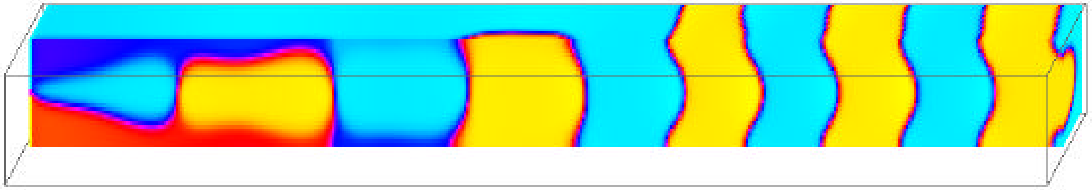
Dependence on imposed pressure gradient, H

Late time behavior, channel 400 X 30 X 30, $d = 1$



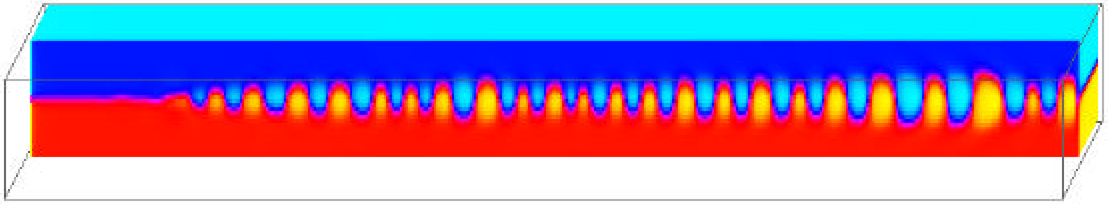
- **Low H:**
  - Irregular stripes in yz directions, slightly distorted by flow:

$H = 3 \cdot 10^{-5}$



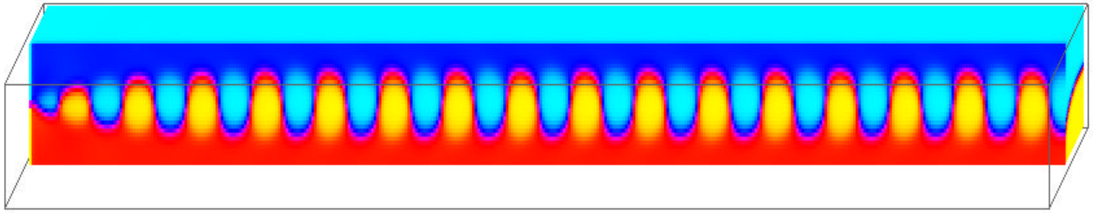
- **High H:**
  - Irregular interface perturbations with small amplitude
    - Perturbations grow far away from inlet

$H = 1.2 \cdot 10^{-3}$

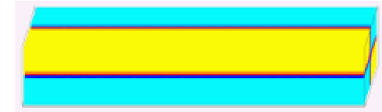


- **Intermediate H:**
  - Regular periodic structure, oscillation in time

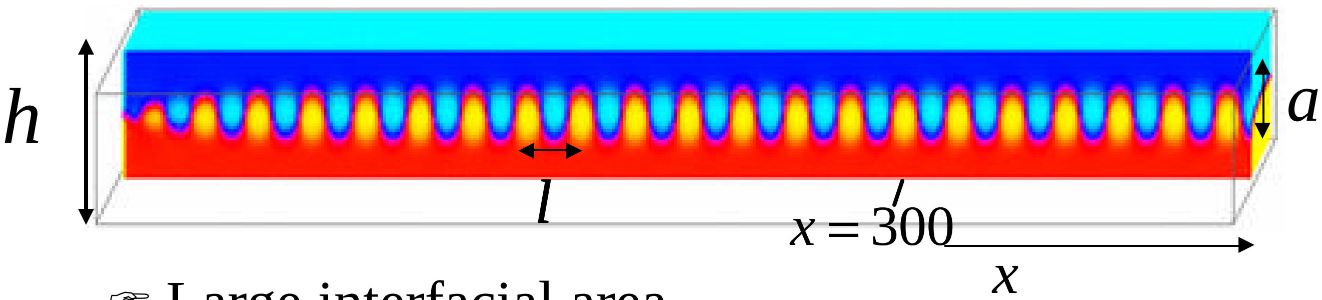
$H = 2 \cdot 10^{-4}$



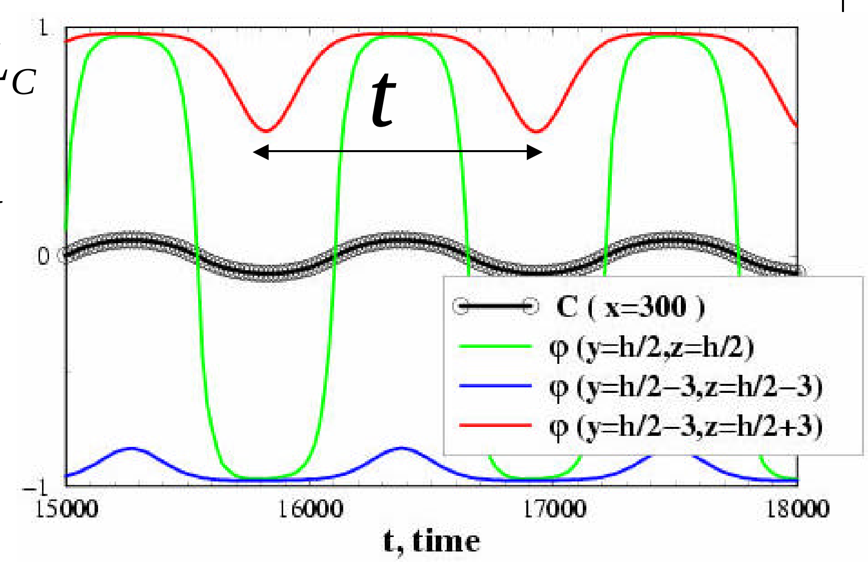
Intermediate H: regular periodic structure



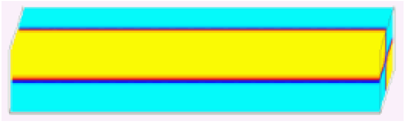
- **Oscillations in time,** $H = 3 \cdot 10^{-4}, \quad d = 1$



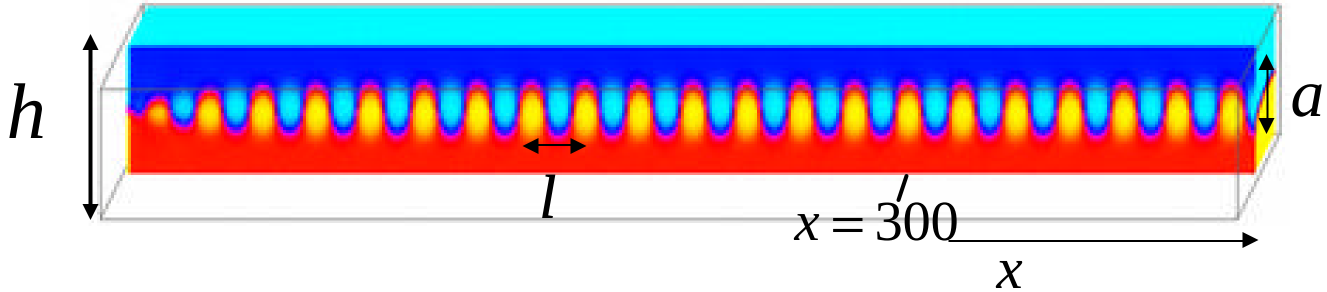
- Large interfacial area
  - Existence is surprising
  - Became quasi-periodic: $L >> L_C$
- All points are moving with the same velocity $u_0 \sim H$
  - "Probe point" at x=300
- A/B fraction integrated over yz
  - $$C(x,t) = \oint dS\, j(\mathbf{r})$$



Intermediate H: regular periodic structure



- **Oscillations in time,** $H = 3 \cdot 10^{-4}, \quad d = 1$

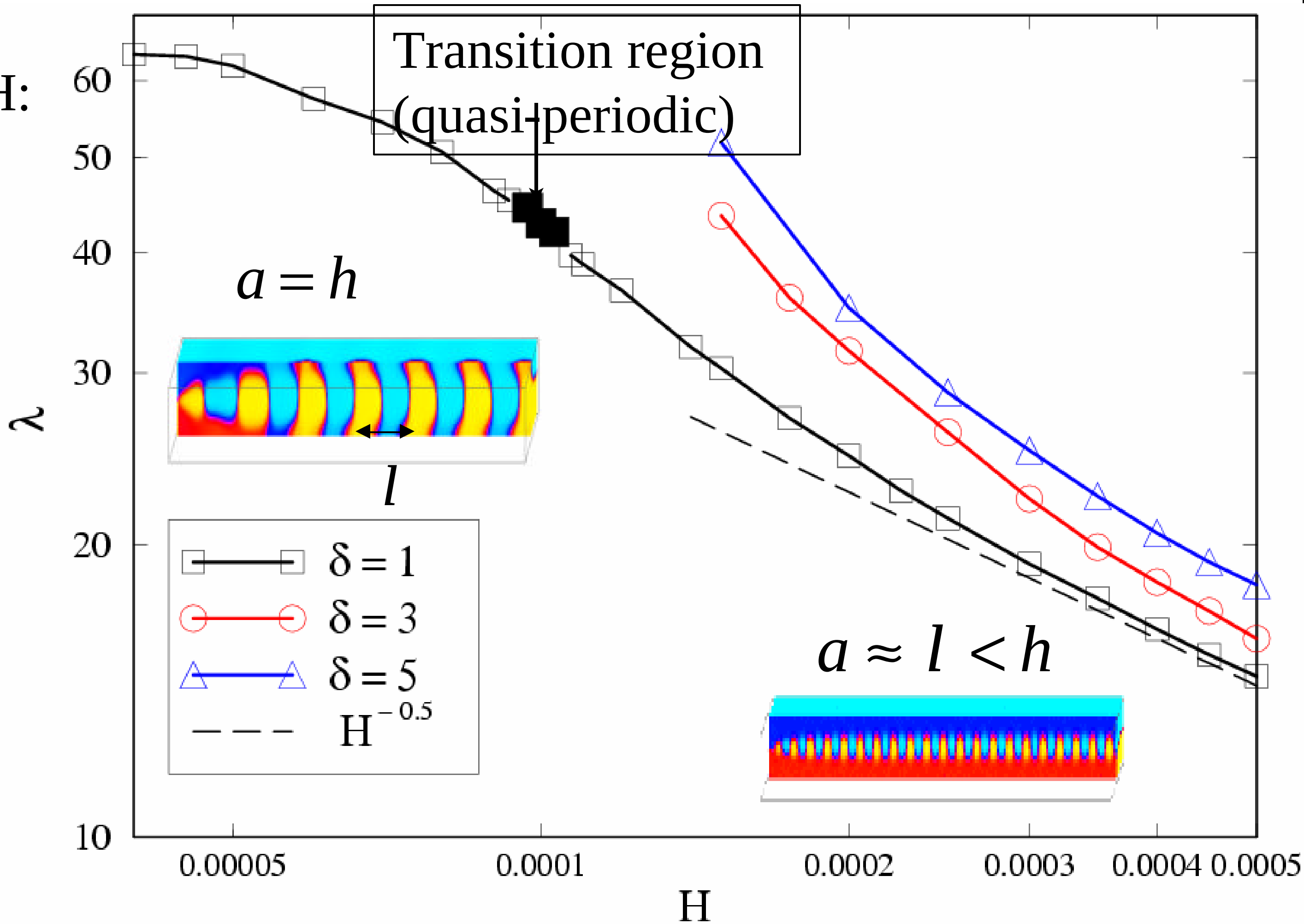


- Non-decaying traveling waves if $L < L_C$
  - Exploit long-lived transient state to create periodic patterns
- Small amplitude of oscillations $a \approx l < h$
  - Periodic patterns do not reach walls
- Scaling for period of oscillations
  - From $t \sim l^3 / s;$ and $t \sim l / u_0; \quad u_0 \sim Hh^2$

    Period in x: $l \sim H^{-1/2}$

Periodic structures: 3 oscillating regimes

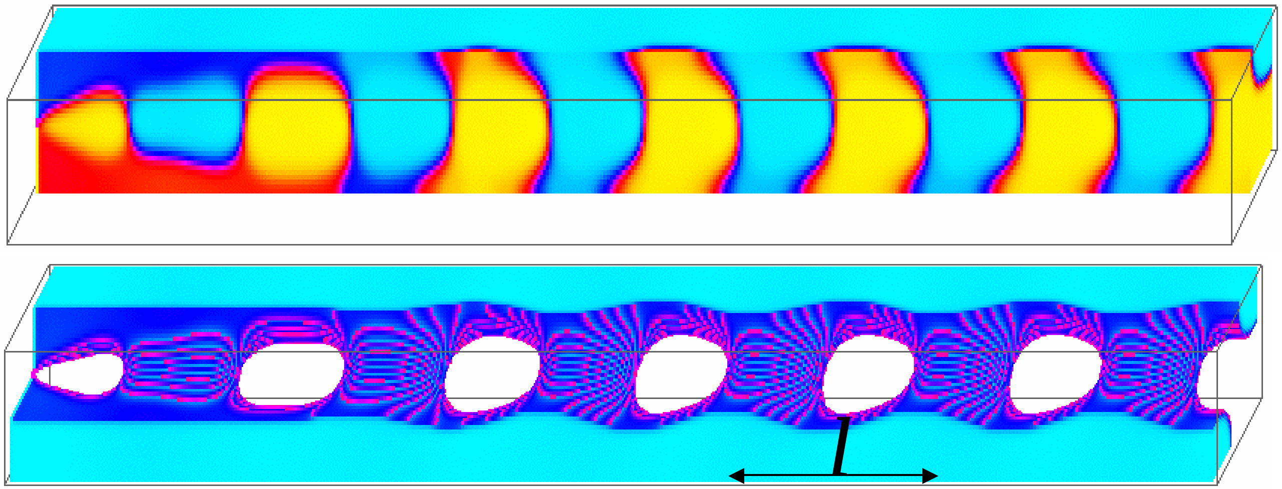
- Period vs. H:



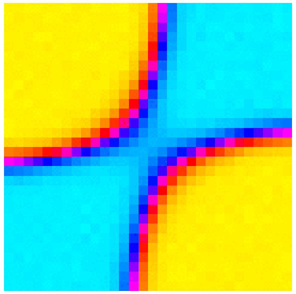
- ☞ Period increases with decreasing in *H*
- ☞ Quasi-periodic region : distortions reach sidewalls, $a \approx h$

Intermediate H: large amplitude oscillations

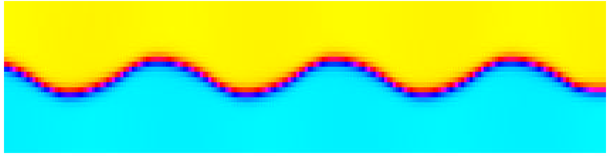
- **Oscillations in time,** $H = 5 \cdot 10^{-5}$



Outlet

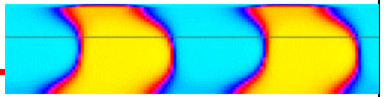


- Amplitude is constrained by height, $a \equiv h$; period $l \approx 2h$
  - Possibility of surface patterning:



- Initial 4 streams are required & strongly depends on velocity and h
- Exists "forever" without noise

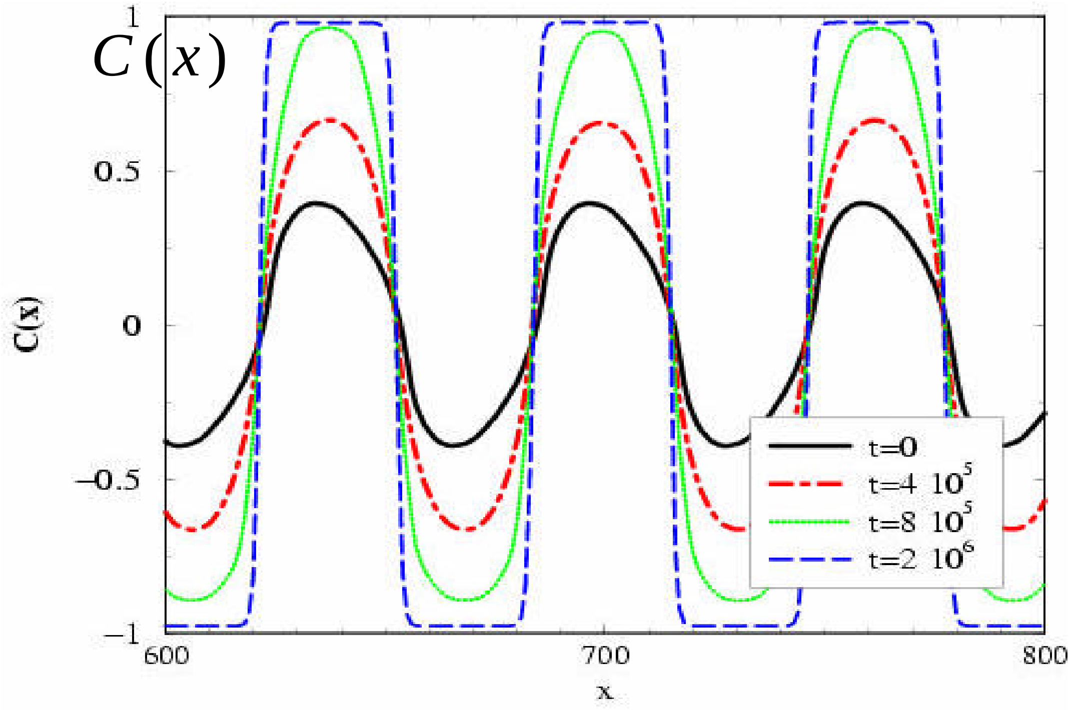
Large amplitude oscillations (Cont.)

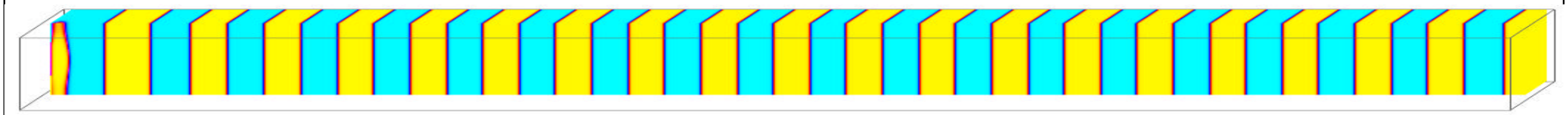


- **Remove pressure gradient (set H=0) after large amplitude structure fully developed**:
  - ☞ Structure evolves into larger patterns:

$$C(x,t) = \oint dS\, j(\mathbf{r})$$

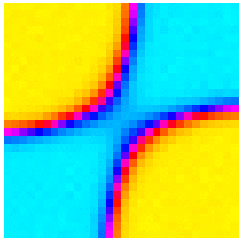
  - ☞ Late times: regular stripes (period $l \approx 2h$)





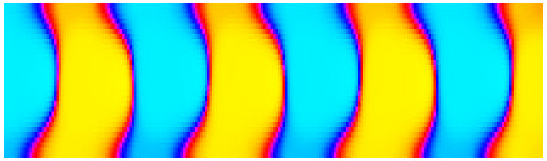
Summary: 4 streams in the microchannel

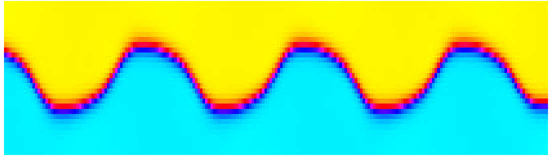
- **Instability of interface between four streams**

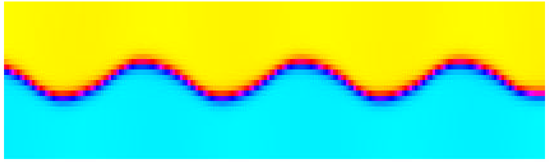


  - "Hot spot" is the source of traveling waves
  - Two types of regular periodic dynamical structures
    - Small amplitude & large amplitude structures

- **Exploit to create gradient, periodic structures in polymeric blend systems**







  - Amplitude decreases from center to sidewalls
  - Surface patterning