Heat and mass transfer experiments in the Center for Energy Research National University Mexico

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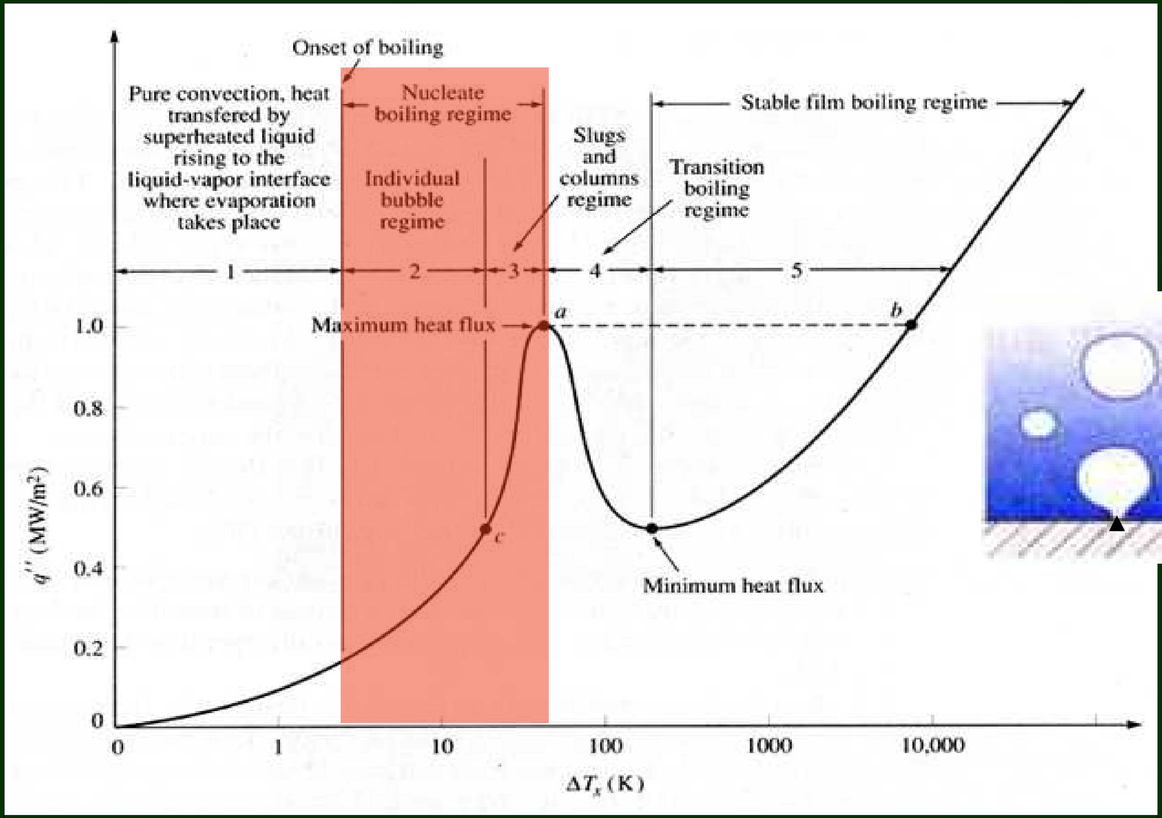
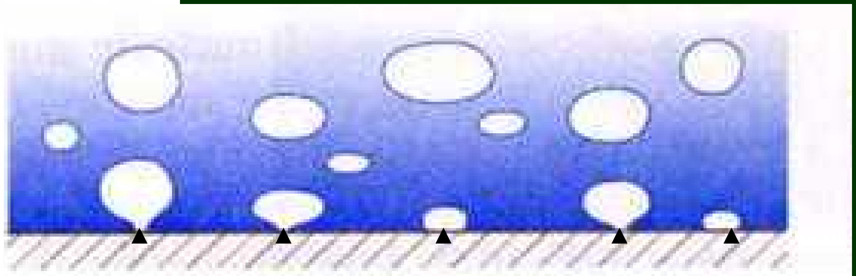
3. Natural convection in a centrifuge

1. Periodicity and bifurcation in capillary boiling

1. Motivation.

Nucleate boiling transfers large amounts of heat per unit mass.





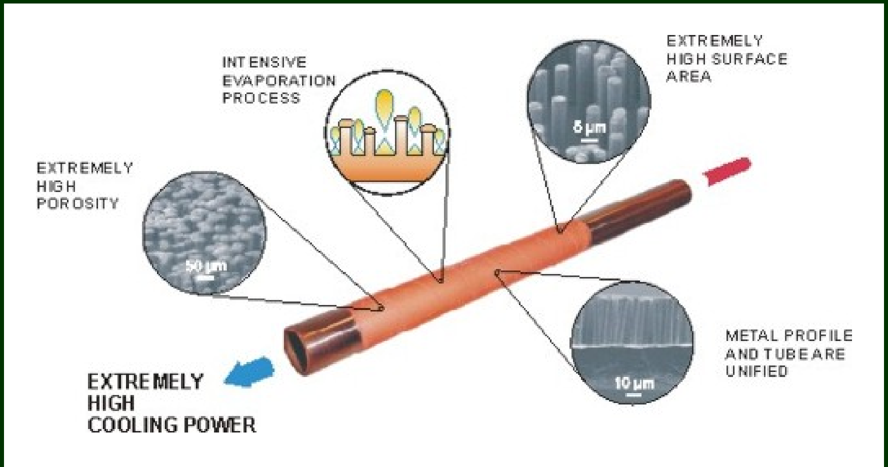
In nucleate boiling, phase change occurs at fractures or small cavities on the walls.

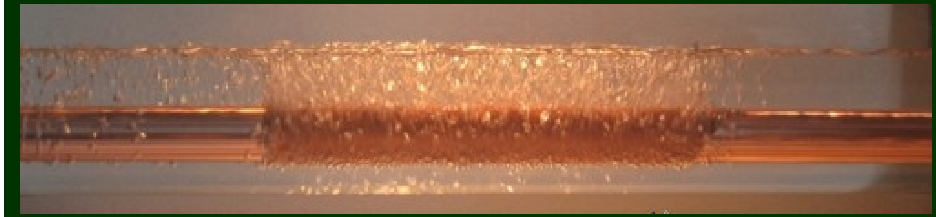
Principles of Heat Transfer , Kreith 1993

S.G. Bankoff AIChE J. (1958): Grooves may function as vapor traps.
V. K. Dhir, Ann. Rev. Fluid Mech. (1998) Review.

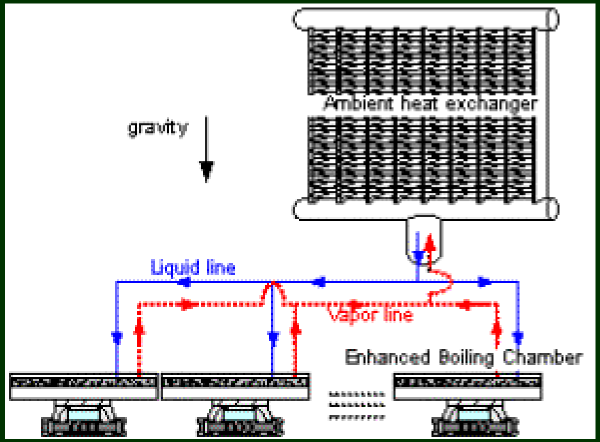
Artificial nucleation sites:

Commercially available surface geometries that promote high performance nucleate boiling.





SDK Technik GmbH

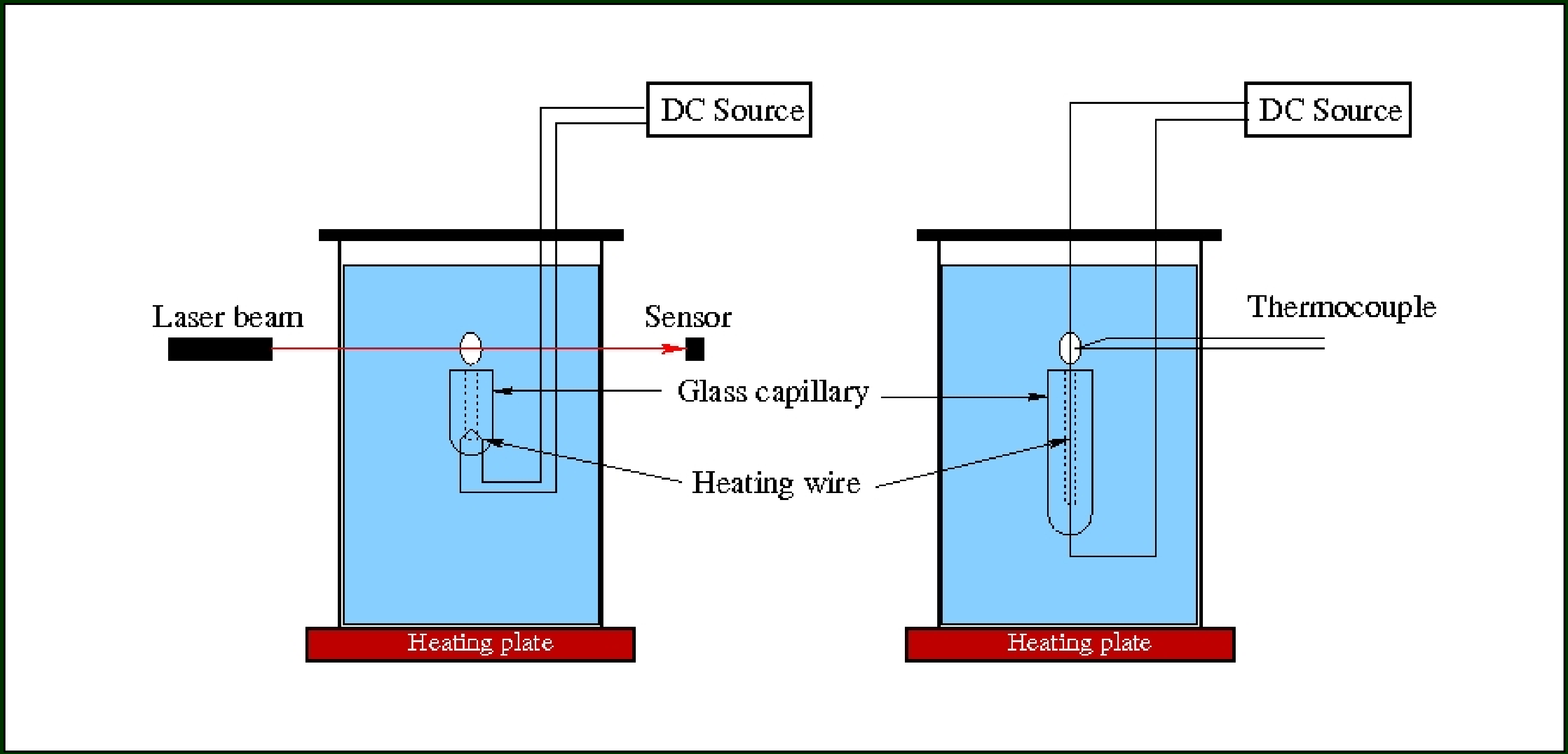


Omegapiezo

Omegapiezo High performance boiling surface, sintered porous surface.

Sintered material copper mesh: 100um-150um

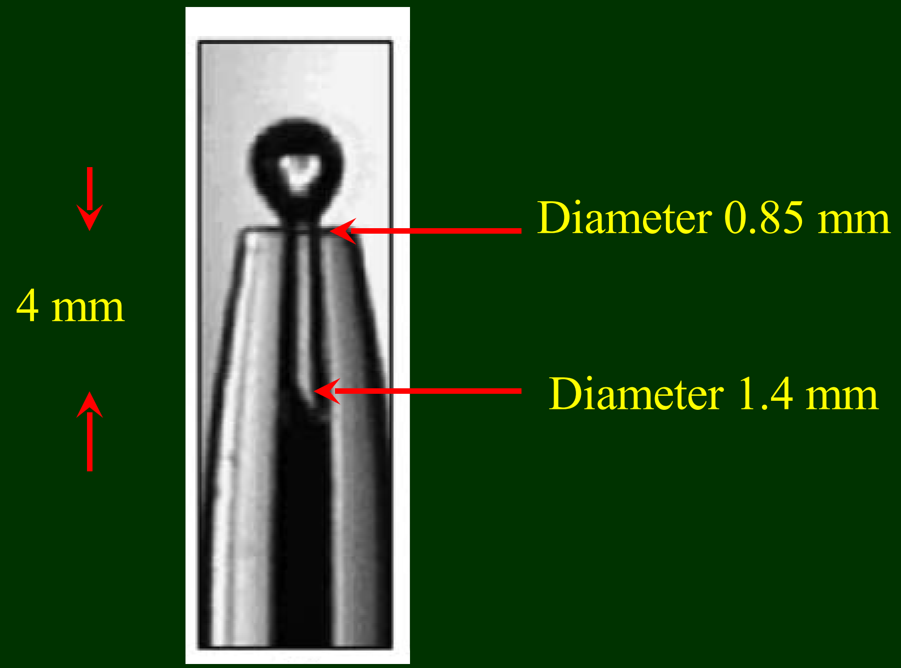
Two models considered for studying artificial nucleation sites.



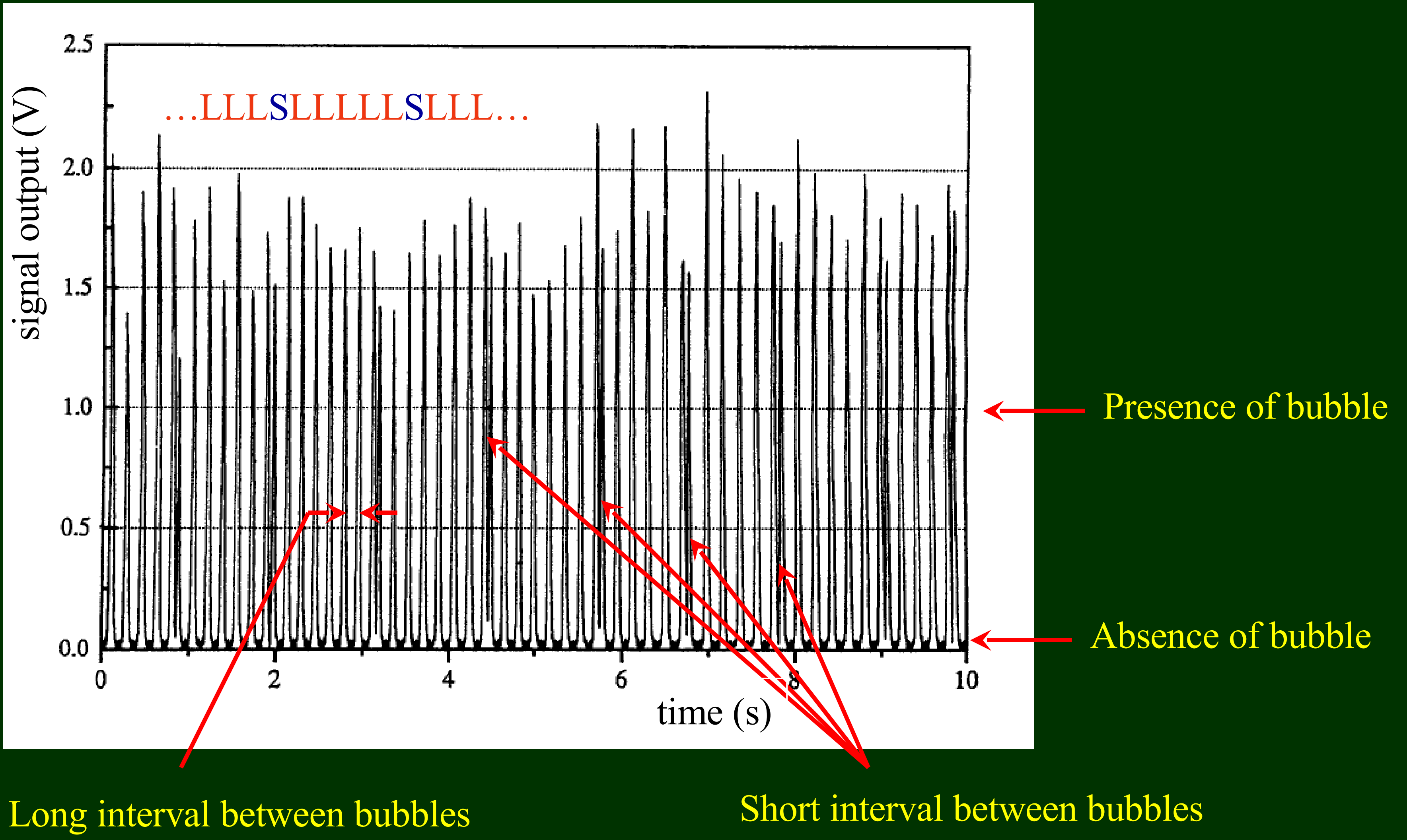
Model 1.
Heating wire at the bottom of the capillary.
Capillary diameter= 0.5 mm , length=4 mm

Model 2.
Concentric heating wire
Capillary diameter= 0.7 mm, length = 60 mm

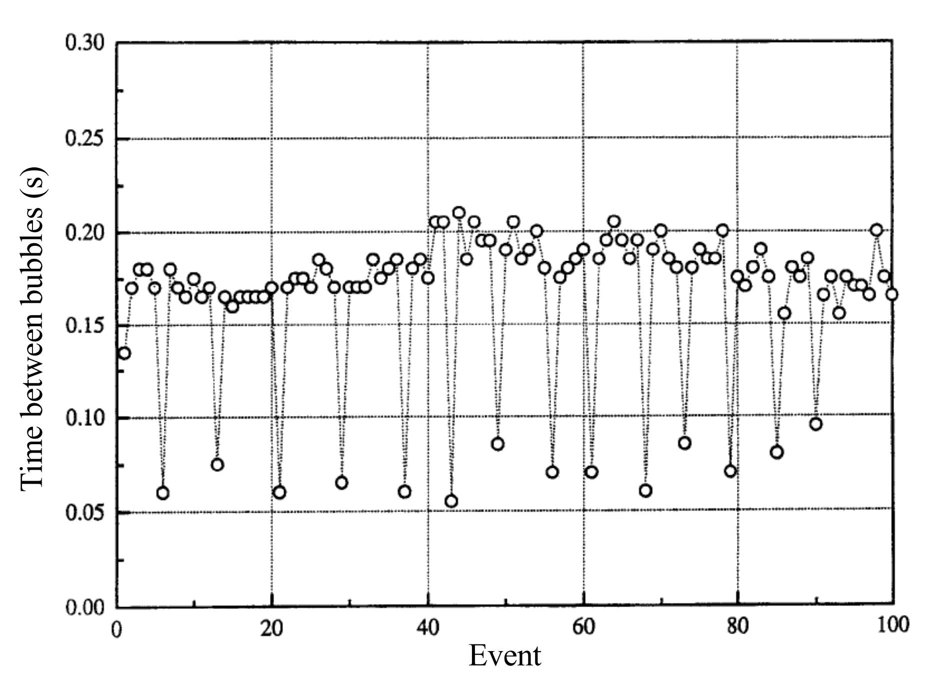
Capillary model 1

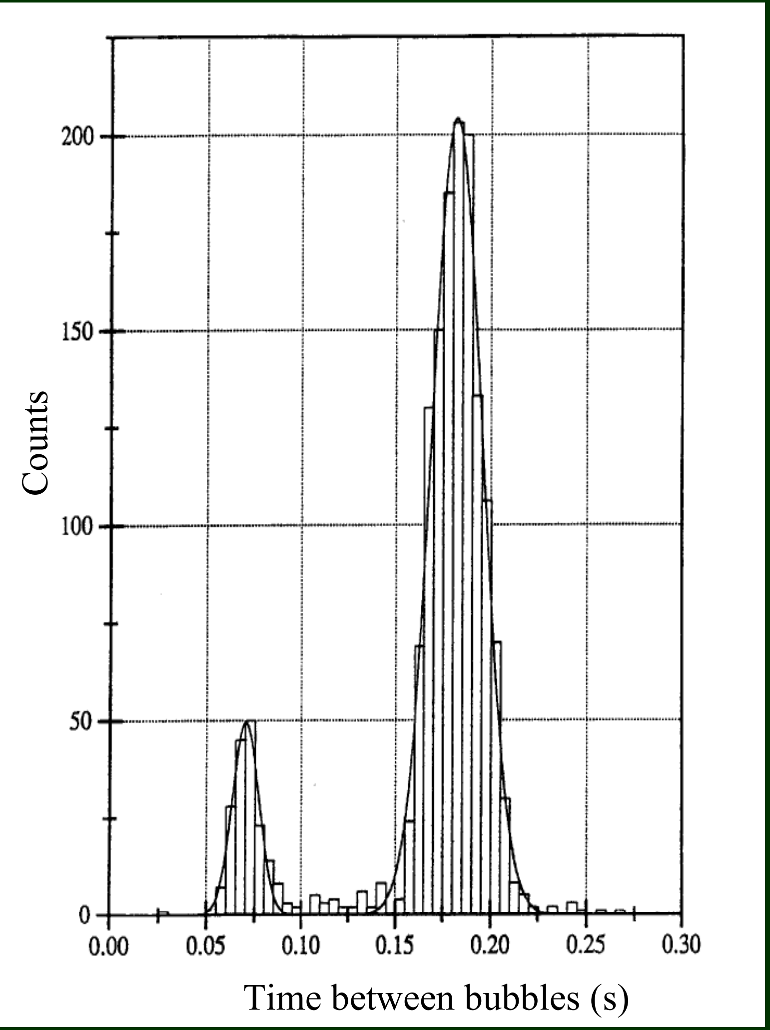


Observations with Model 1: Bubble transit at the tip of the capillary



Observations with Model 1

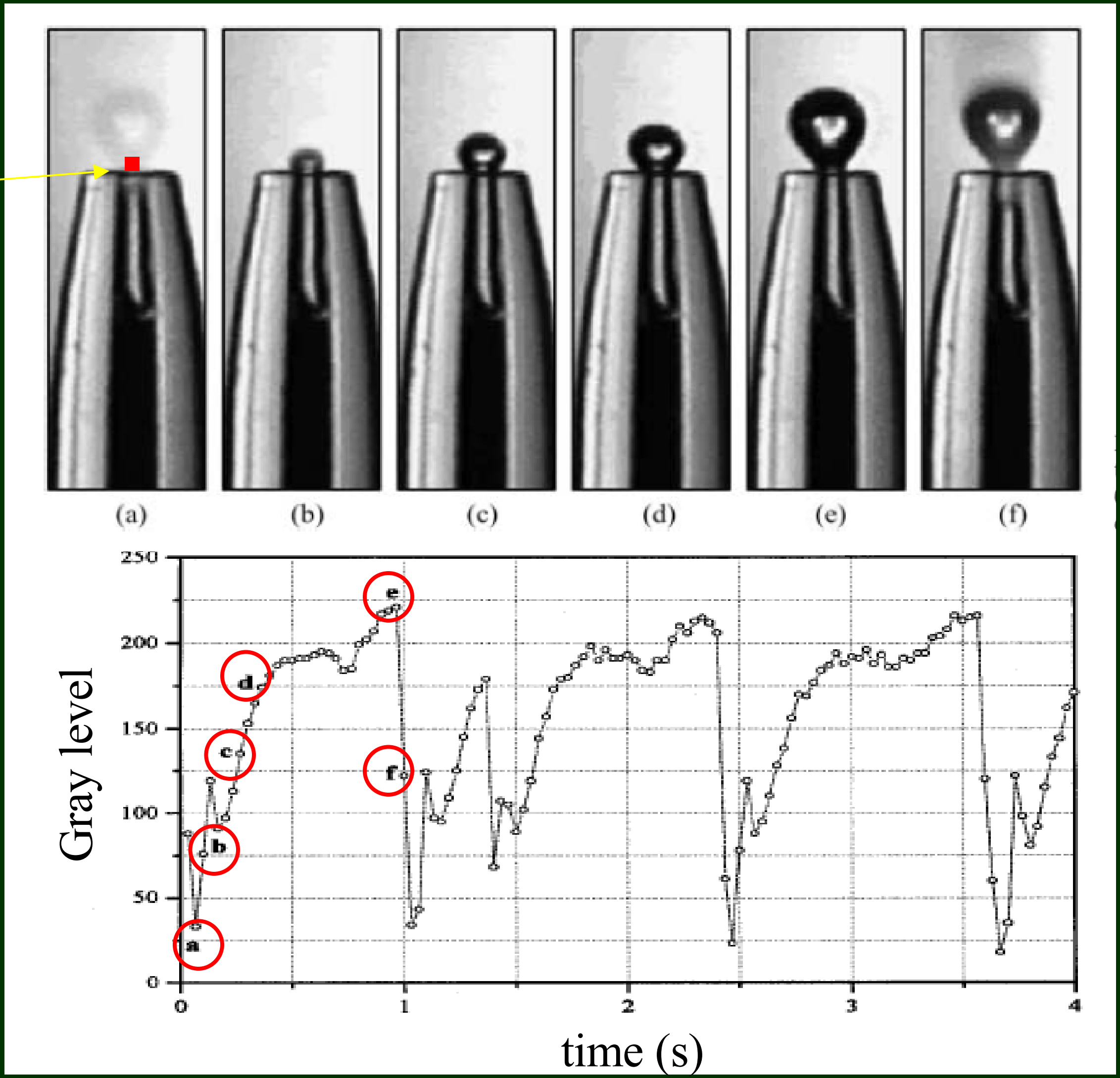




Average long interval ~ 0.18 s
Average short interval ~0.075 s

Visualization

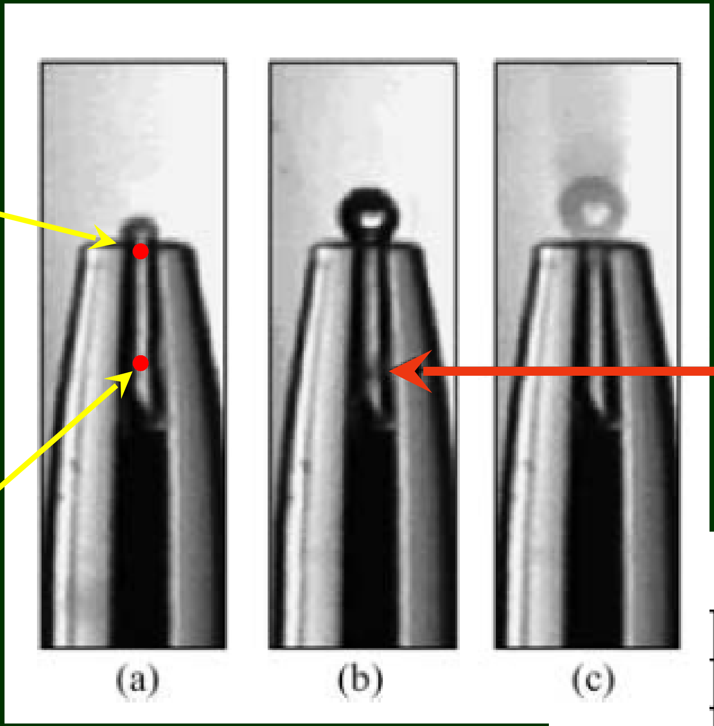
Gray level
monitor



Origin of the double frequency…

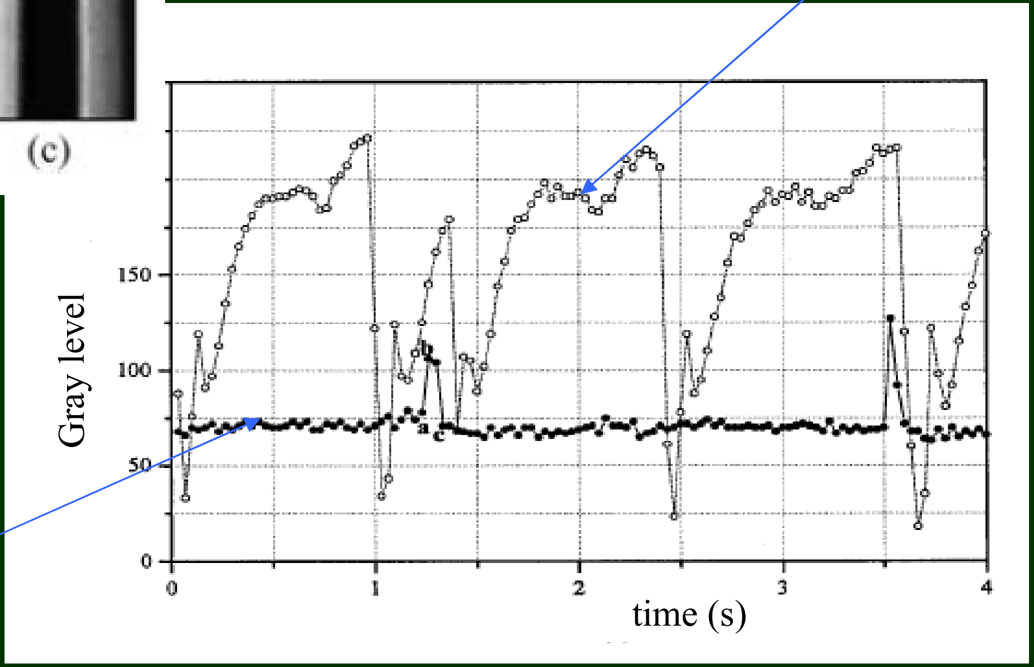
monitor 1

monitor 2



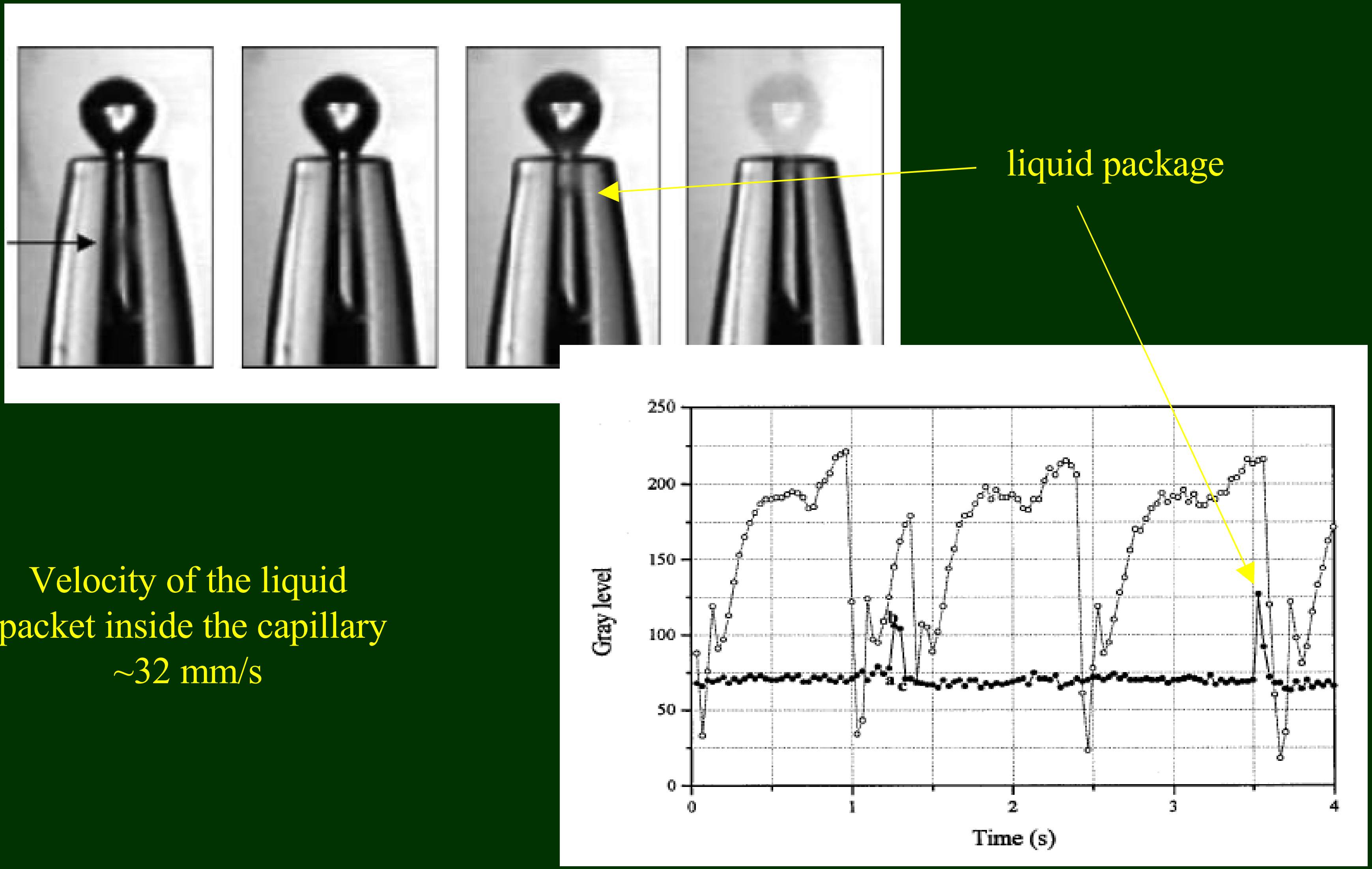
liquid packet

monitor 1



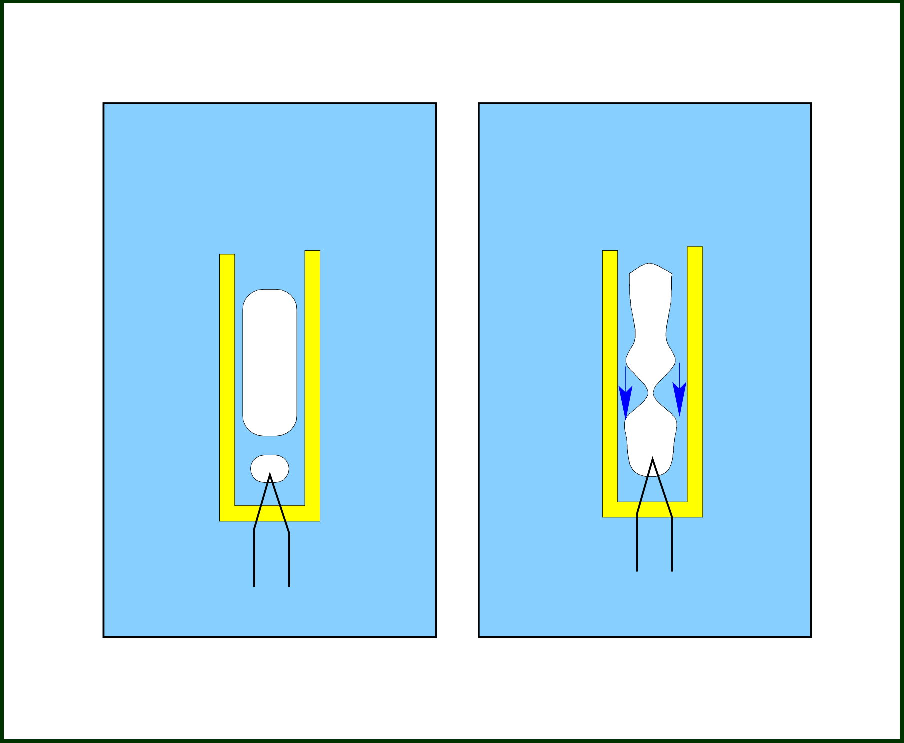
monitor 2

…but liquid packet and natural bubble departure sometimes coincide



Velocity of the liquid packet inside the capillary ~32 mm/s

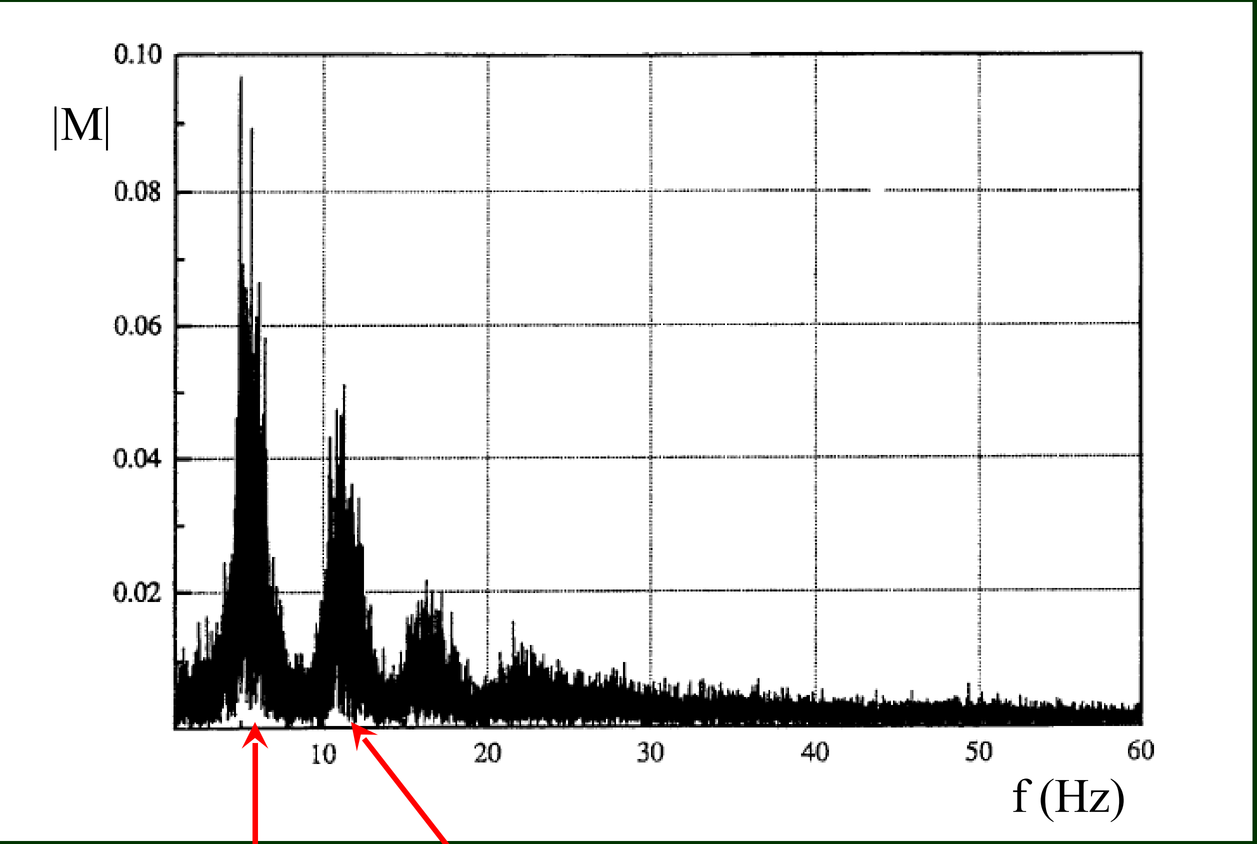
Observations indicate that the liquid packets can be formed by two mechanisms:



liquid accumulation at the bottom of the capillary.

waves on the descending liquid films.

Power spectrum

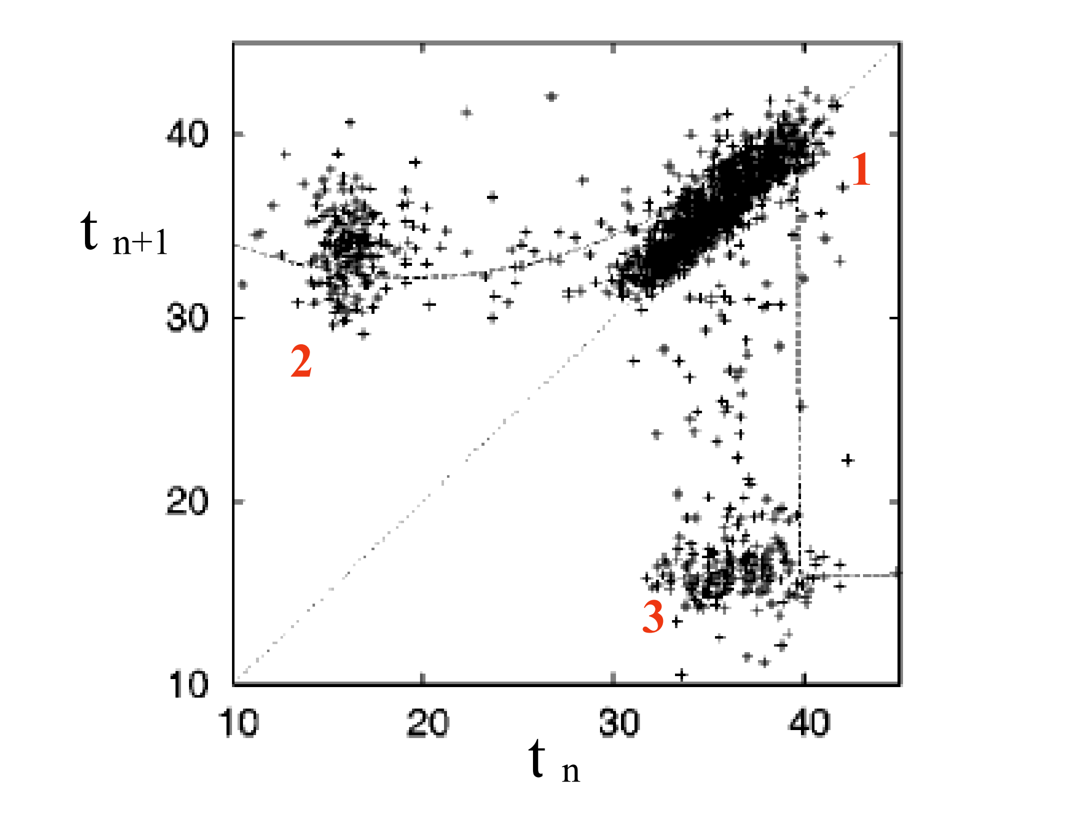


Single bubbles (~5.5 Hz)

Short period events (~12 Hz)

* 1000 bubbles, 160 packages.

Return map for the time interval T^n between subsequent bubbles.



1 Long ⇨ Long
2 Short ⇨ Long
3 Long ⇨ Short

Model for the time interval T_n between subsequent bubbles.

$$T_{n+1} = \begin{cases} a(\varphi_n) + c(T_n - b)^2 + \eta\xi_n & T_n < d(\varphi_n) \\ 16 + \eta\xi_n & T_n > d(\varphi_n) \end{cases}$$

ξ_n : white noise

$$\langle \xi_n \rangle = 0 \quad \langle \xi_n \xi_m \rangle = \delta_{m,n}$$

$$a(\phi_n) = 31 + 1.2\cos(\varphi_n)$$

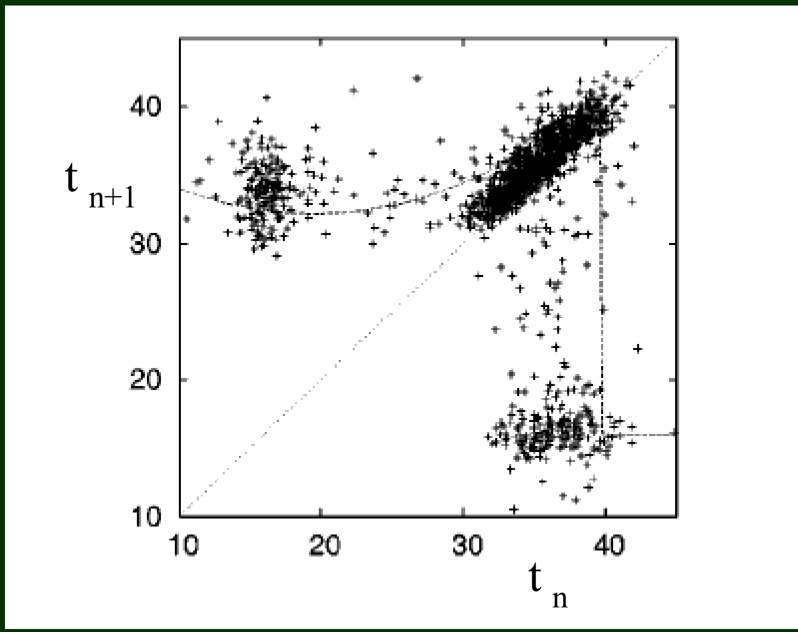
$$b = 19.5$$

$$c = 0.0205$$

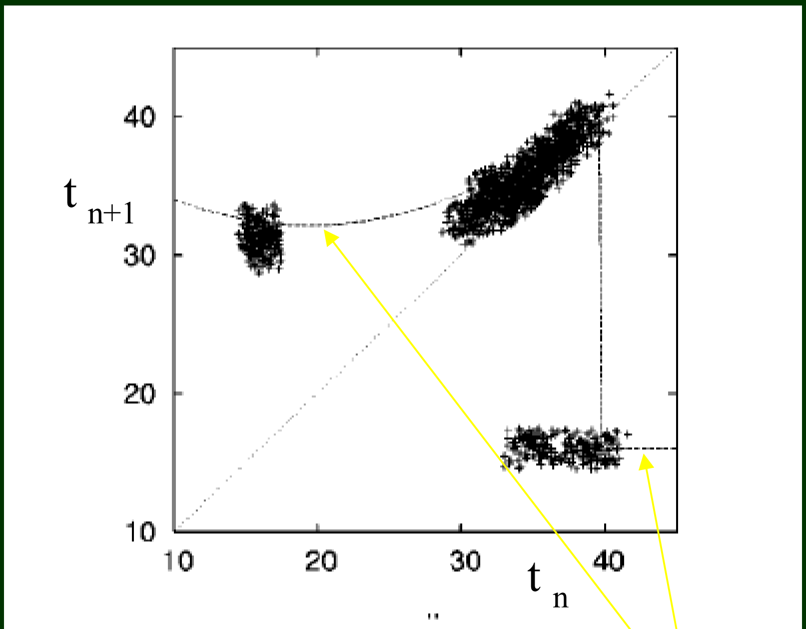
$$d(\varphi_n) = 36.8 + 2.9\cos(\varphi_n)$$

$$\eta = 0.13$$

Experiment

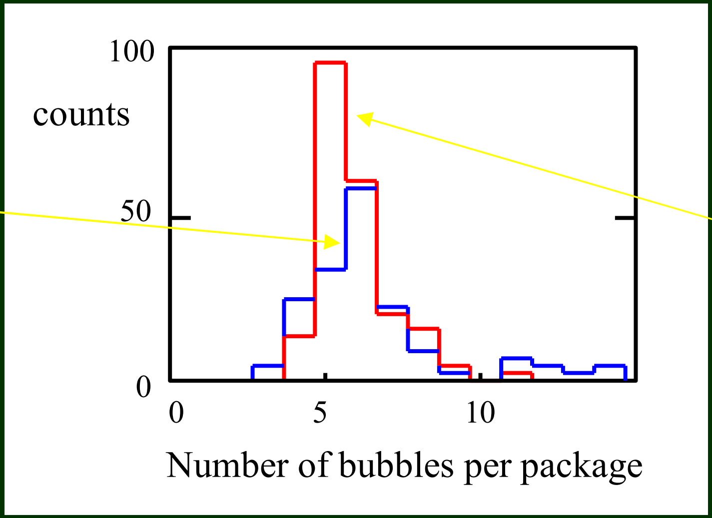


Model



Model with $\varphi_n = 0$

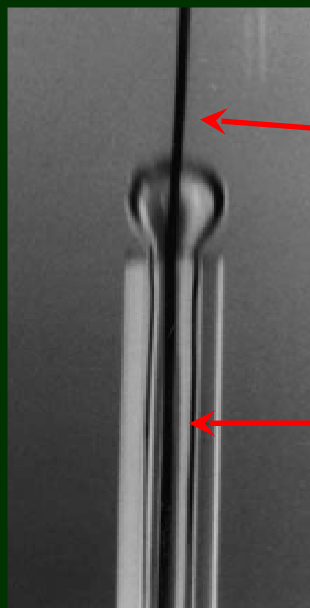
Experiment



Model

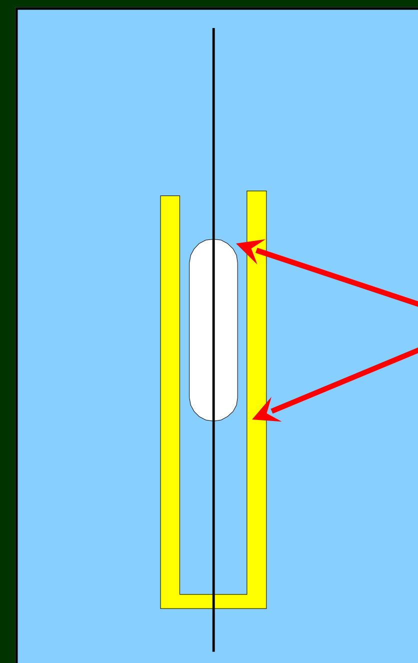
Capillary model 2

60 mm



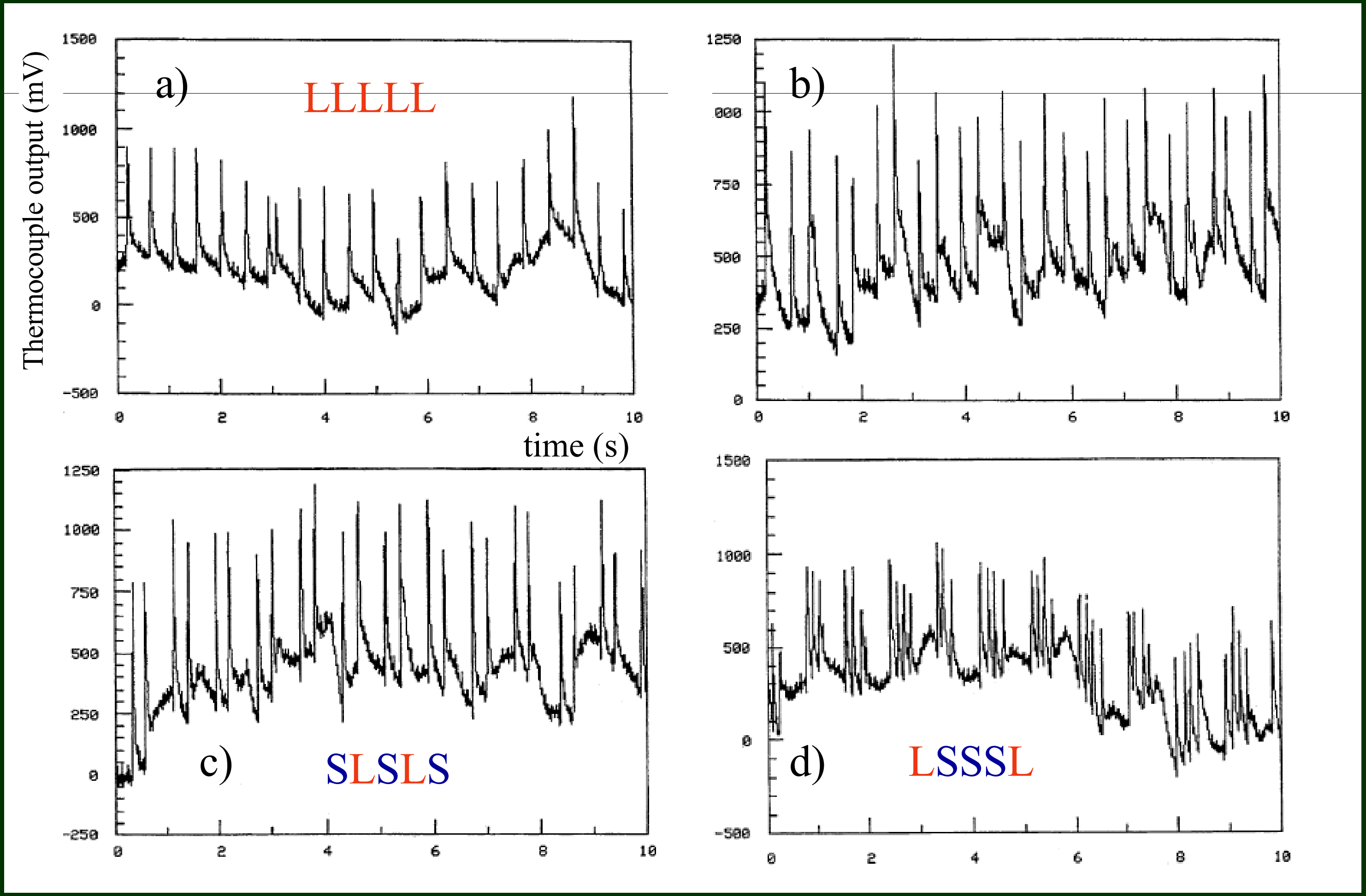
Wire diameter
0.254 mm

Capillary
Internal diameter
1.4 mm



Upper and lower
ends move

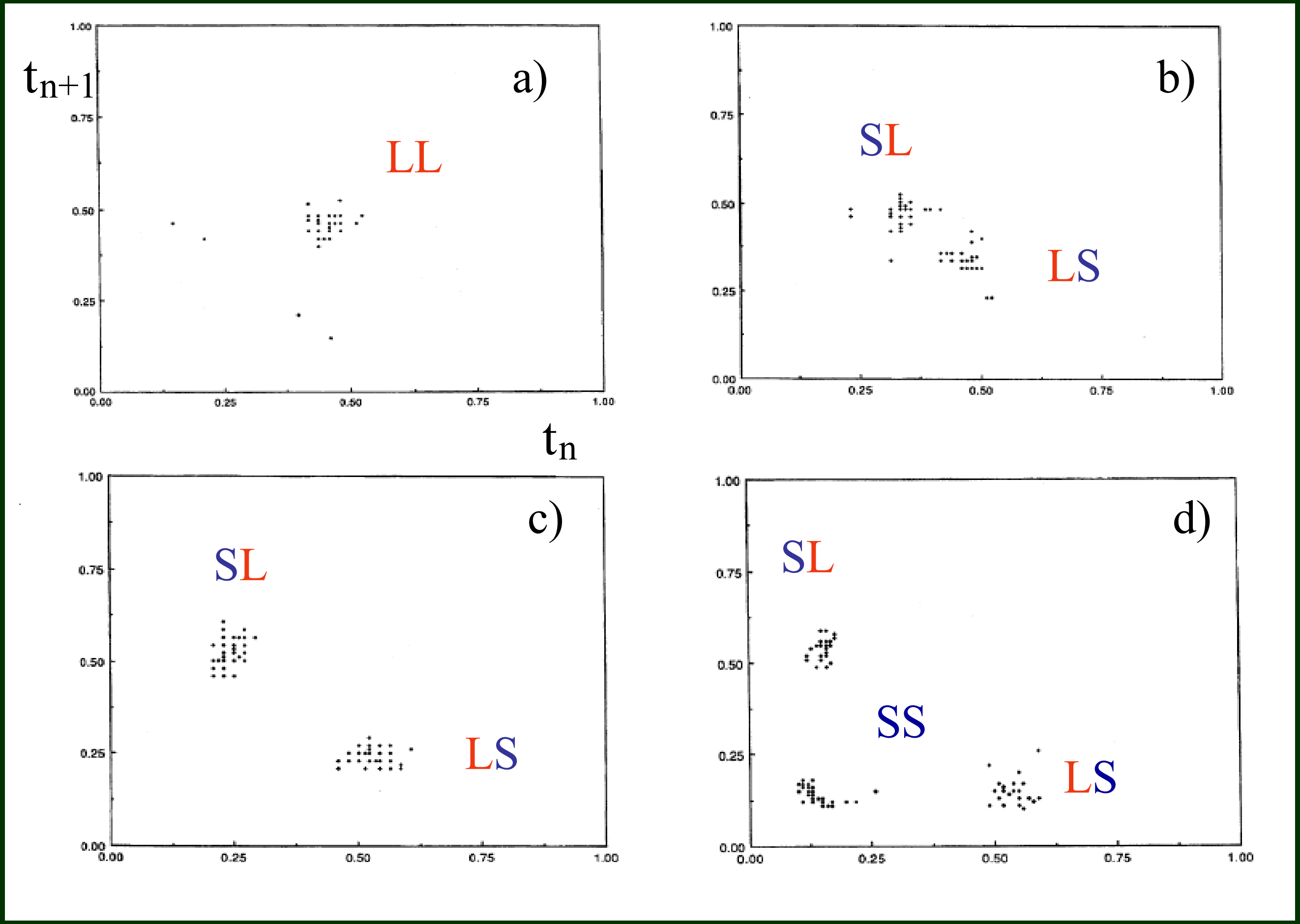
Observations with Model 2: Bubble transit at the tip of the capillary



Period doubling

a) 15 W/m, b) 18 W/m, c) 22 W/m, d) 24 W/m

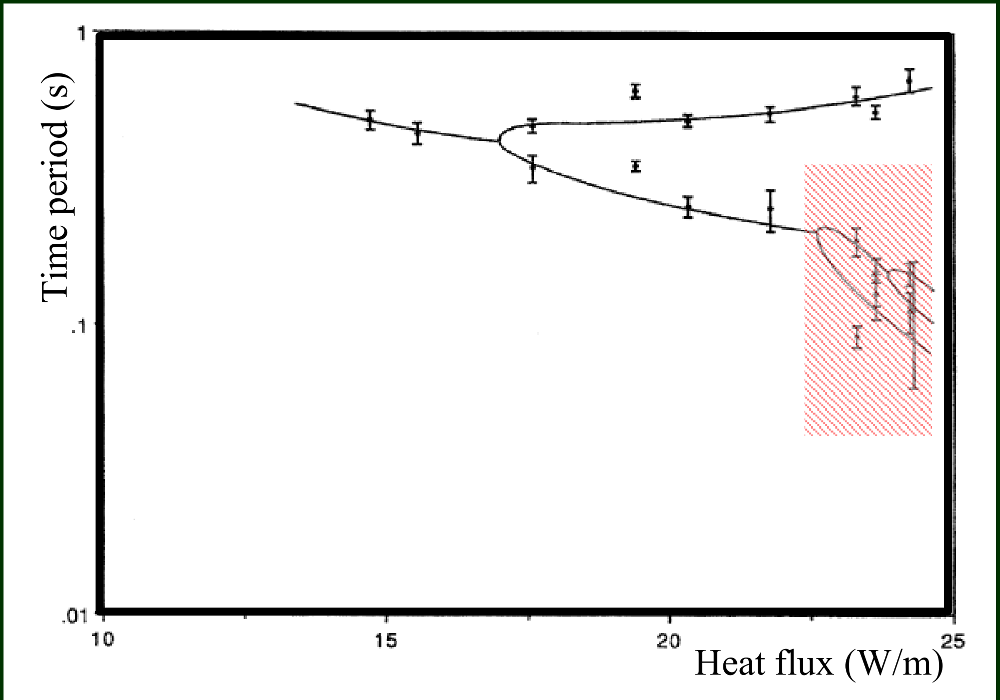
Observations with Model 2: Return maps



Period doubling

a) 15 W/m, b) 18 W/m, c) 22 W/m, d) 23 W/m

Observations with Model 2: Bifurcation diagram



Summary

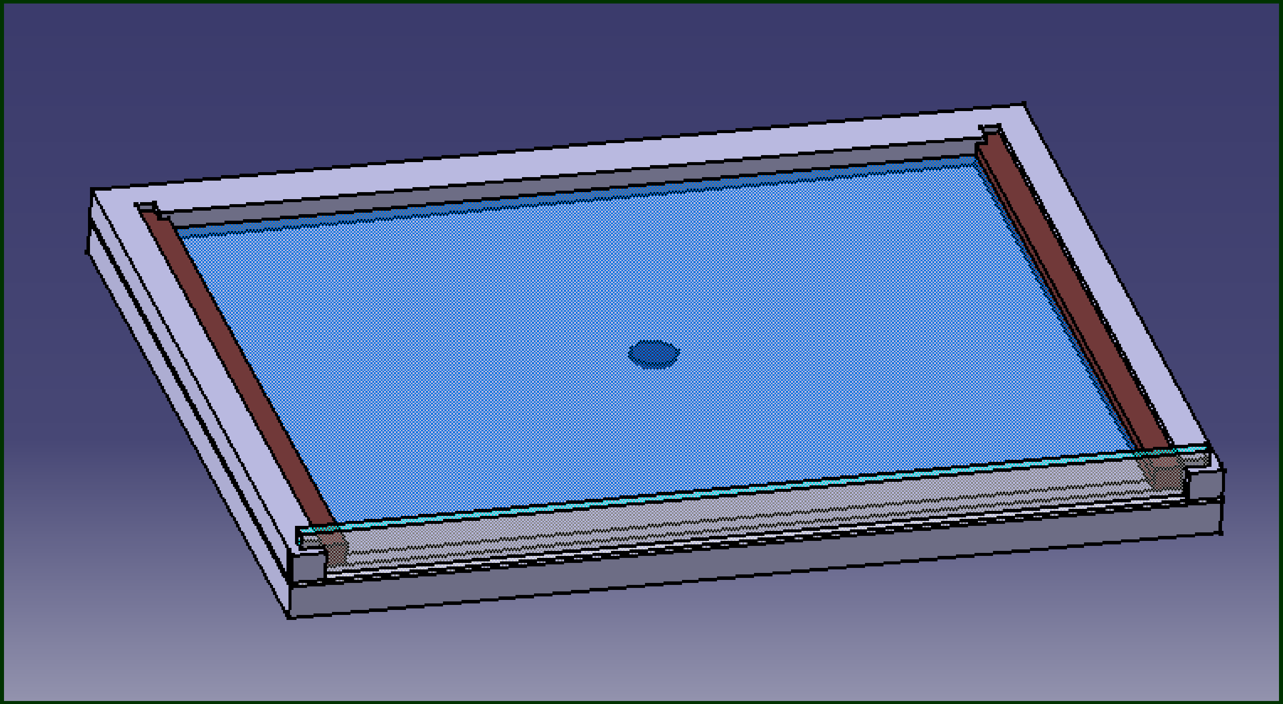
*We studied capillary boiling as a model of artificial nucleation.

* Bubble emission (and heat transfer) depend strongly on the geometry and on the dynamical interaction of liquid and vapor inside the capillary.

* Period doubling of bubble emissions has been observed for long capillaries.

2. Quasi 2D-vortices generated by the Lorentz force in an electrolyte

Electrolyte container



Working fluid: Sodium bicarbonate solution
Fluid layer depth: 4 mm
Maximum magnetic field: 0.33 T
Magnet diameter: 19 mm
Electrical current : Jo = 5-100 mA

Experimental setup

Particle Image Velocimetry

Scaling

Distance: magnet diameter	D
fluid layer depth	*h*
Time:	D^2/ν
Velocity (1):	$U_\nu = \nu/D$
Electrical current:	Jo
Magnetic field:	Bo
Lorentz force:	JoBo
Velocity (2): $\nu U/D^2 \sim JoBo$	$U = JoBoD^2/\nu$
Electrical conductivity	σ

Nondimensional parameters

- Reynolds number

  $Re = UD/\nu = J_oB_oD^3/\nu = U/U\nu$

- Hartmann number

  $Ha = B_o D (\sigma/\rho\nu)^{1/2}$

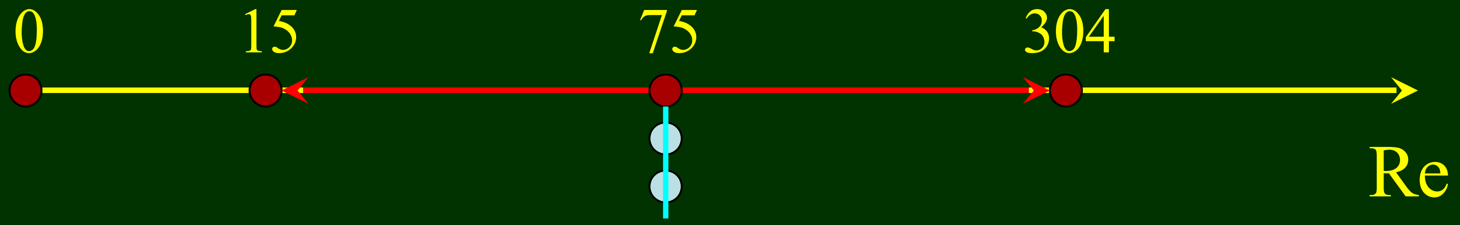
- Depth of the fluid layer

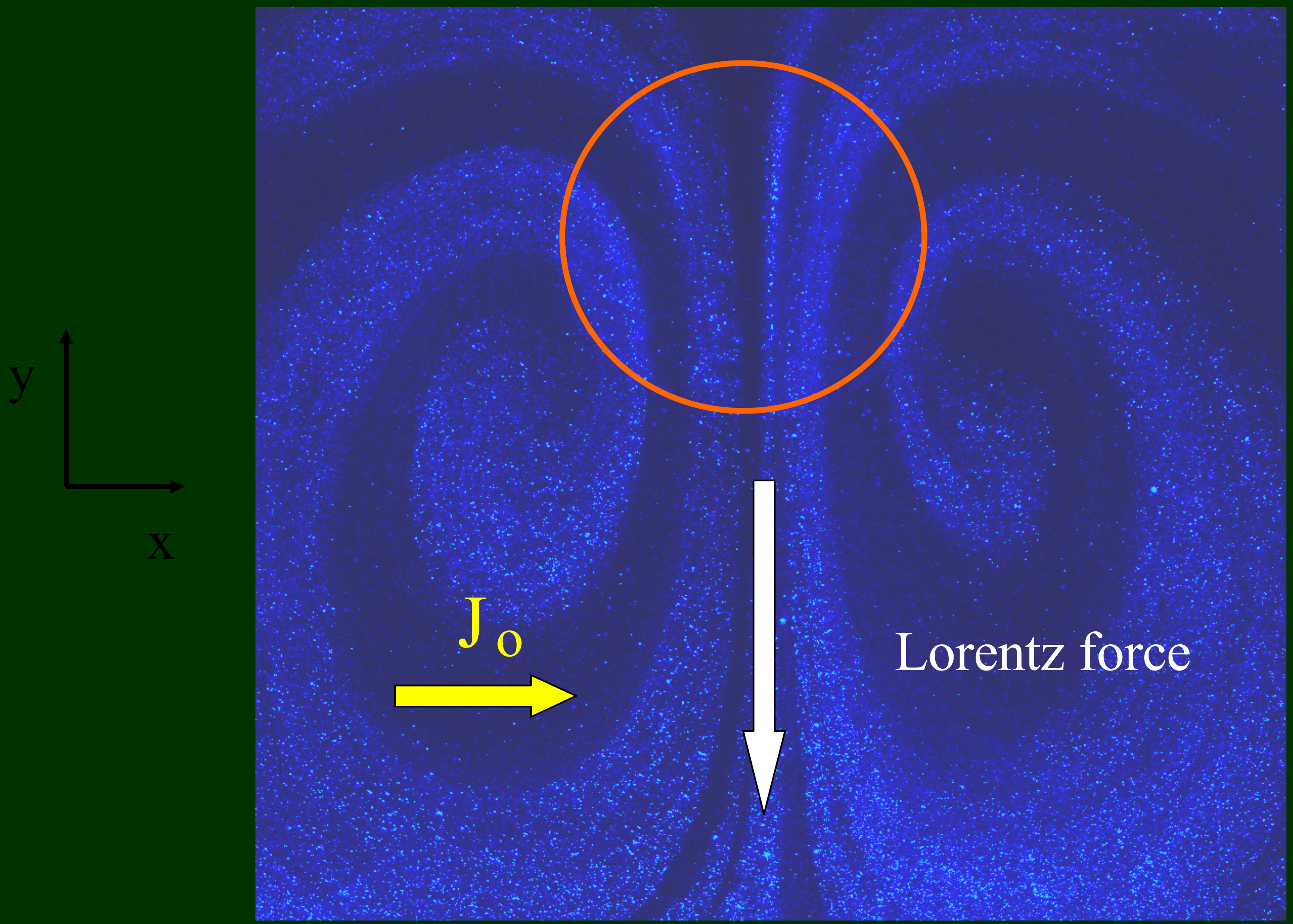
  $h = \mathit{h}/D$

Experimental observations.

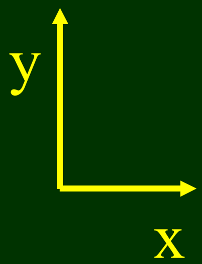
Ha = 0.3

h = 0.21




y
x
J o
Lorentz force

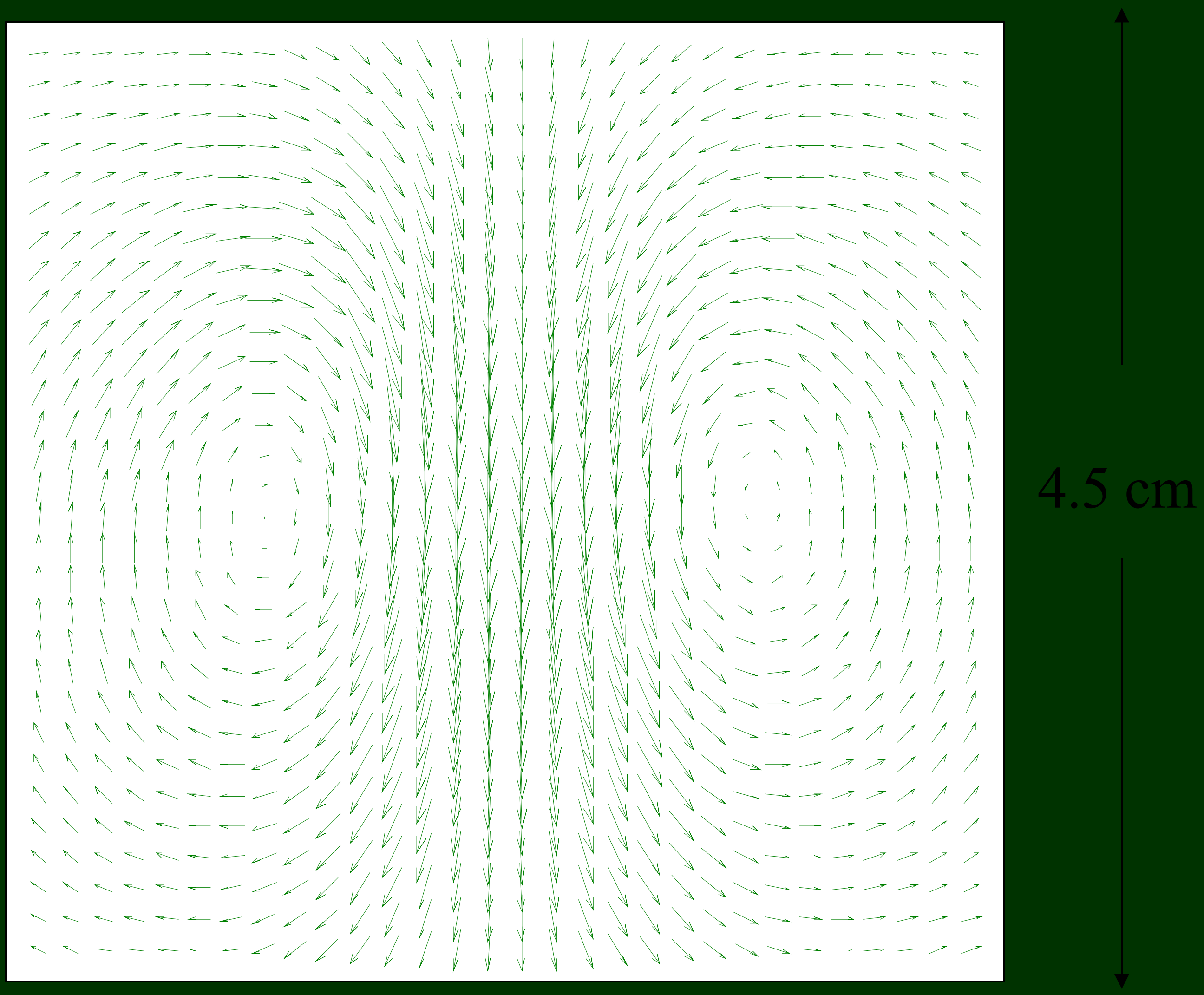
Velocity field, upper layer (z = 3.75 mm)



J_o =25 mA

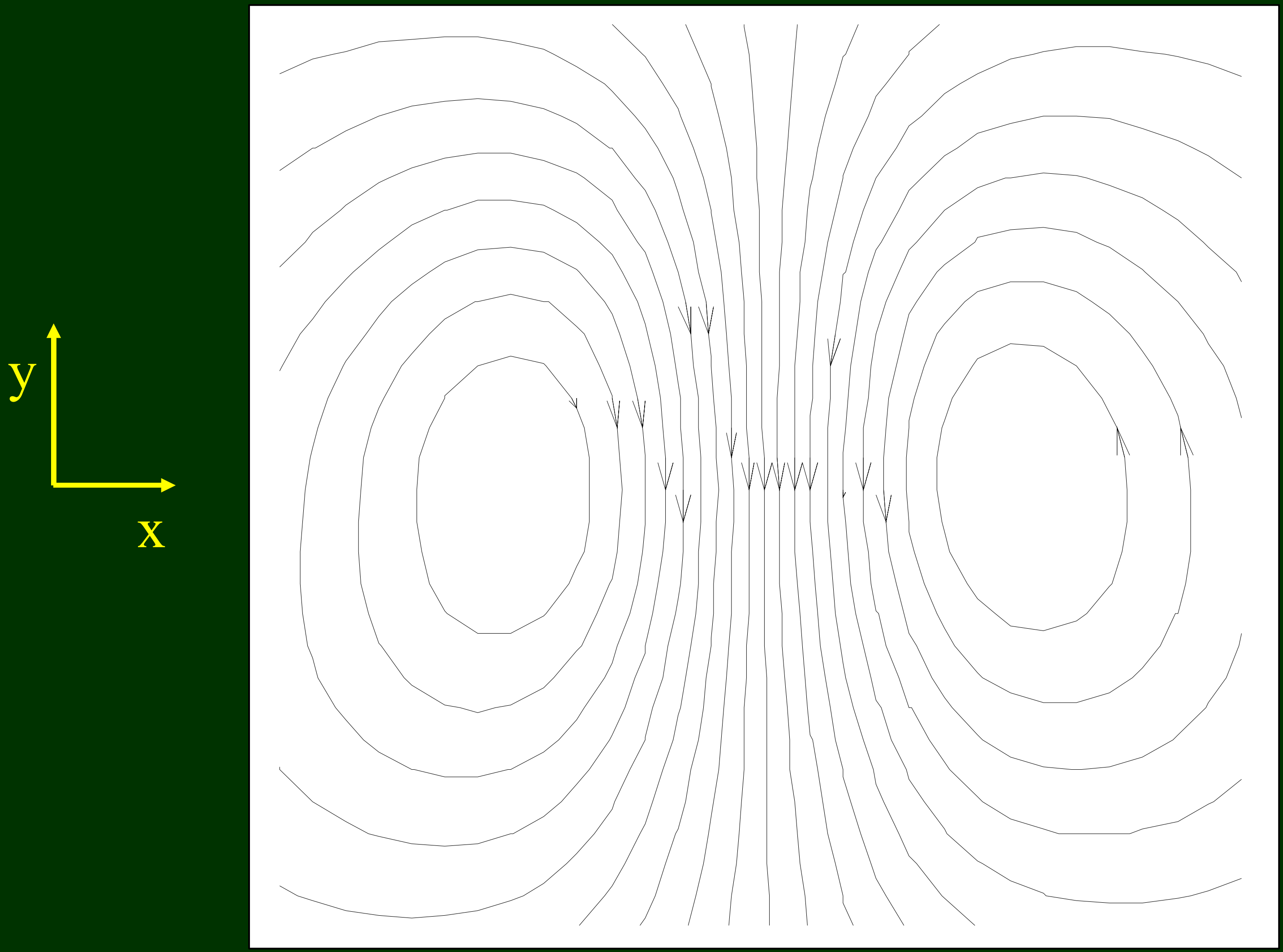
Ha=0.3

Re=75

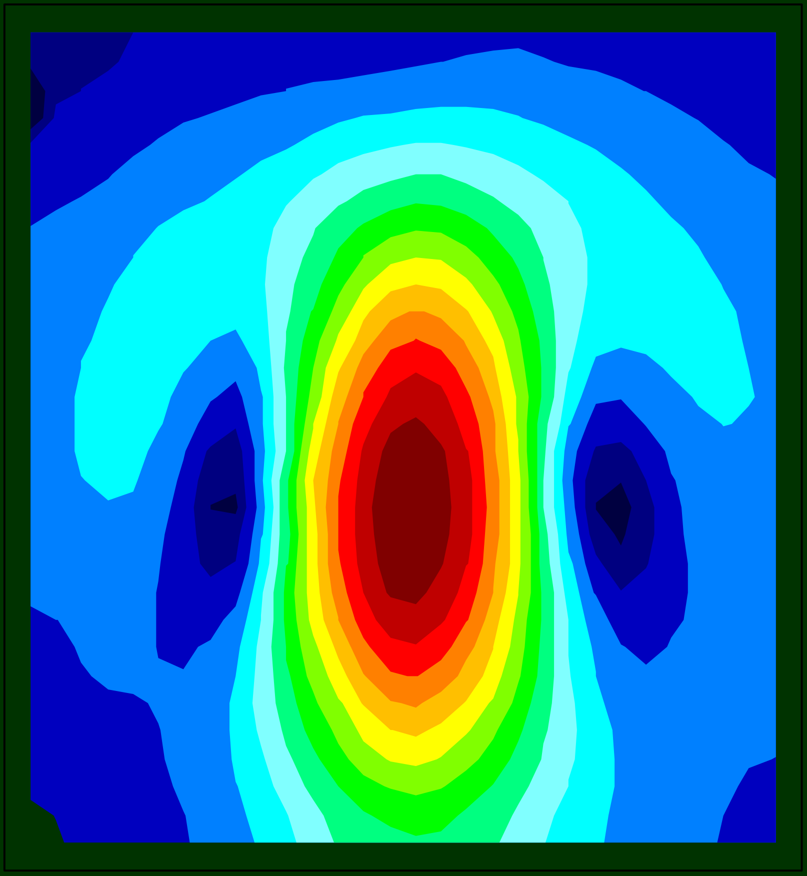


Stream lines

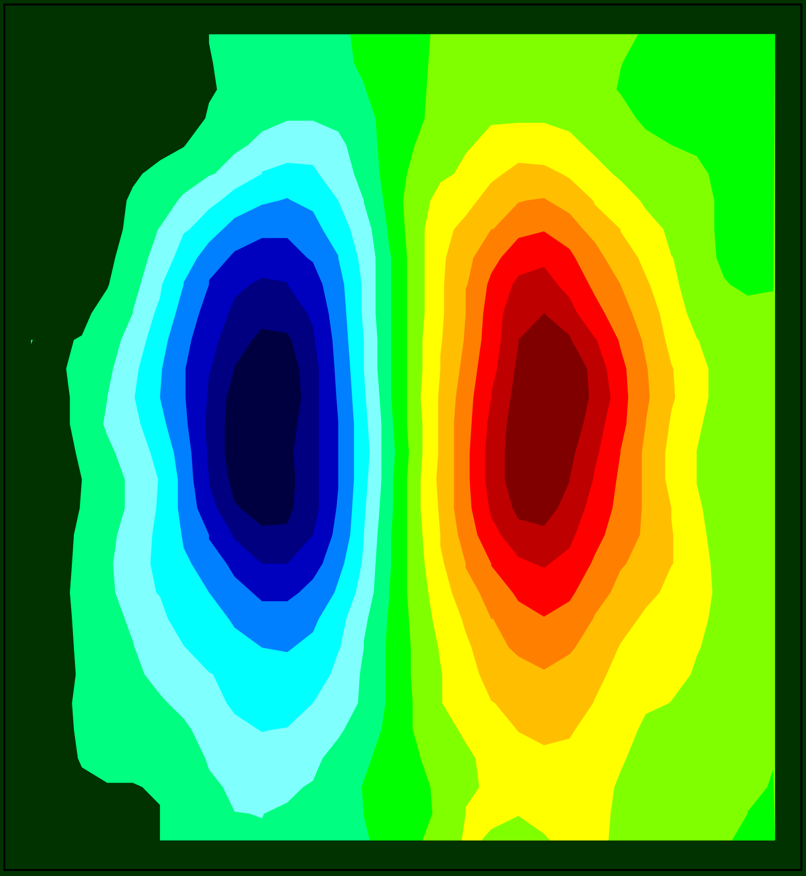
Jo =25 mA, Re = 75, Ha =0.3

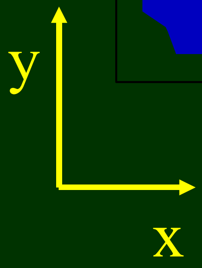


Velocity



Vorticity



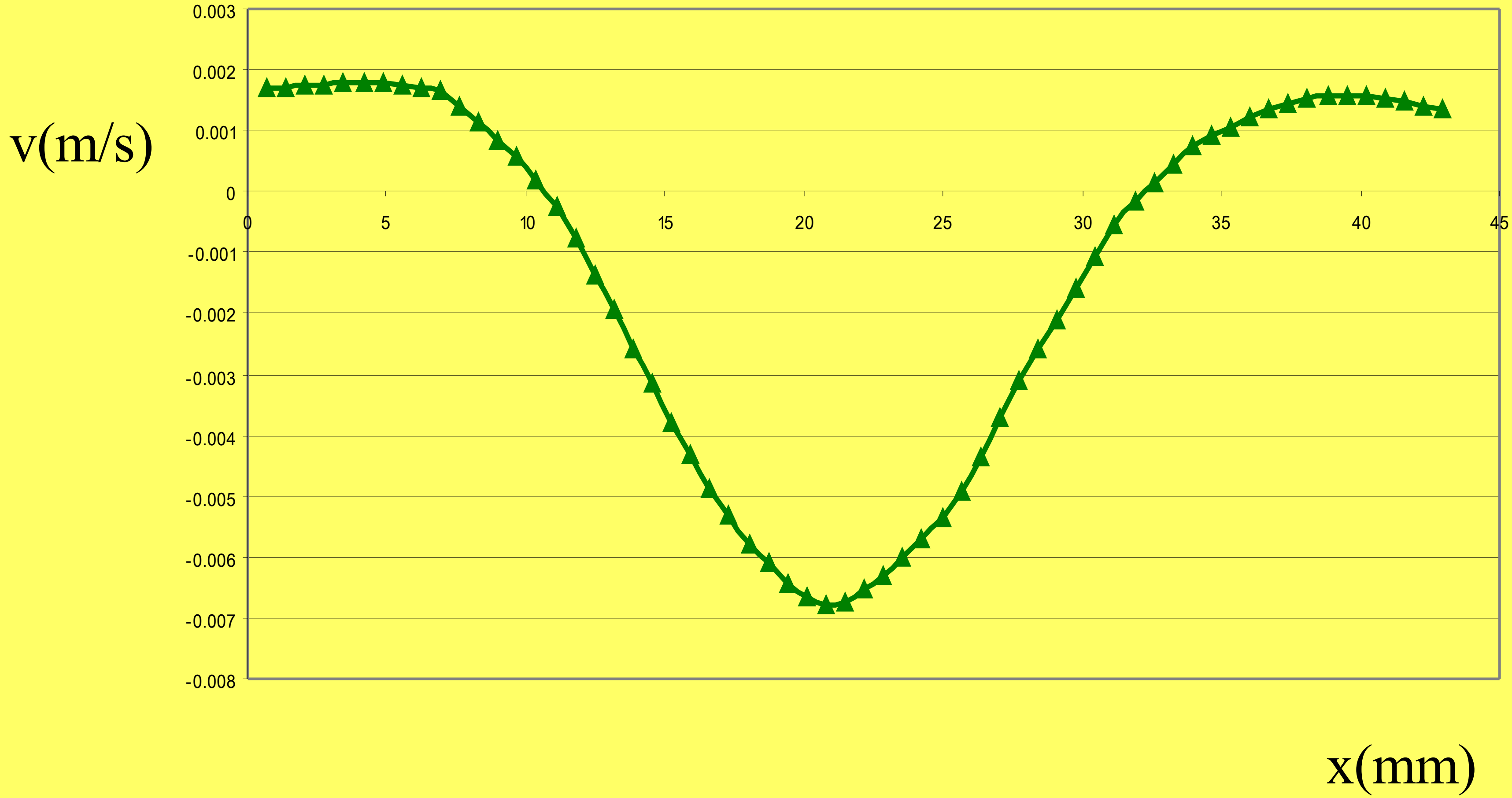


$v_{max} = 6.7$ mm/s

$\omega = 1.05\ s^{-1}$

Jo =25 mA, Re = 75, Ha =0.3

y-component of velocity

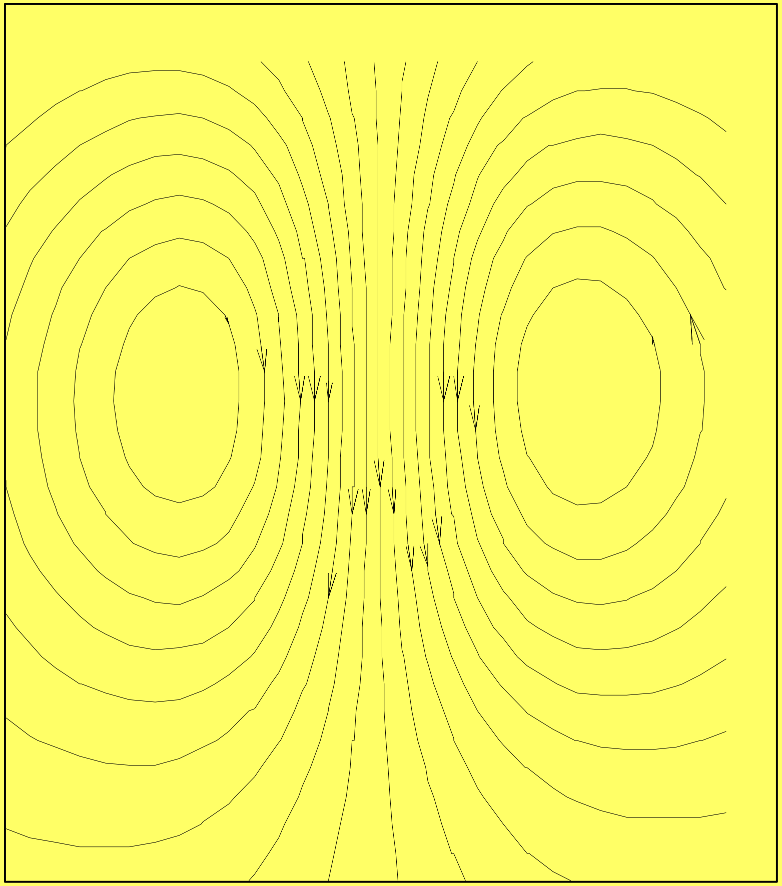


Jo = 25 mA, Re = 75

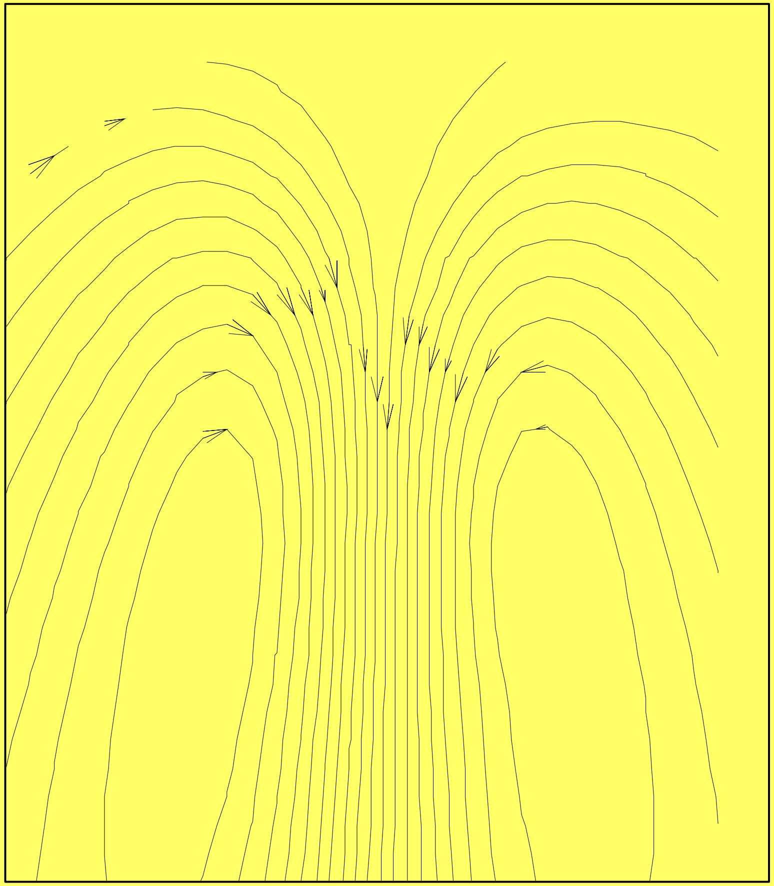
h = 3.5 mm, y = vortex center

Stream lines

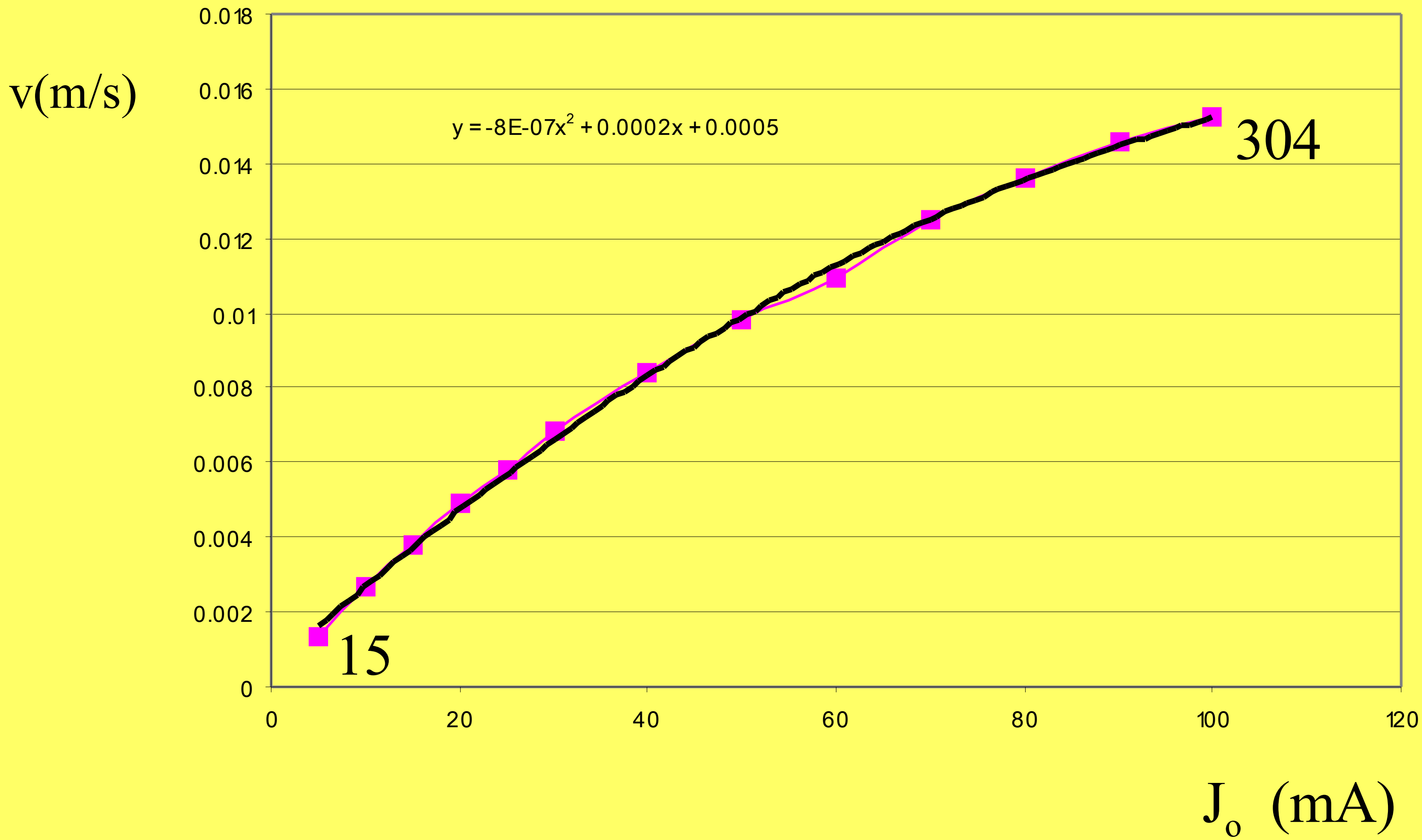
J_o = 10 mA, *Re*=30, Ha=0.3



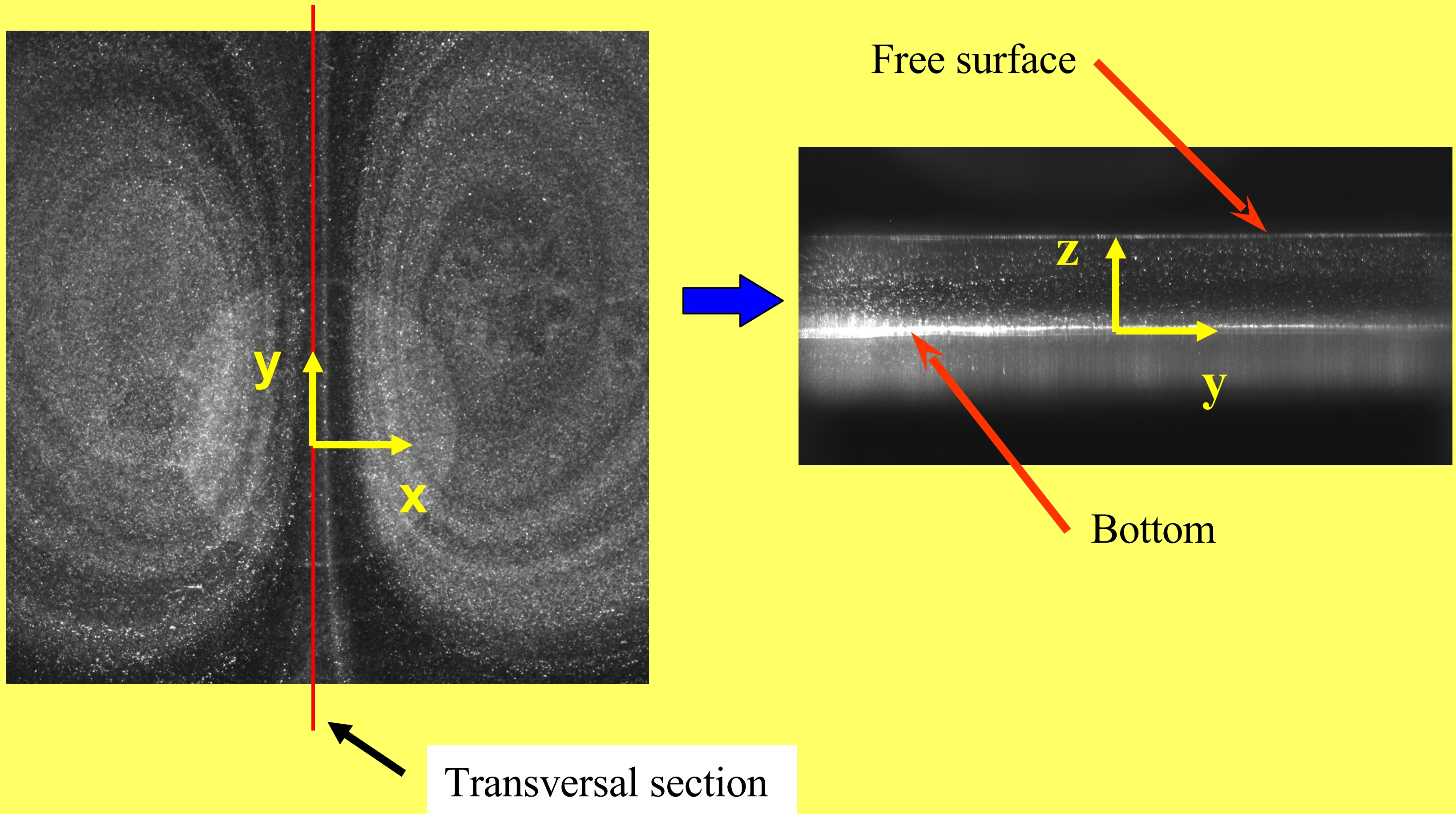
J_o =100 mA, *Re*= 304, Ha=0.3

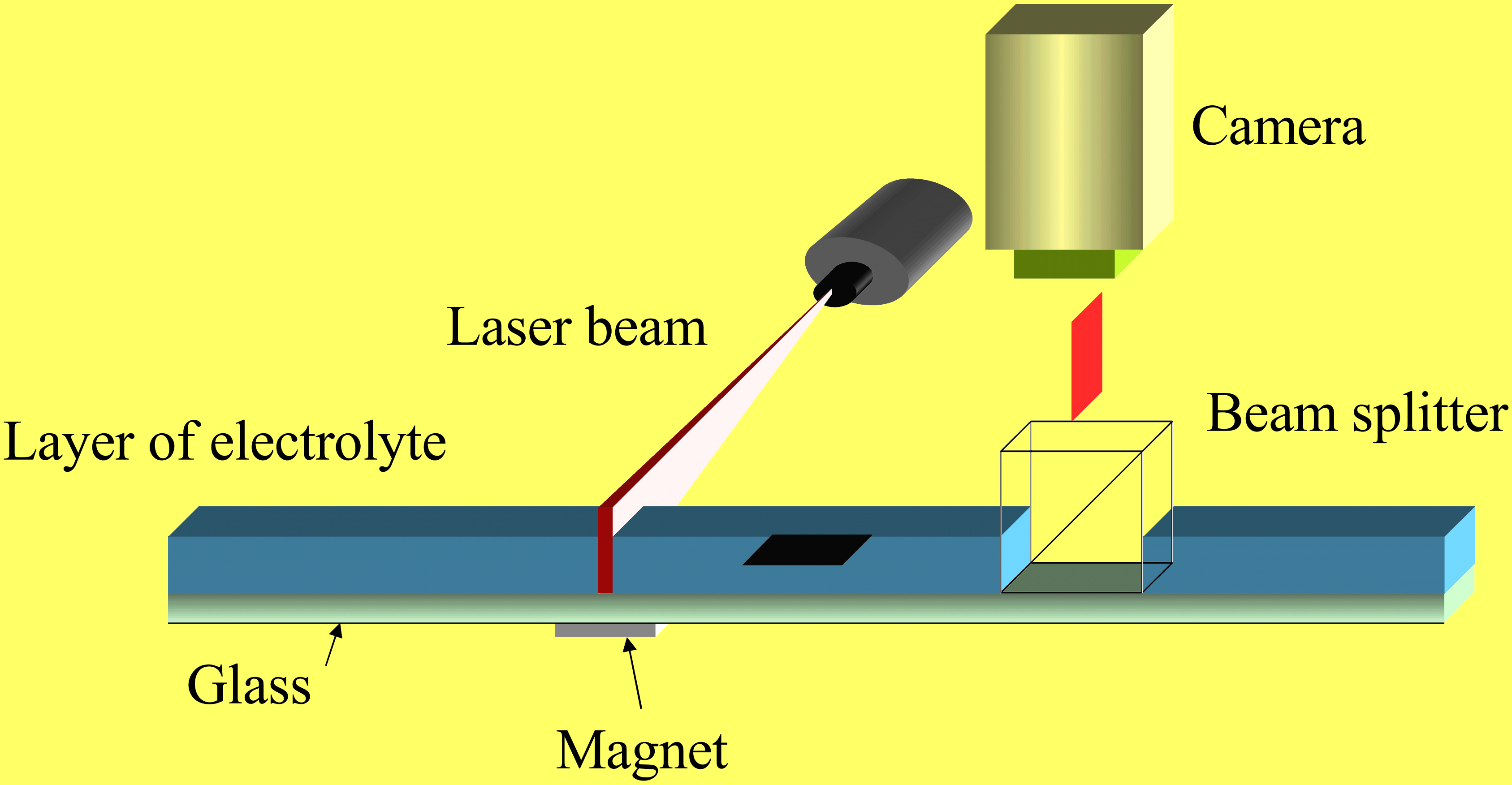


Maximum velocity vs J_o

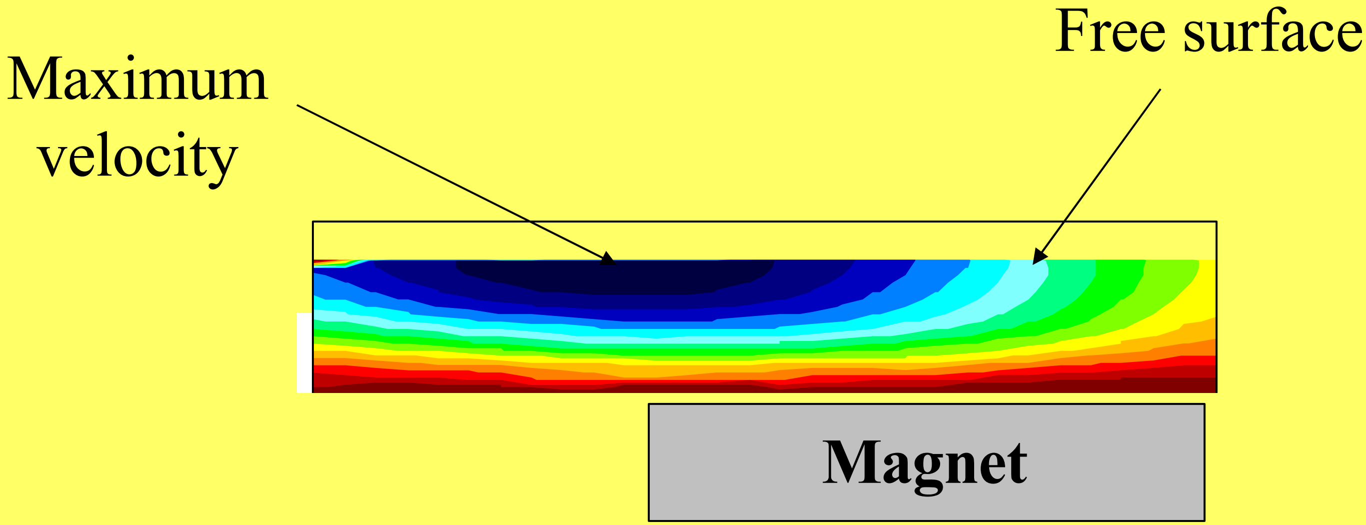


Velocity profiles as functions of *z*



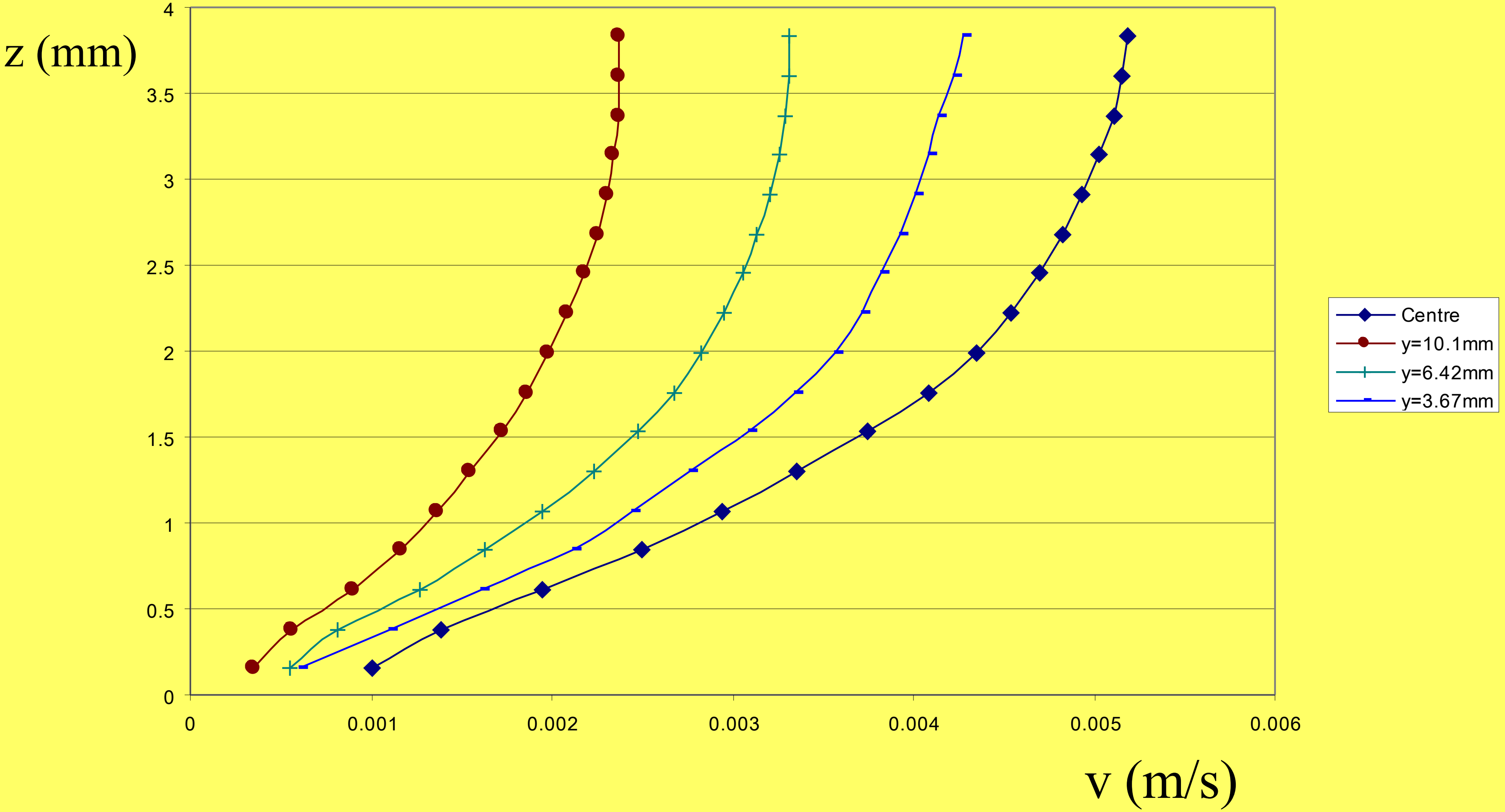

Camera
Laser beam
Beam splitter
Layer of electrolyte
Glass
Magnet

Contours of velocity magnitude



Velocity profiles as functions of z

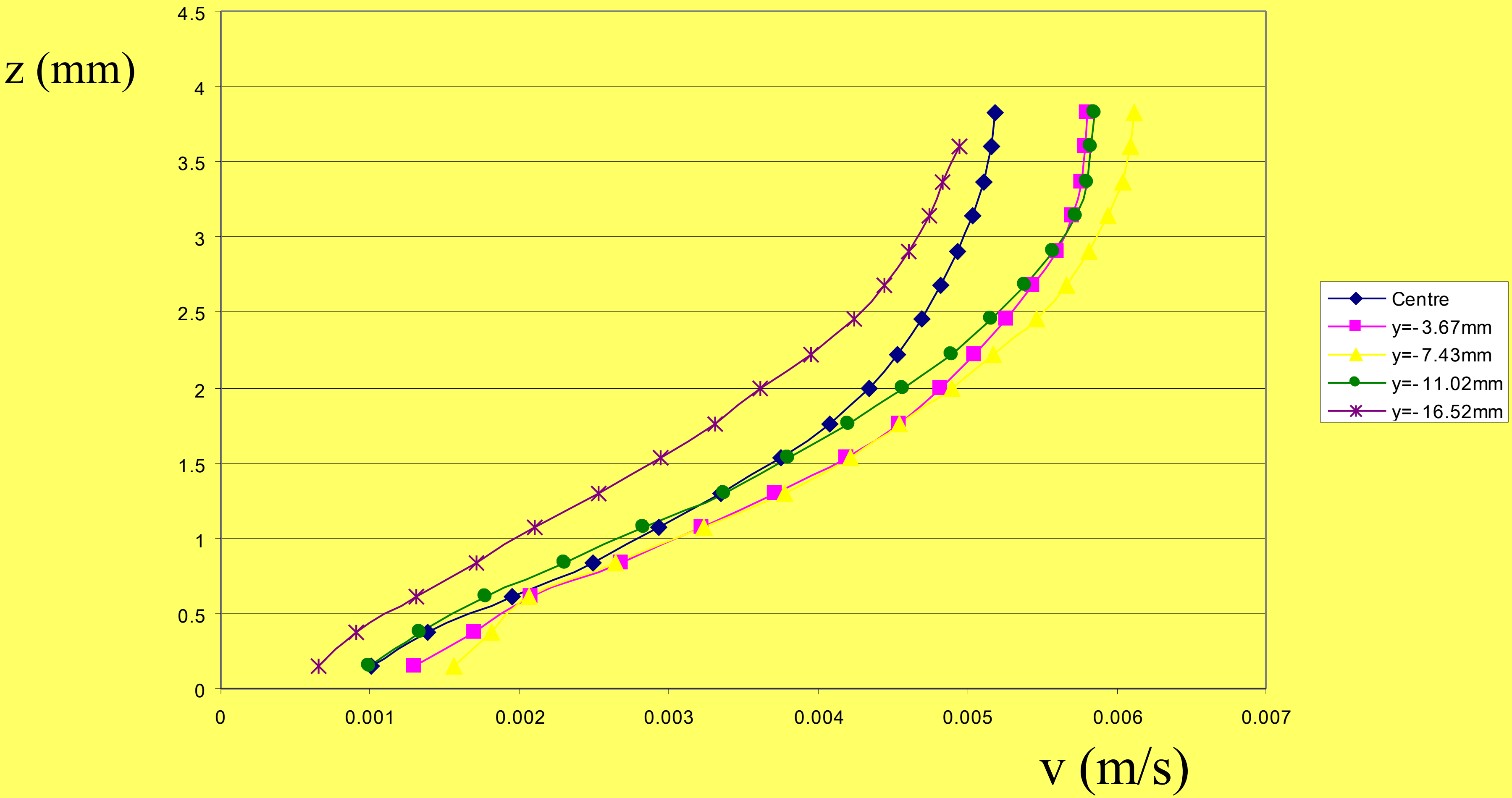
(Upstream of the center of the magnet)



$J_o = 25$ mA, Re = 75, h = 4mm

Velocity profiles as functions of z

(Downstream of the center of the magnet)



$J_o = 25$ mA, Re = 75, h = 4mm

Steady, two dimensional model
(likely to be useful for the upper regions of the fluid layer)

$$(u, v, w) = (u(x, y), v(x, y), 0)$$

$$\vec{B}_o = B_z^o(x, y)\hat{k}, \qquad \vec{b} = b_z(x, y)\hat{k}$$

$$\vec{j} = (-1 + j_x^i)\hat{i} + j_y^i\hat{j}$$

Governing equations, two dimensional model

$$\frac{\partial u}{\partial t} + \left(u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\frac{\partial p}{\partial x} + \nabla_{\perp}^{2} u - Ha^{2} \frac{\partial b_z}{\partial x} \; B_z^0$$

$$\frac{\partial u}{\partial t} + \left(u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} \right) = -\frac{\partial p}{\partial y} + \nabla_{\perp}^{2} v + \mathrm{Re}\, B_z^0 - Ha^{2} \frac{\partial b_z}{\partial y} B_z^0$$

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \qquad\qquad 0 = \nabla_{\perp}^{2} b_z - \left(u \cdot \nabla_{\perp} \right) B_z^0$$

$$j_x = M \frac{\partial b_z}{\partial y} \qquad j_y = -M \frac{\partial b_z}{\partial x} \qquad M = \frac{\sigma B o U_v}{Jo}$$

Magnetic field for a point dipole

$$B_z^o = \frac{\mu_o}{4\pi}\frac{3mz^2 - mr^2}{r^5} + \frac{2}{3}\mu_o m\delta(x)\delta(y)\delta(z)$$

Evaluated at z=0

$$B_z^o = -\frac{\mu_o m}{4\pi}\frac{1}{r^3} + \frac{2}{3}\mu_o m\delta(x)\delta(y)$$

Vorticity equation

$$\frac{\partial \omega_z}{\partial t} + \left(u \frac{\partial \omega_z}{\partial x} + v \frac{\partial \omega_z}{\partial y} \right) = \nabla_\perp^2 \omega_z + \mathrm{Re} \frac{\partial B_z^0}{\partial x}$$

Stream function

$$\nabla_\perp^2 \varphi = -\omega_z$$

Magnetic induction

$$0 = \nabla_\perp^2 b_z - \left(u \cdot \nabla_\perp \right) B_z^0$$

For small Re

$$\omega_z = \omega_z^{(o)} + \text{Re}\,\omega_z^{(1)} + \text{Re}^2\,\omega_z^{(2)} \ldots$$

$$u = u^{(o)} + \text{Re}\,u^{(1)} + \text{Re}^2\,u^{(2)} \ldots$$

$$v = v^{(o)} + \text{Re}\,v^{(1)} + \text{Re}^2\,v^{(2)} \ldots$$

A linearized solution may be attempted with

$$\omega_z^{(o)} = u^{(o)} = v^{(o)} = 0$$

Vorticity equation order Re

$$\nabla_{\perp}^{2}\omega_{z}^{(1)} = \frac{\partial B_{z}^{0}}{\partial x}$$

Stream function

$$\nabla_{\perp}^{2}\varphi^{(1)} = -\omega_{z}^{(1)}$$

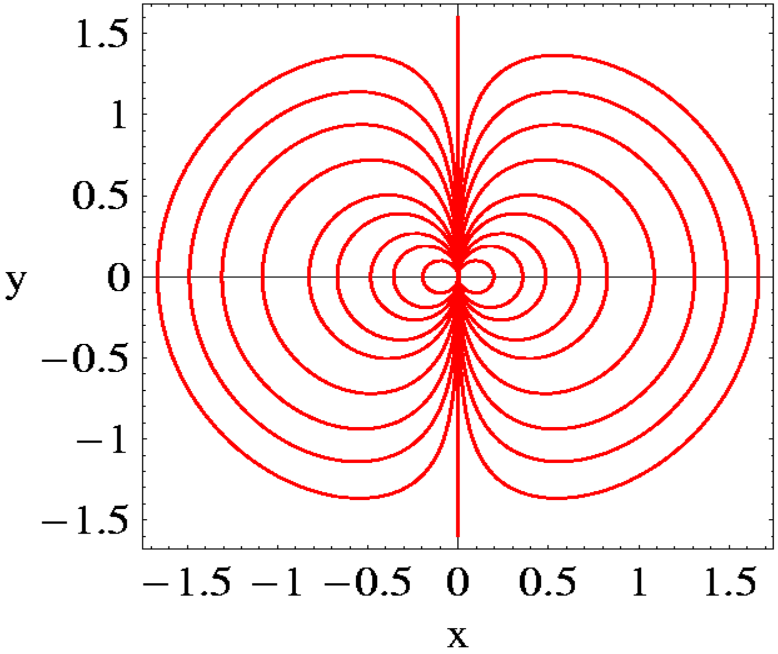
The solution diverges for r=0 and r→∞:

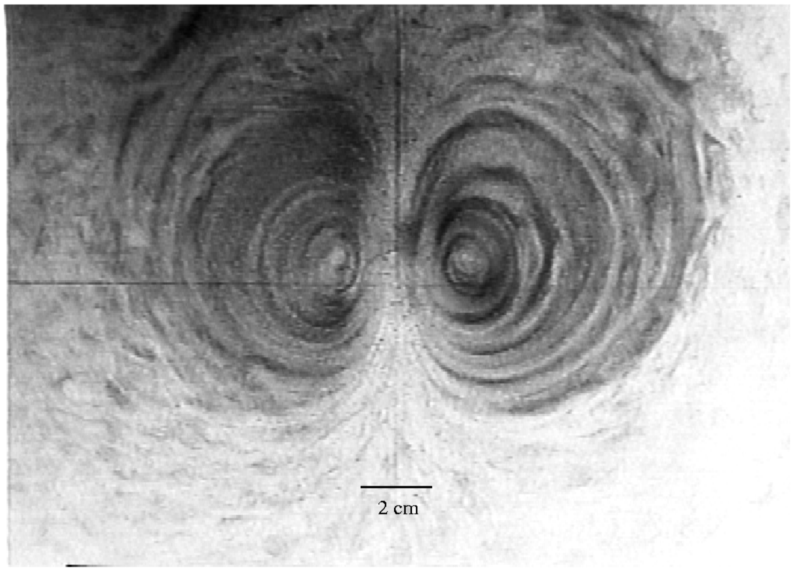
$$\varphi^{(1)} \approx r \ln r \cos\theta$$

similar to the Stokes paradox

The solution is not altogether usless...

GK Batchelor





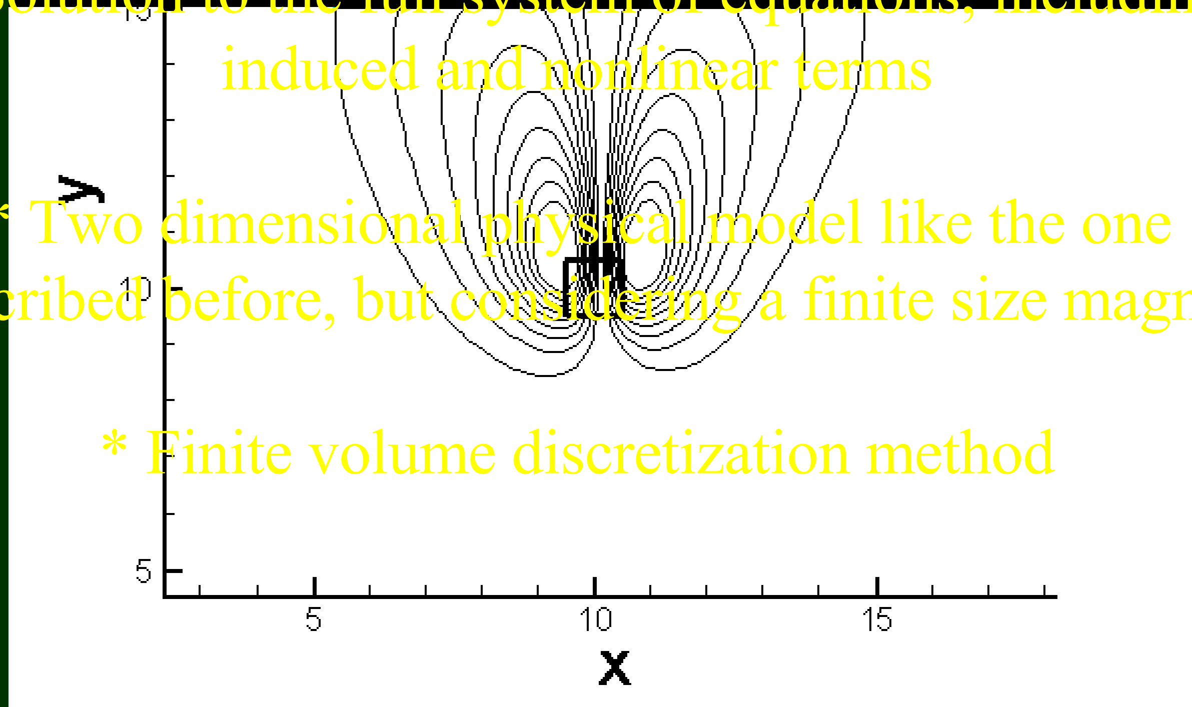
Salas, Cuevas & Ramos, Magnetohydrodynamics, **37** (2001)

Numerical solution is required

* Solution to the full system of equations, including induced and nonlinear terms

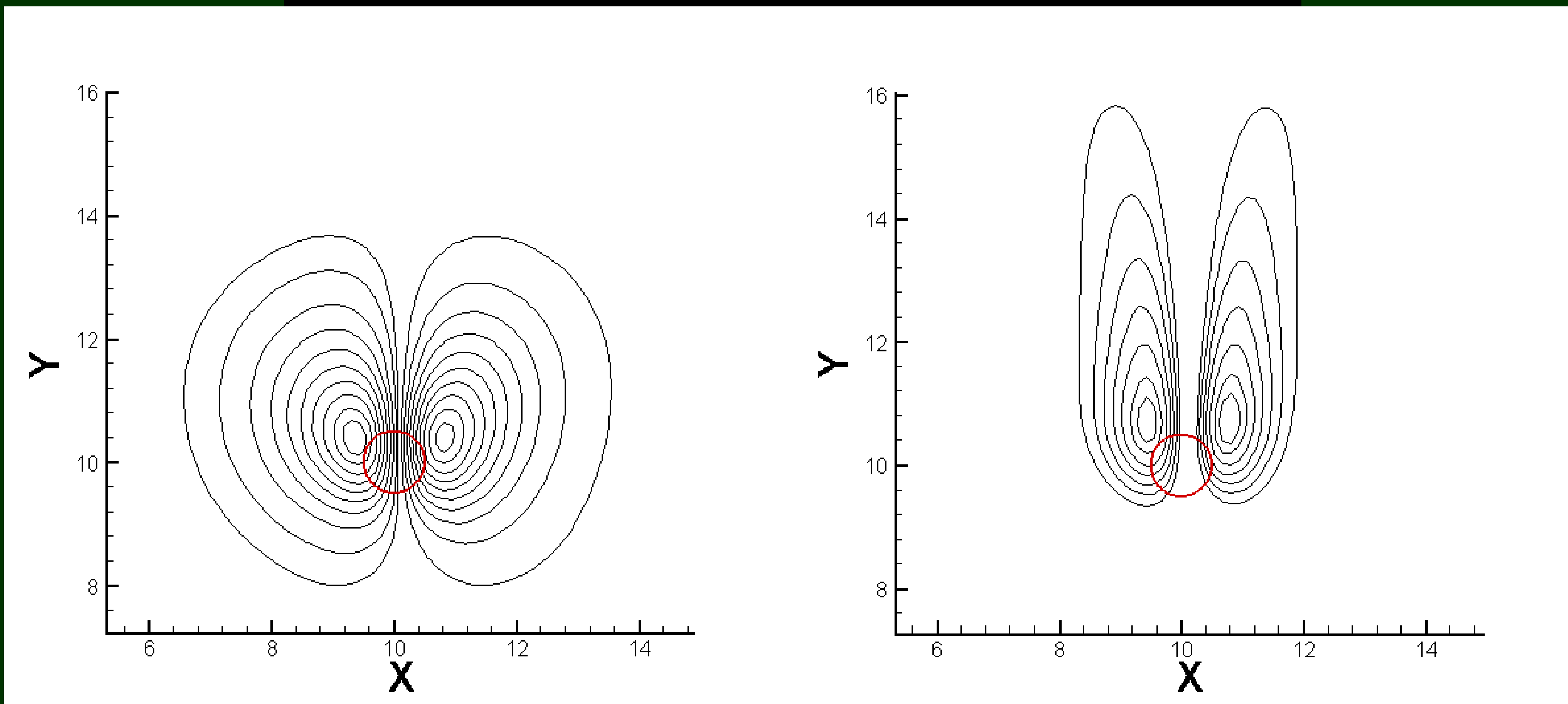
* Two dimensional physical model like the one described before, but considering a finite size magnet

* Finite volume discretization method



Numerical results

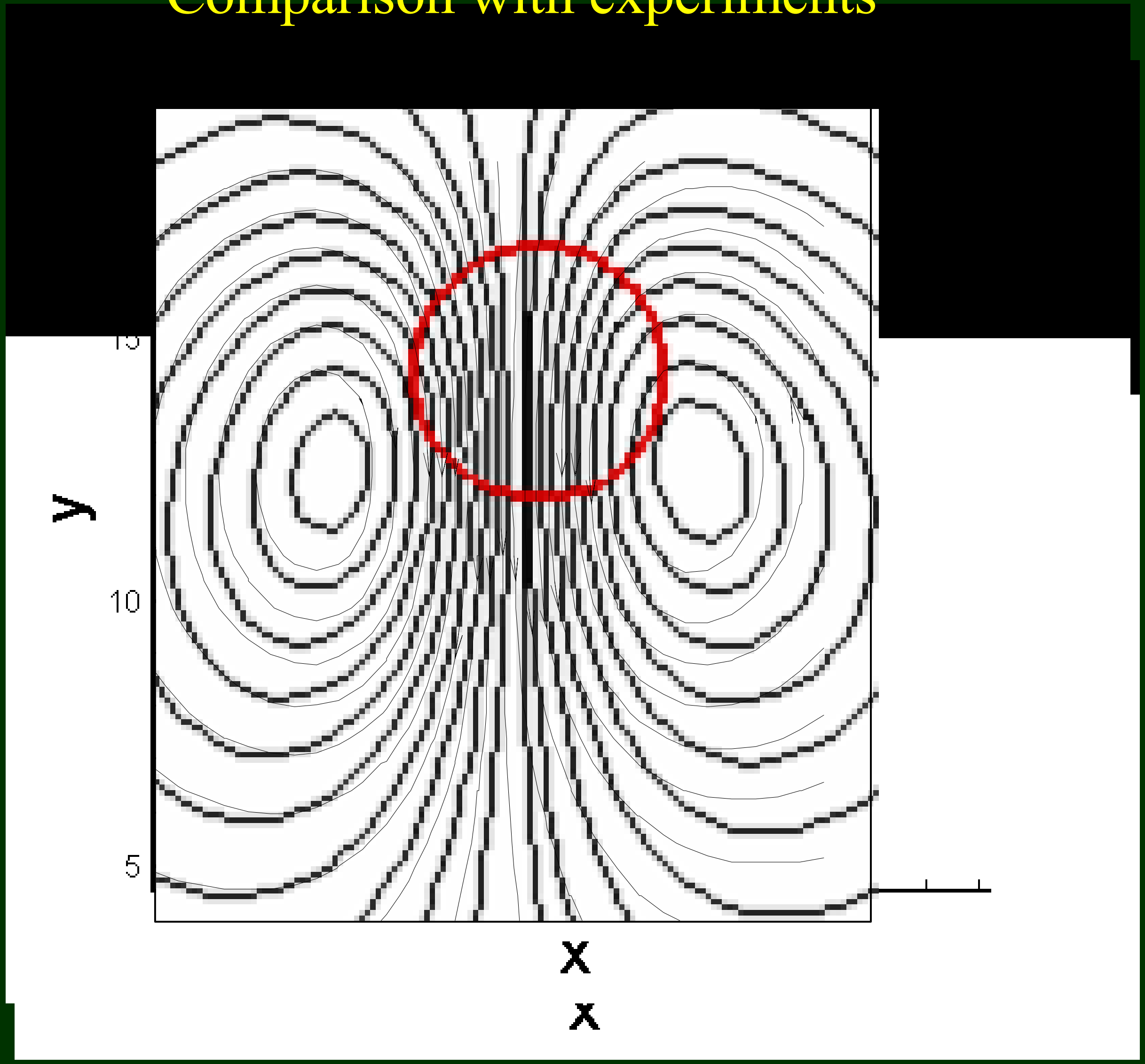
Stream lines dipolar magnetic filed



Re=60, Ha=0.2

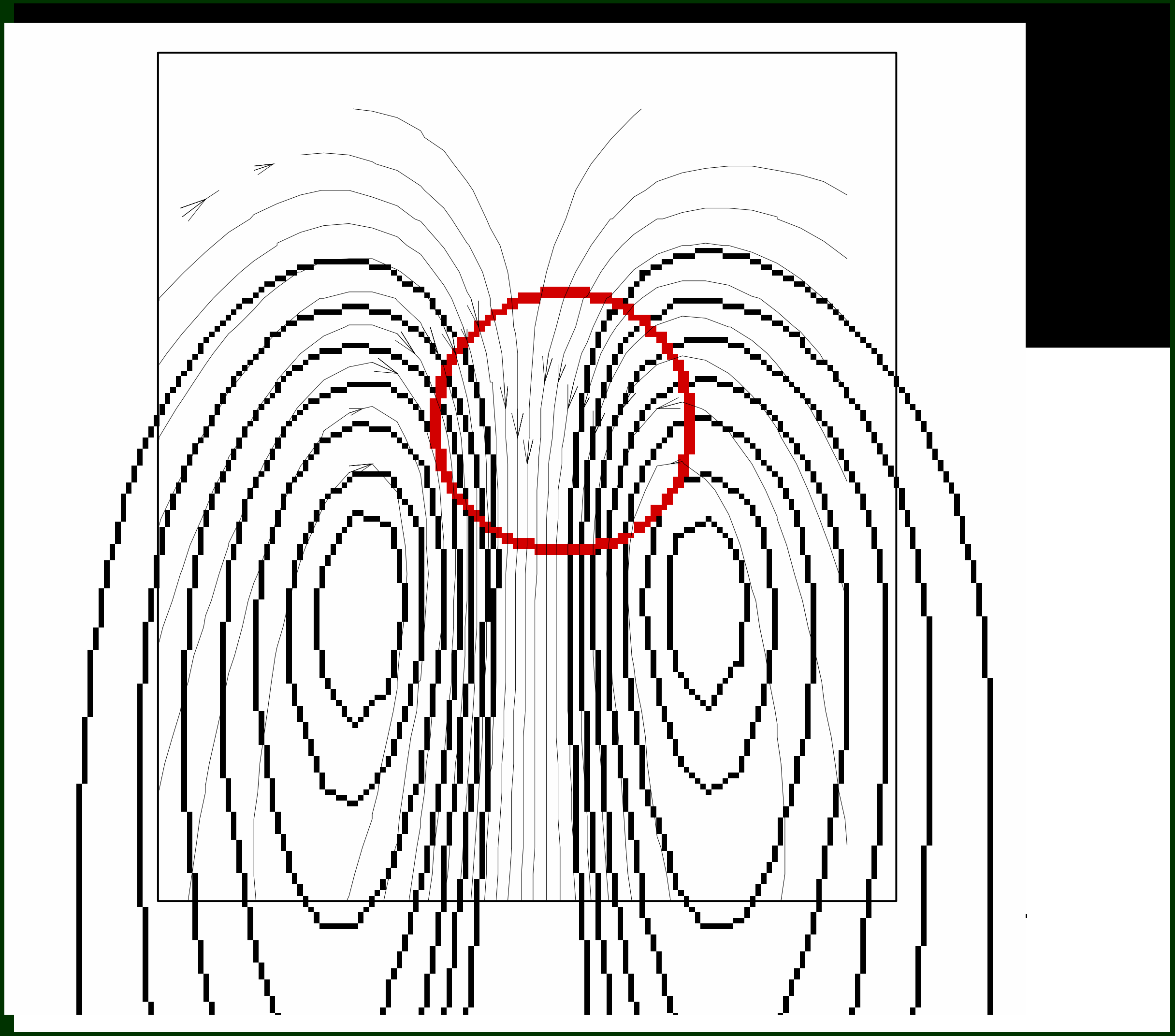
Re=300, Ha=0.2

Comparison with experiments



Re= 30 (60), Ha=0.2

Comparison with experiments



Re=300, Ha=0.2

Summary

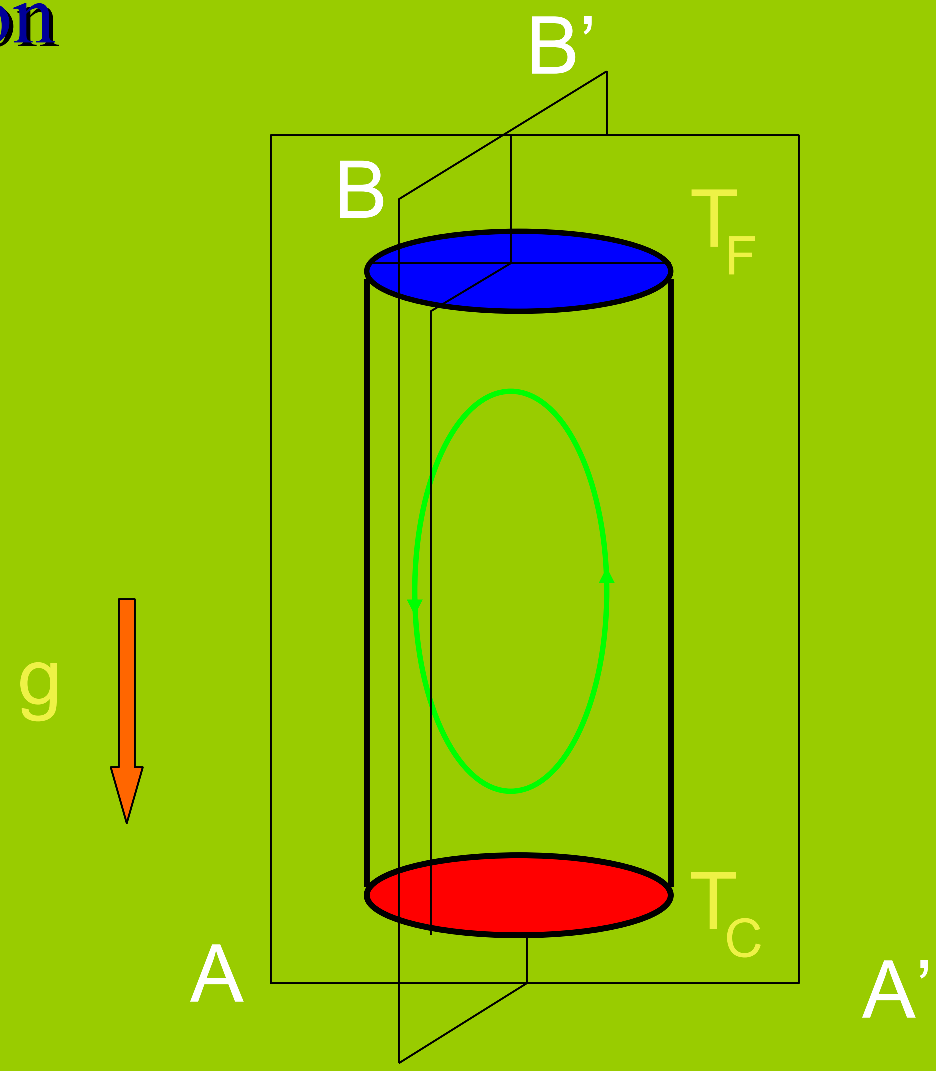
*A class of electromagnetically driven flows in shallow fluid layers has been observed.

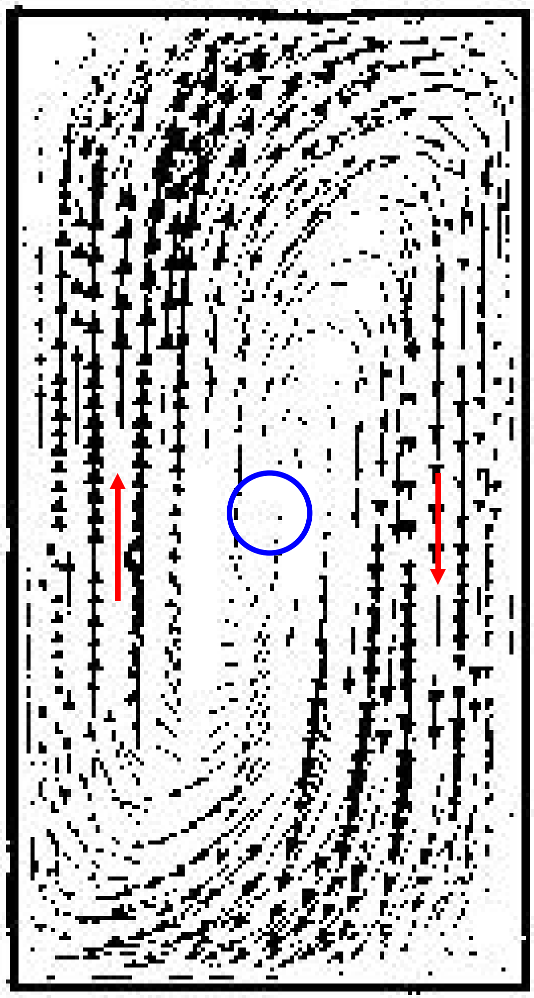
*For the experimental conditions examined, the influence of the bottom wall extends up to approximately 3 mm.

*A two dimensional model that includes nonlinear effects captures some features of the experimental observations.

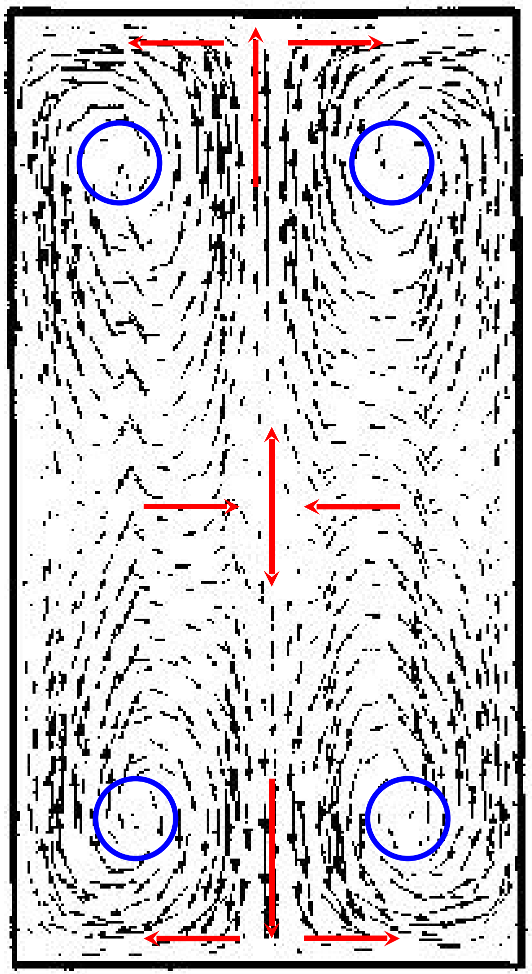
3. Natural convection in a centrifuge

No rotation



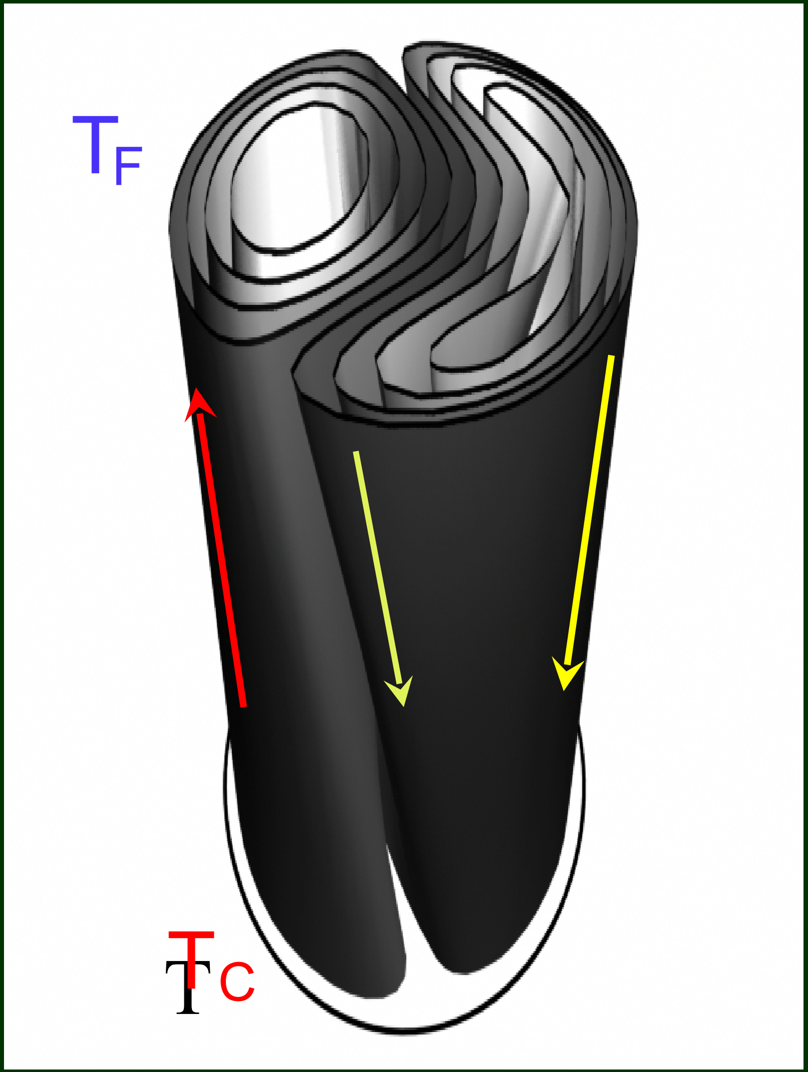


Plane AA’



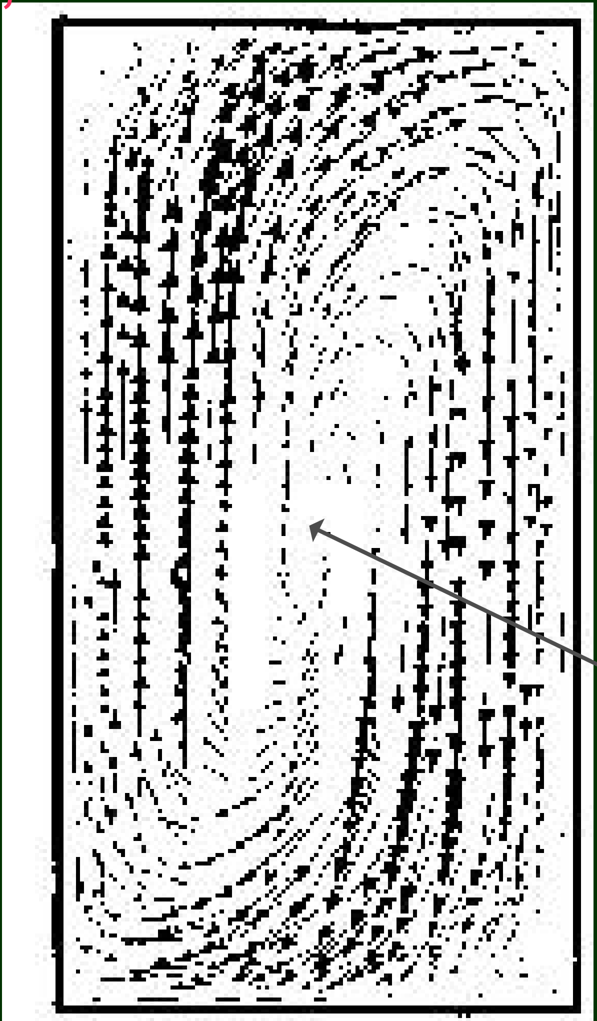
Plane BB’

Pr=6, Ra=7.5×10^4, A=0.25

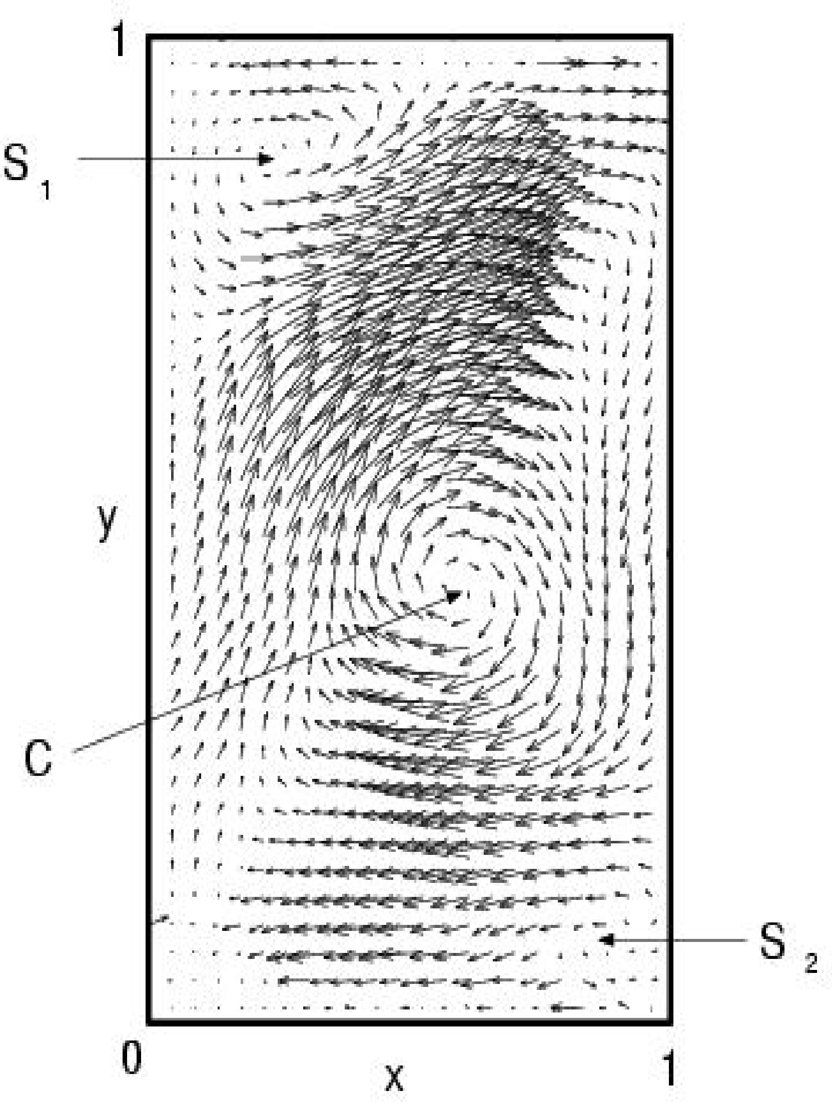


T_F
T_C

AA’

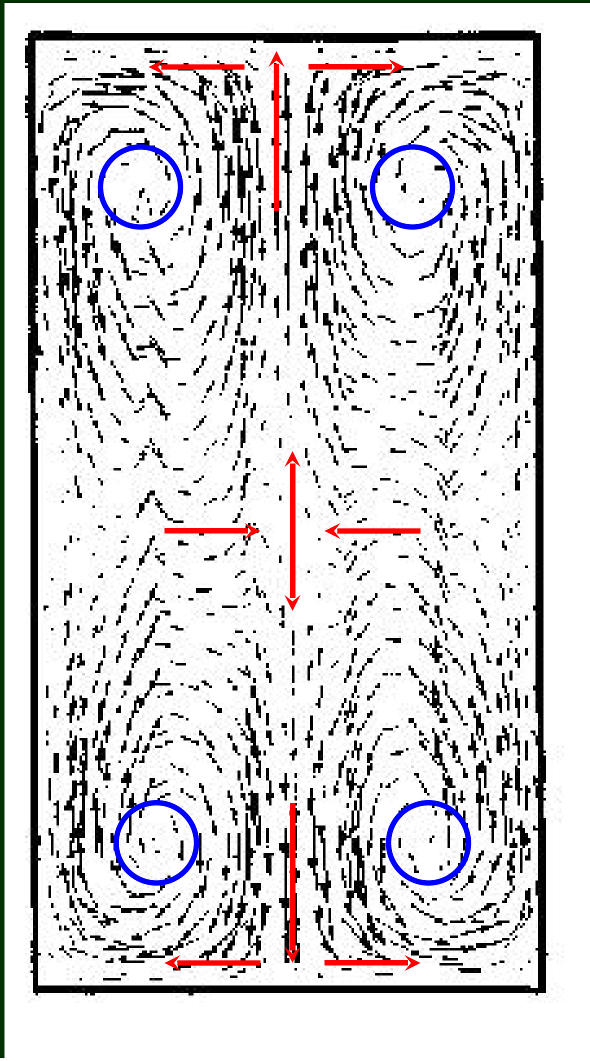


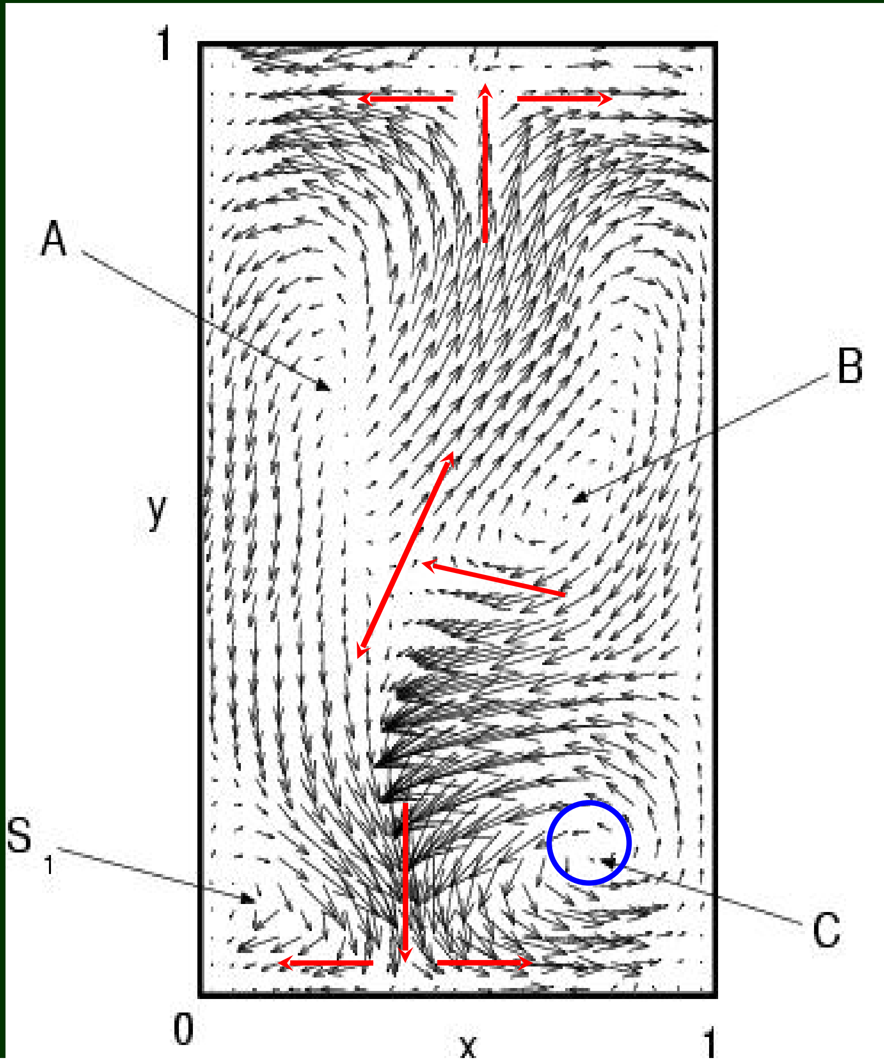
Teórico, $Ra \sim 5x10^5$



Experimento, $Ra = 2.5x10^6$

BB’

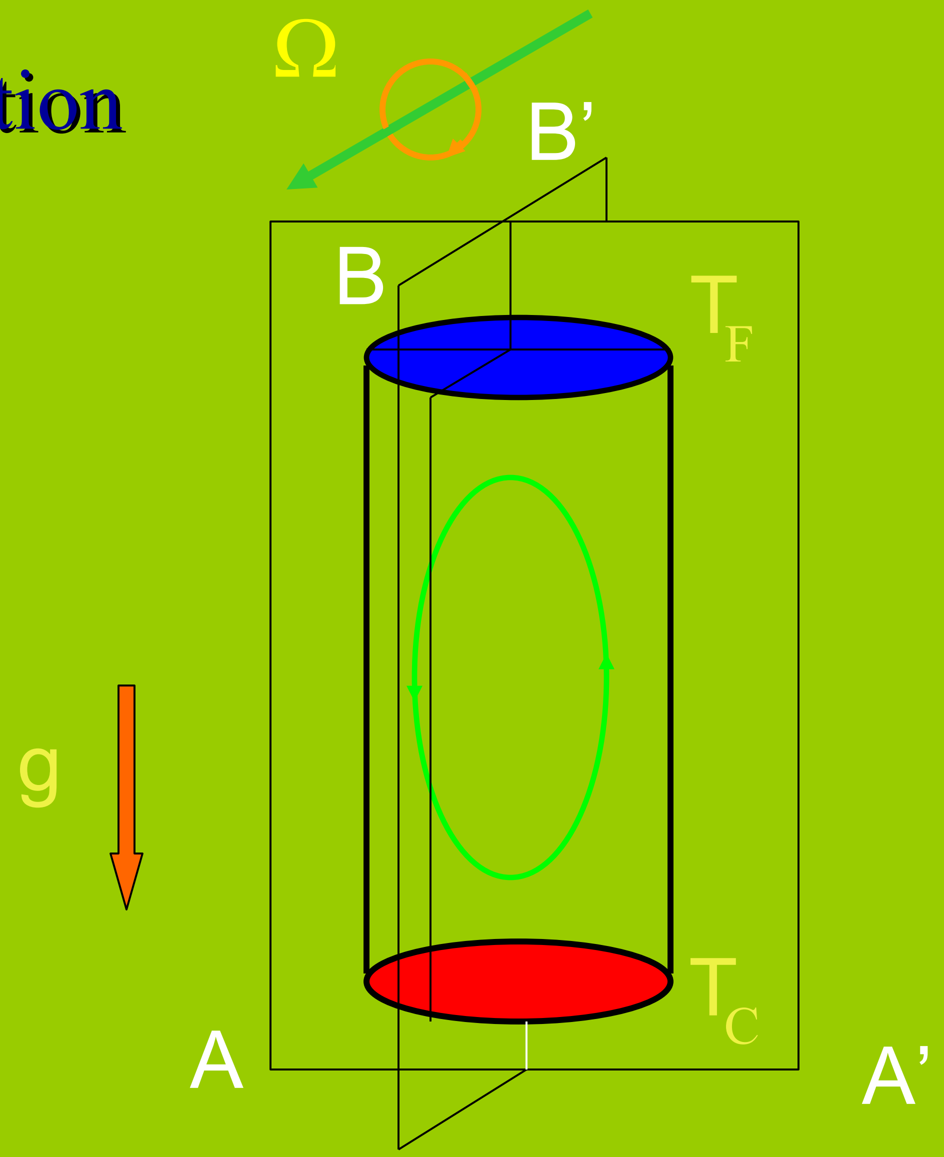




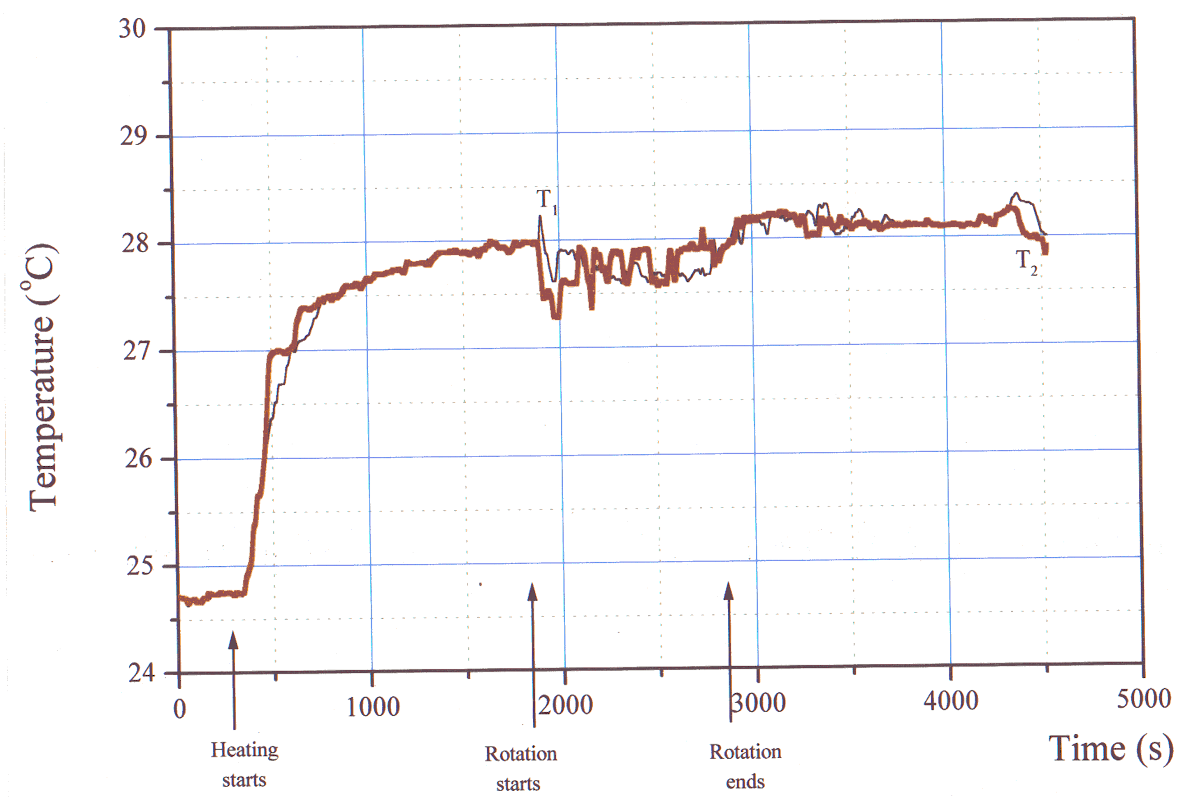
Teoría, Ra ~5x10^{5}

Experimento, Ra = 2.5 x 10^{6}

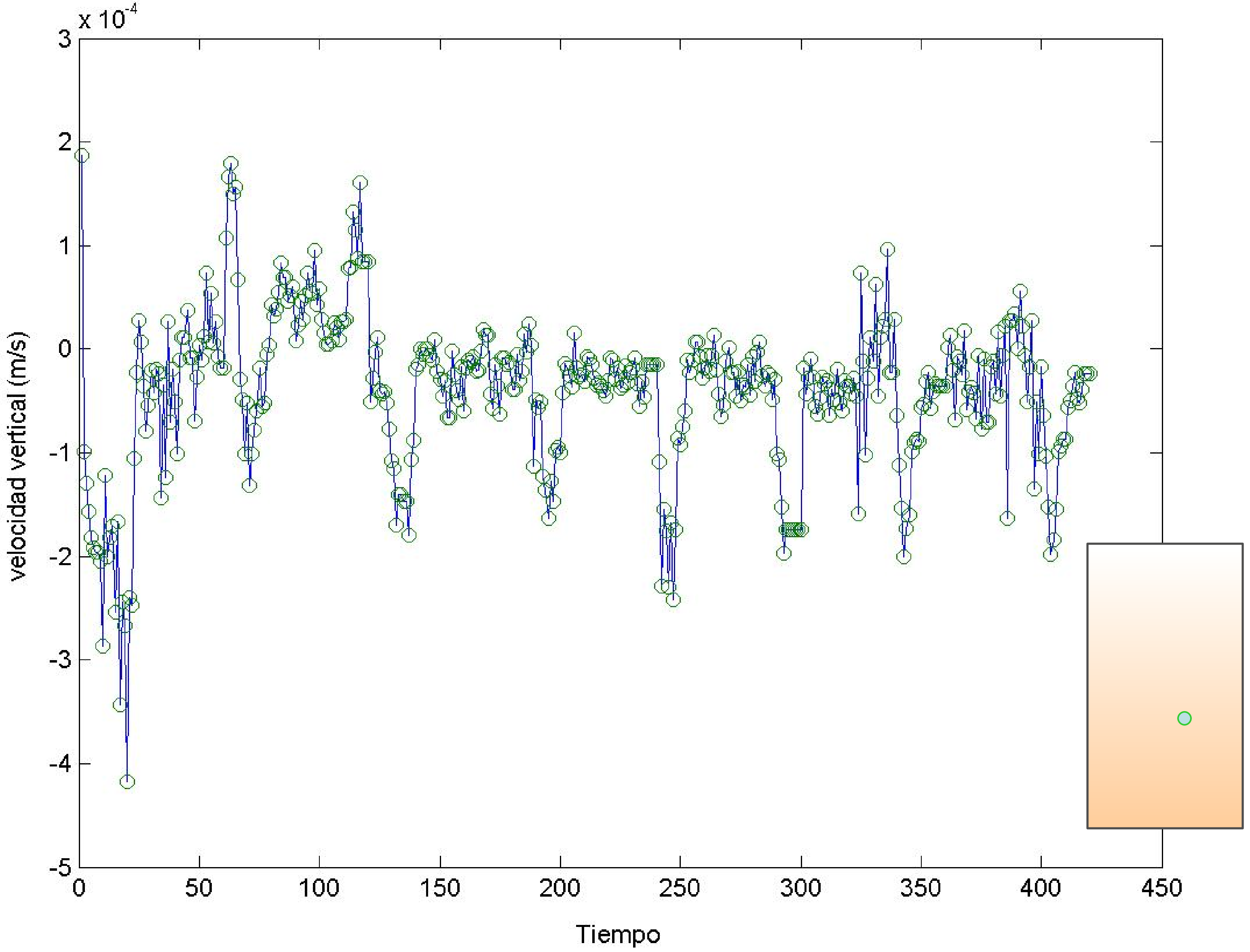
With rotation



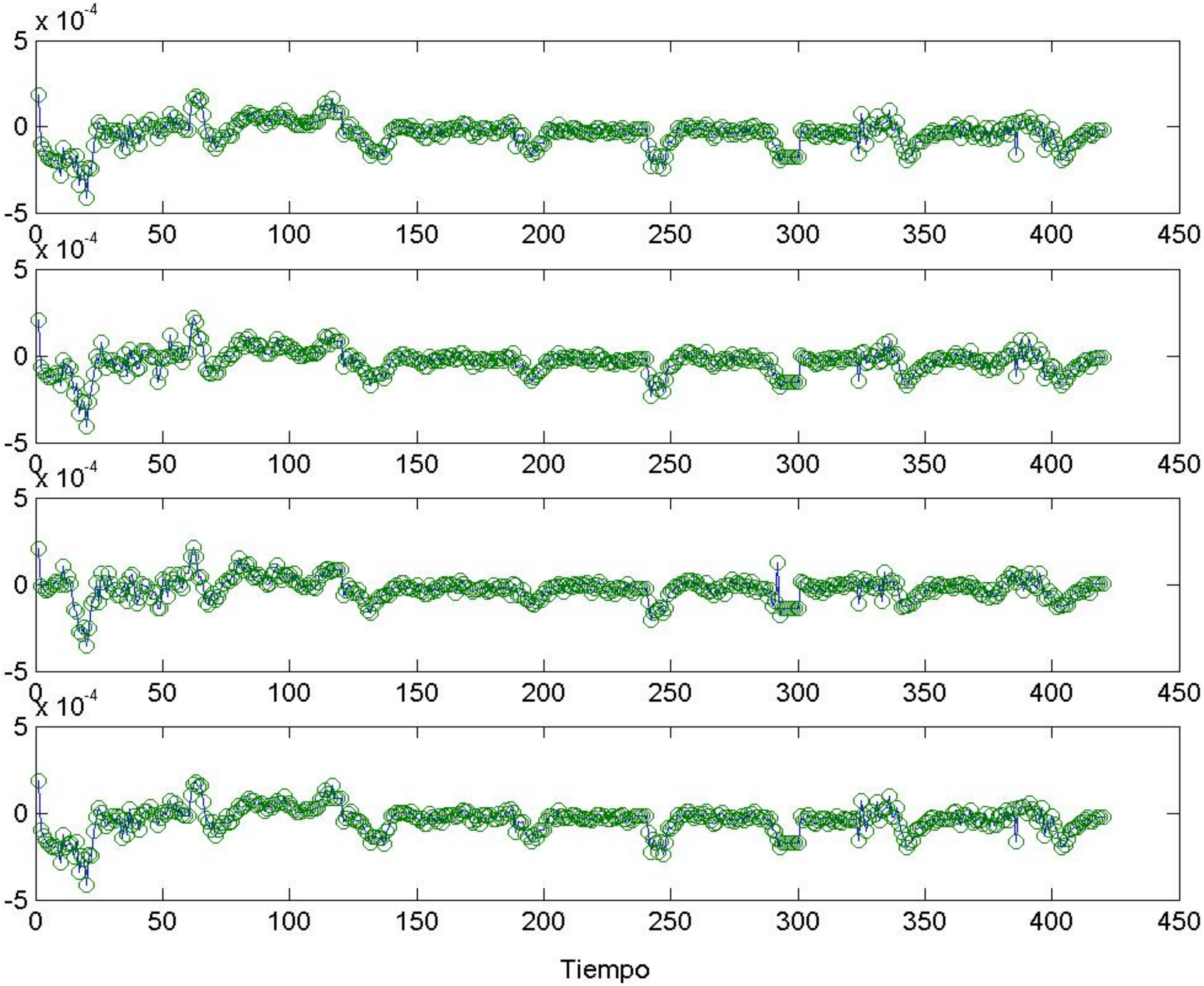
Centrifuge

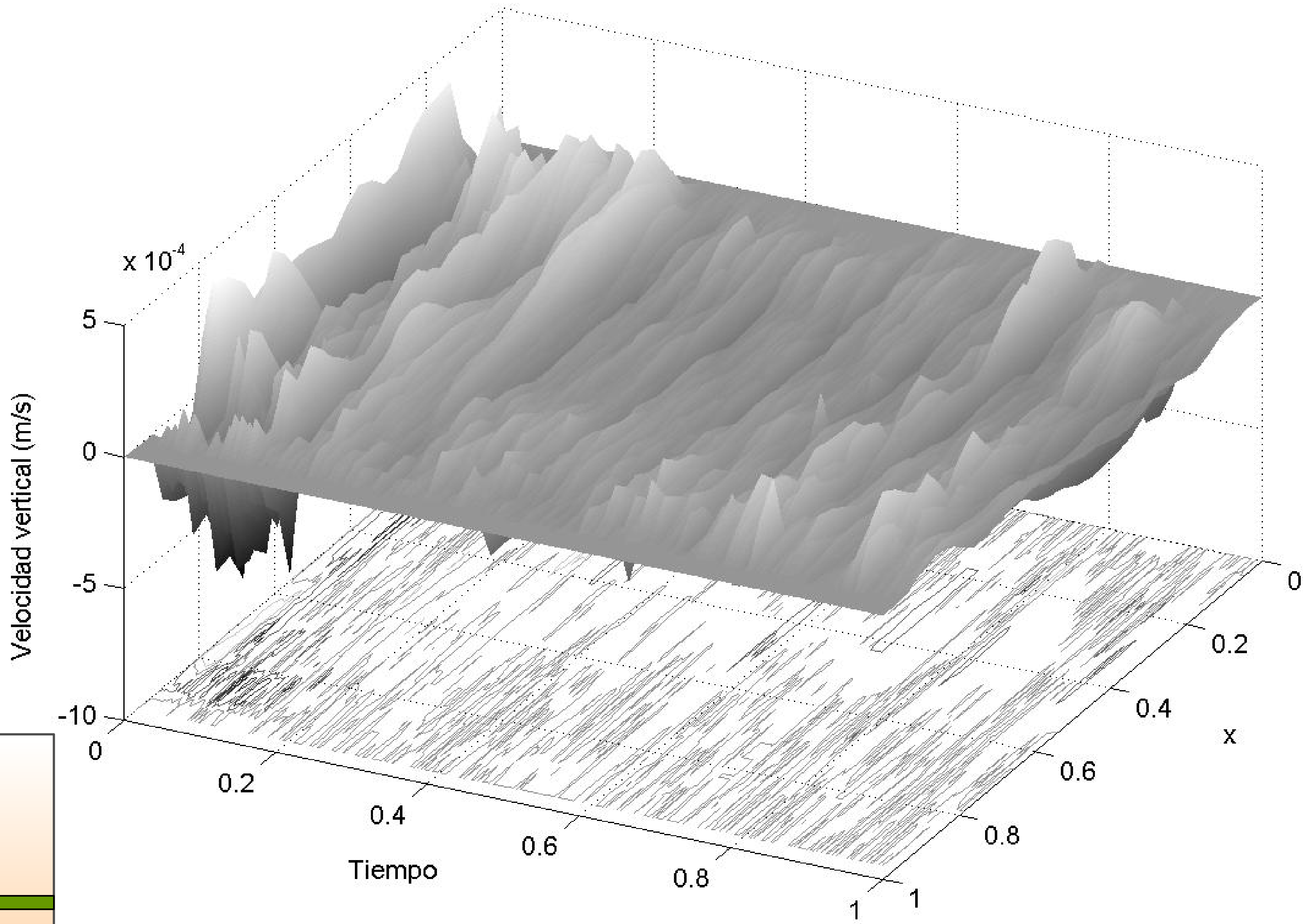


Pr=6, A=0.28, Ra = 2.5 x 10^4, Ta = 1.7 x 10^7

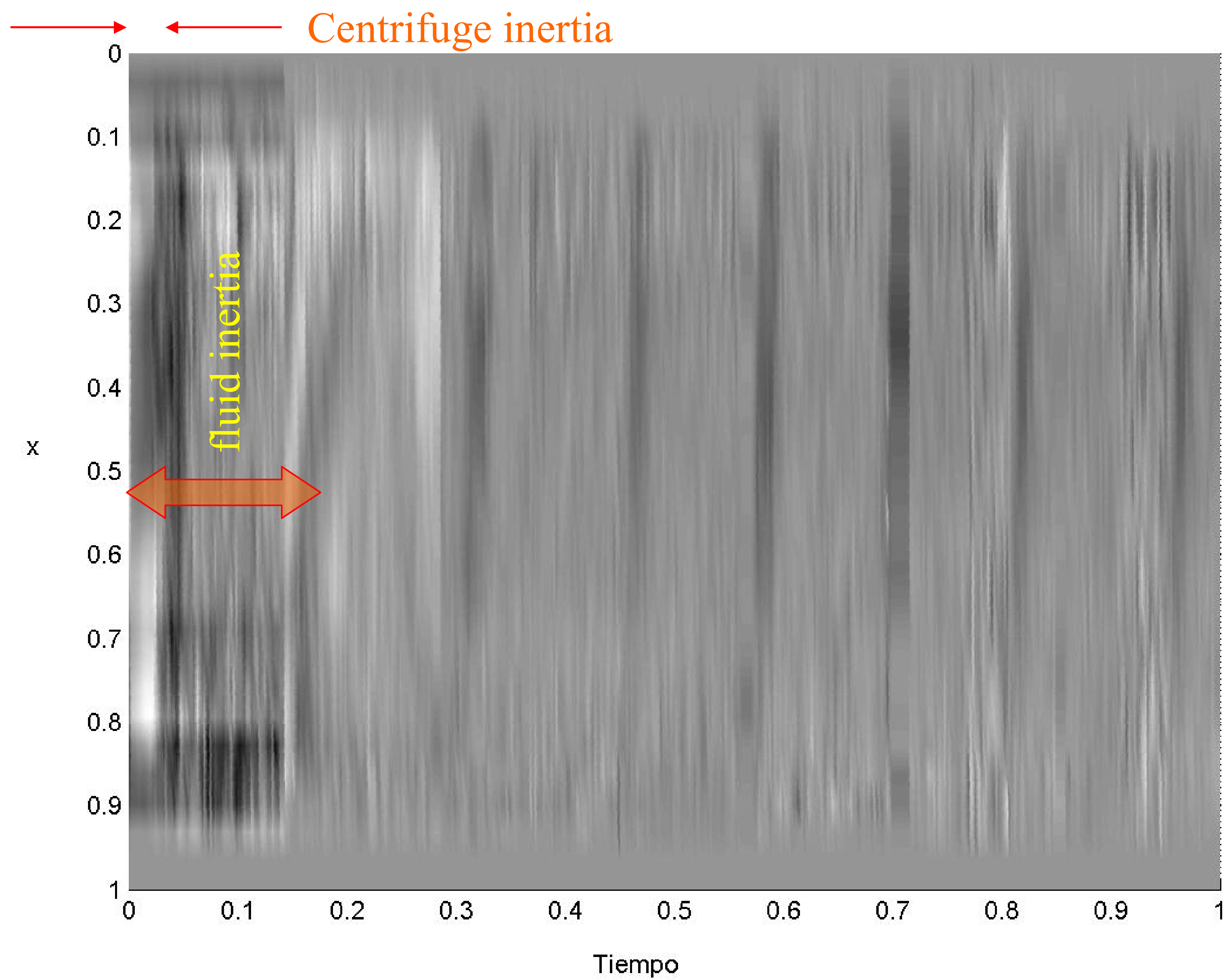


x 10^-4
3
2
1
0
-1
-2
-3
-4
-5
velocidad vertical (m/s)
0
50
100
150
200
250
300
350
400
450
Tiempo


x 10-4
5
0
-5
0
50
100
150
200
250
300
350
400
450
x 10-4
5
0
-5
0
50
100
150
200
250
300
350
400
450
x 10-4
5
0
-5
0
50
100
150
200
250
300
350
400
450
x 10-4
5
0
-5
0
50
100
150
200
250
300
350
400
450
Tiempo



x 10^-4
5
0
-5
-10
Velocidad vertical (m/s)
0
0.2
0.4
0.6
0.8
1
Tiempo
0
0.2
0.4
0.6
0.8
1
x



Centrifuge inertia
fluid inertia
x
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Tiempo

Summary

* **No Rotation**: One single, no axisymmetric cell (AA’), four vortices (BB’)

* **Rotation**: Time dependent flow, characteristic time 55 s.

The End