Investigating Coherent Structures of Quasi Two-Dimensional Flows Subject to Electromagnetic Forces
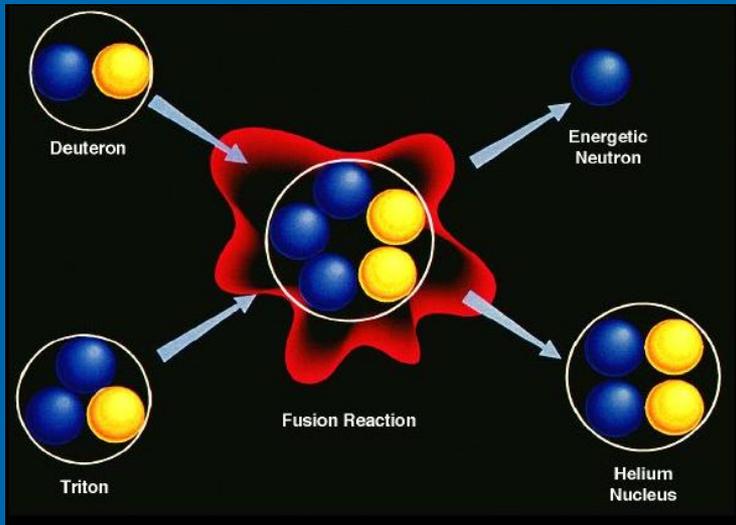
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Outline

- Introduction and Motivation

- Experimental setups, the square and cylindrical container & diagnostics: tracers, laser sheet

- Motion inside the square container: Generation of coherent vortices, secondary vortices and emergence of diagonal jets

- Motion inside the cylindrical container: stationarity and the flow dynamics

- Conclusion and Future work

2D turbulence in nuclear fusion

Deuteron

Triton

Energetic
Neutron

Fusion Reaction

Helium
Nucleus

Fusion requirements:

• High energy due to the mass difference ($E=\Delta m c^2$) between initial and final atoms.

• high density ($\sim 10^{20}$ m^{-3})

• High temperature (~ 10 keV)

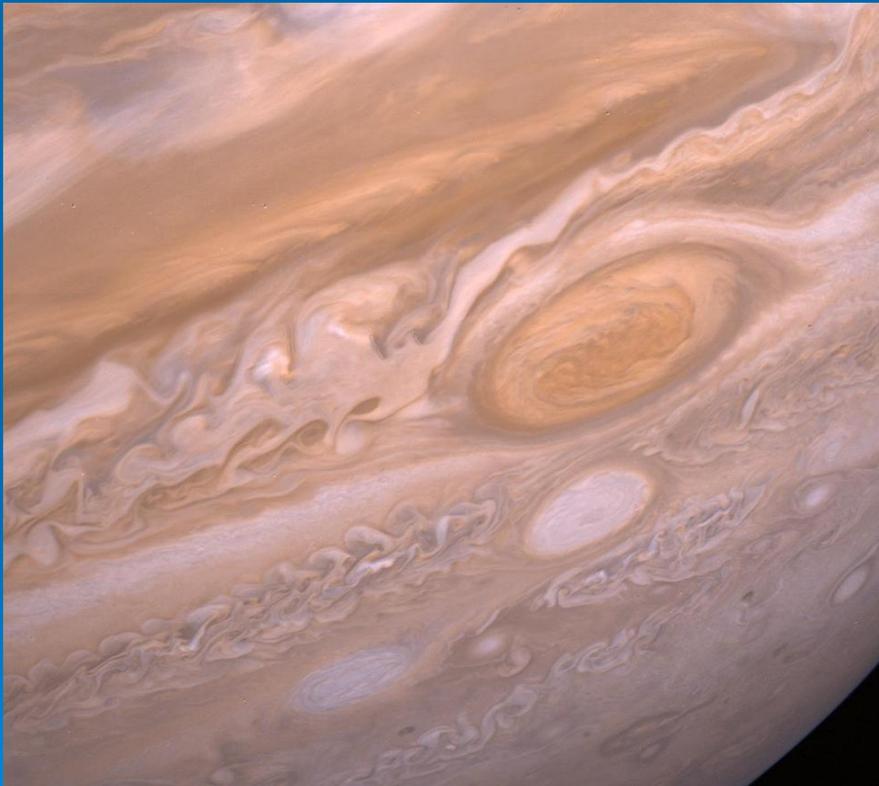• Long time particles and energy confinement.

Major Fusion problem:

• High level of particles and energy losses through turbulence occurring in the perpendicular direction to the main magnetic field.

• Turbulence in magnetic fusion devices is quasi-2D because of the strong toroidal magnetic field.

• *Need for a better understanding of 2D turbulence*
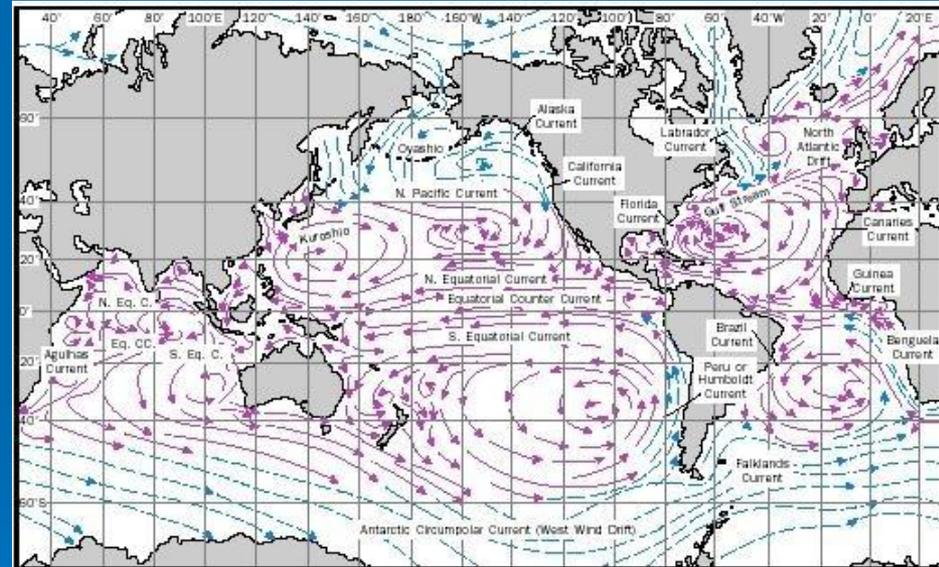

Un-confined region

Confined region
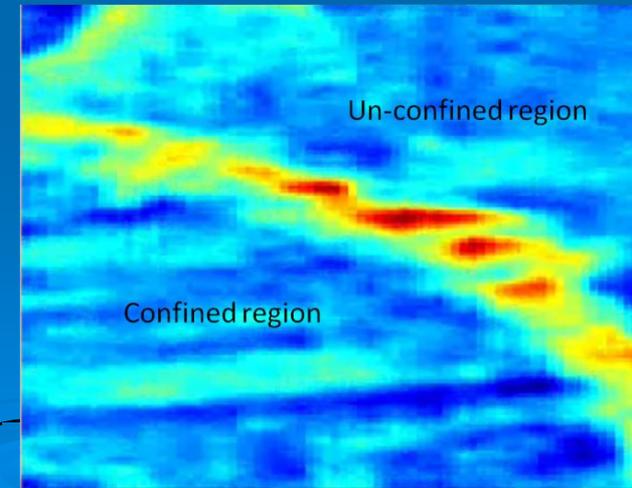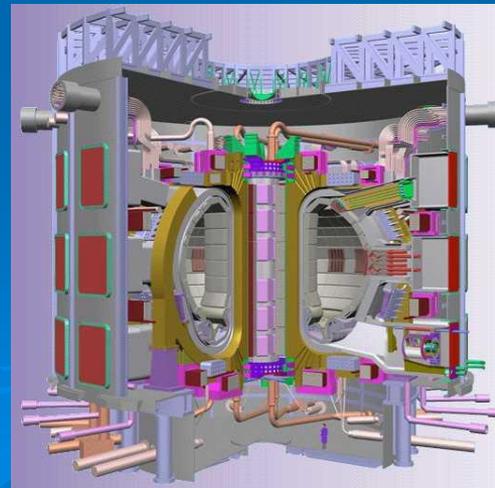
Atmospheric and oceanic turbulence

- Large scale motion of the atmosphere is driven by pressure and temperature gradients.

- The thickness of the atmosphere or the oceans is much smaller than planets radii


- Oceanic surface currents driven by winds.

- Frictional stress.

Atmospheric turbulence on Jupiter.

Motivation

➢ To reduce the loss of particles and energy by 2D turbulence in a tokamak, hence increasing its efficiency in producing energy

➢ To understand the atmospheric and oceanic circulation for weather predictions

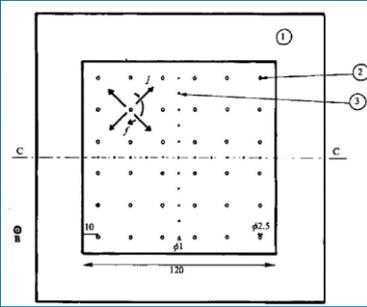➢ Simple experiments help to illustrate and understand large scale complex motion.
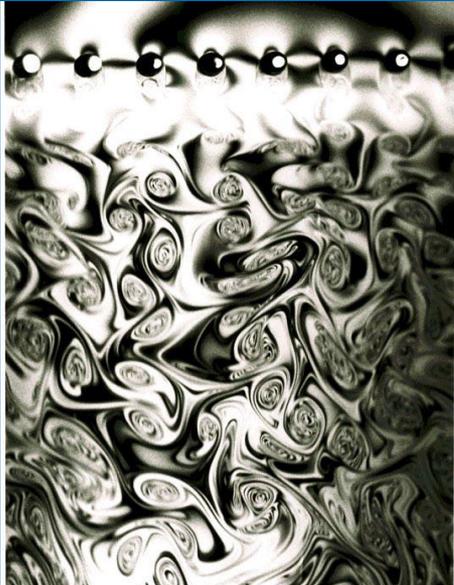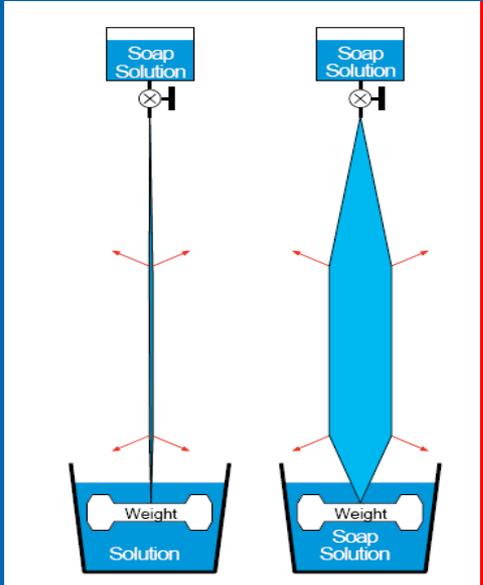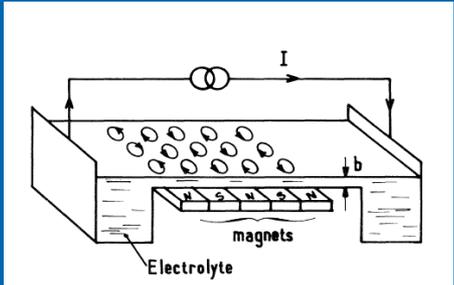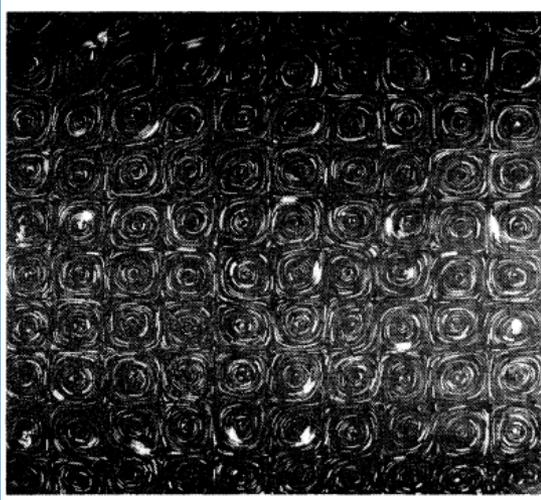
Soap films

Y.Couder, 1984, Two dimensional grid turbulence in a thin liquid film, J.Physique Lett. 45, 353

Lorentz force driven experiments

J.Sommeria 1986 J.Fluid Mech.170, 130

OUR GOALS

1- Build new experimental setups for turbulence studies and install adequate diagnostics

2- Develop numerical codes to analyze the flow: flow images, velocity field, distribution functions, statistics

3- Open up the possibility to study accurately the quasi two-dimensional properties of the flow

A new concept: Two-dimensional electromagnetic forcing to study Quasi-2D dynamics

➤ A transparent electrically non conducting container is filled with <u>conducting solution</u>

➤ <u>Electrodes</u> are inserted at the inner edges of the tank.

➤ An upward axial <u>magnetic field</u> created by permanent magnets or electromagnets.
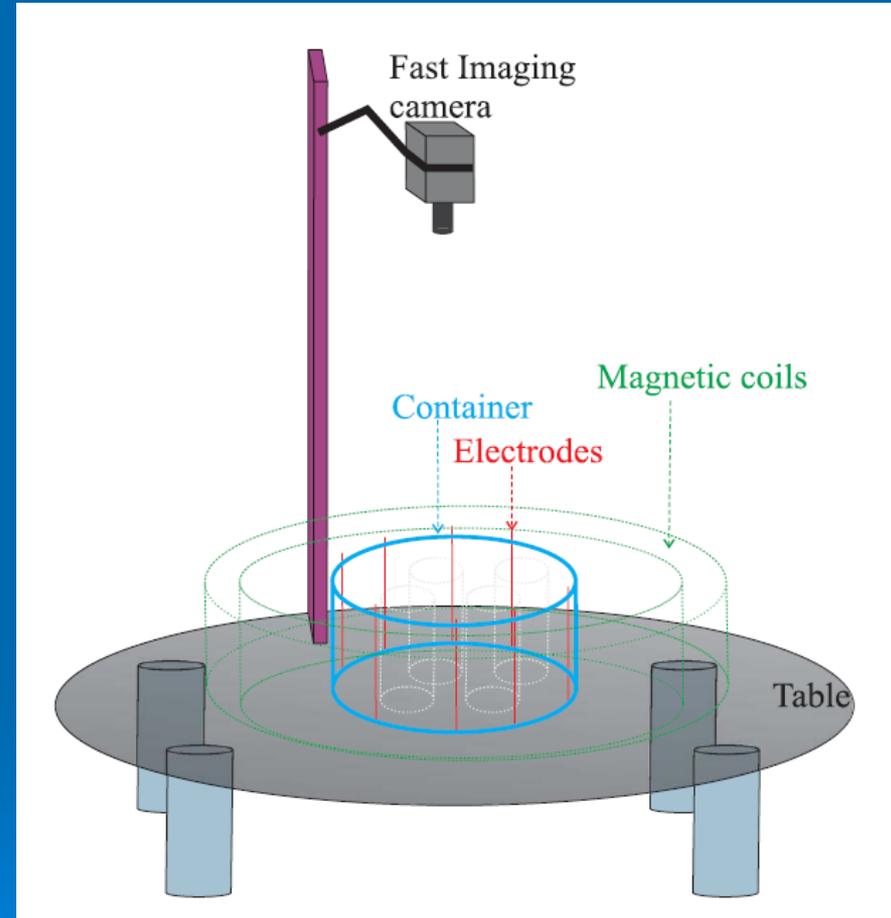
52 electrodes inserted at the 4 edges of the container, connected to a DC power supply, creating the driving electric field between consecutive electrodes separated by 2 cm
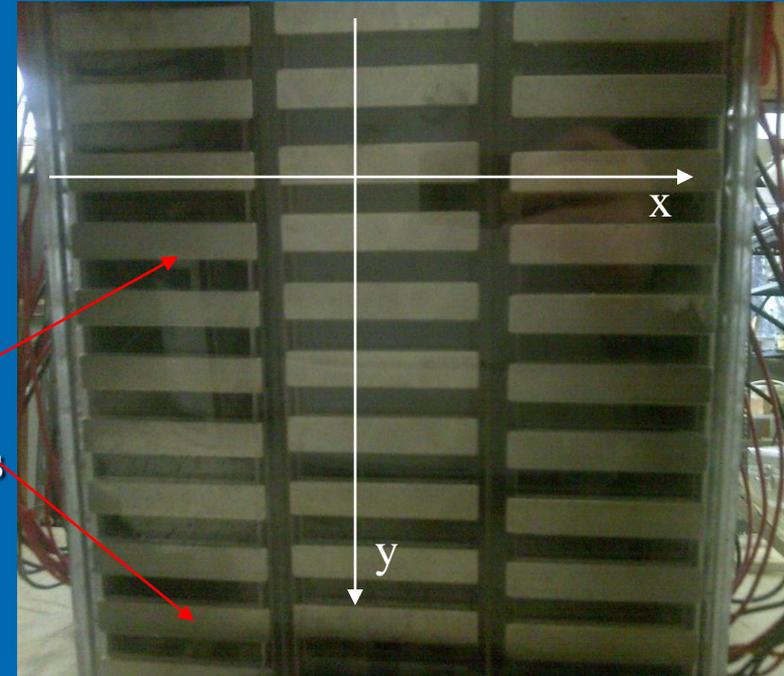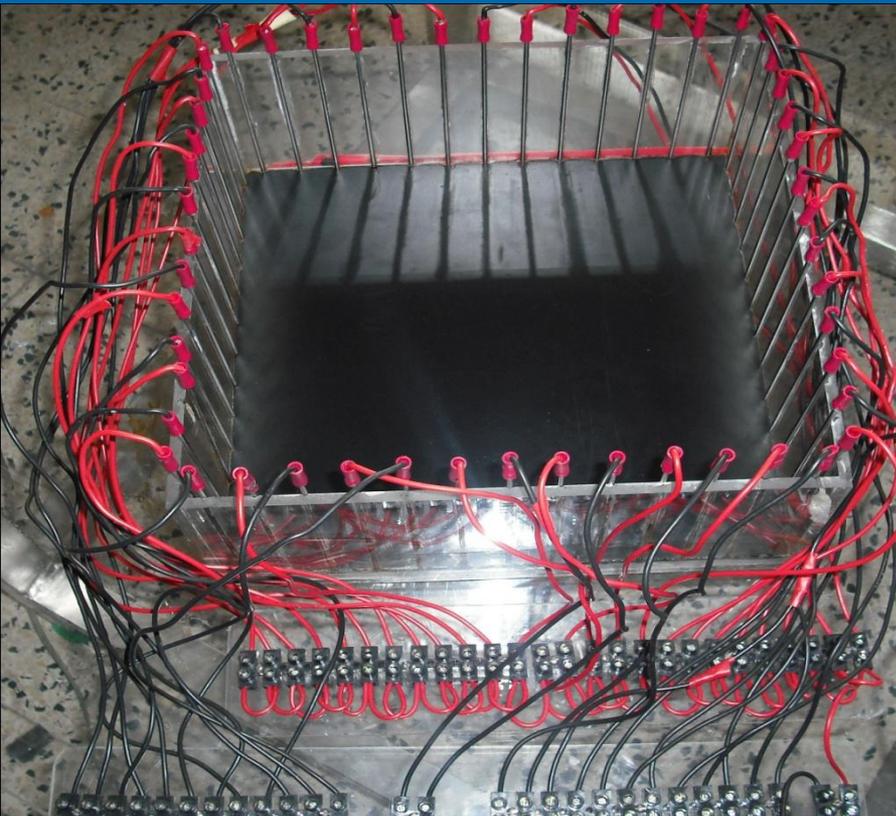
Bar

magnets

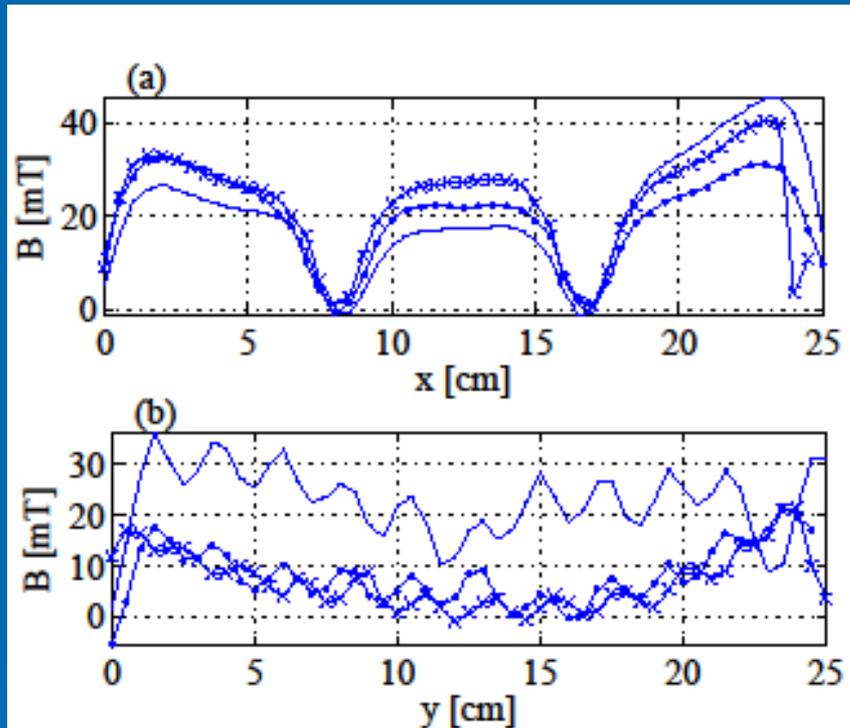<u>Permanent magnets inserted from below:</u>
Made of Neodymium.
Dimensions: 7.62cm×1.27 cm×0.63 cm.
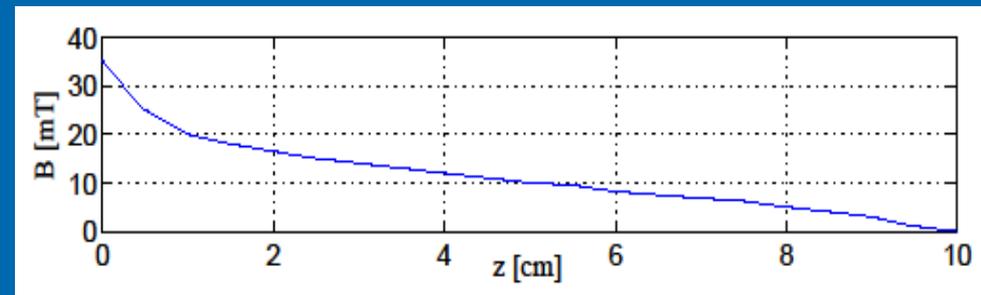Magnetic field on top of a magnet: 250 mT.

Magnetic field measured in the *x* and *y* directions

Magnetic field in the z direction

Conductive Solution: Potassium Hydroxide (KOH) dissolved in distilled water

Maximum conductivity at 27% of water mass is: $\sigma = 550 \, \text{Siemens/m}$
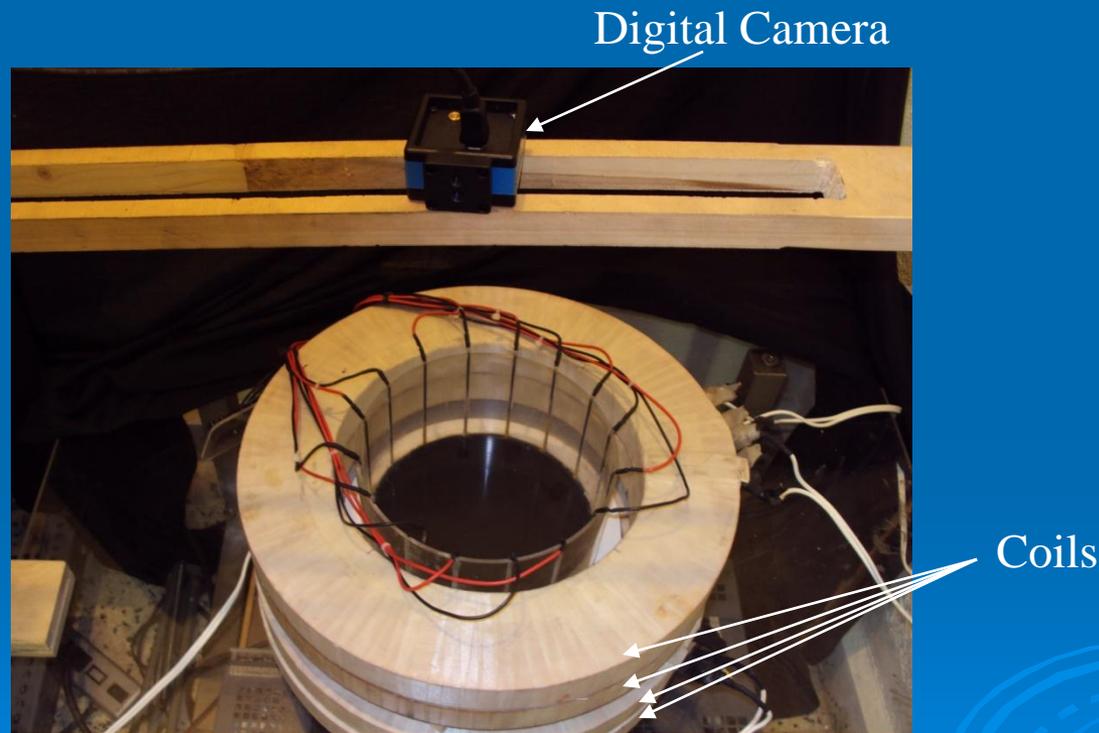
Solution density: $\rho = 1000 \, \text{Kg/m}^3$

Solution magnetic permeability: $\mu = 1.256 \times 10^{-6} \, H/m$

Solution kinematic viscosity: $\dfrac{v}{\rho} = 10^{-6} \, \text{m}^2/s$

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The Cylindrical Container

- Cylinder of diameter 20 cm made of Plexiglas.
- 16 electrodes inserted at the edge => distance between two electrodes = 3 cm
- Four coils surrounding the container create the required magnetic field.
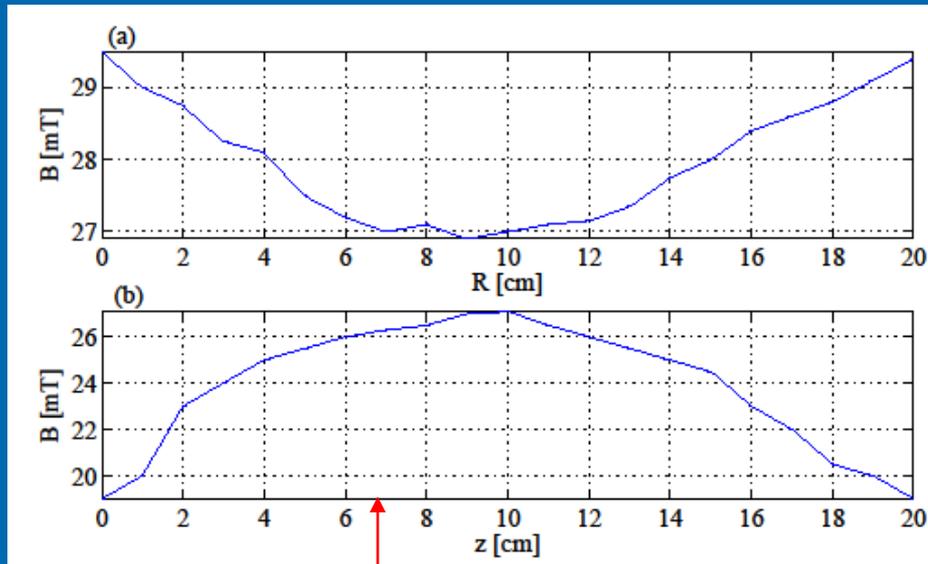
Digital Camera

Coils

- *Between the upper two coils and the lower two coils, a 5 cm spacing is left for the laser sheet.*
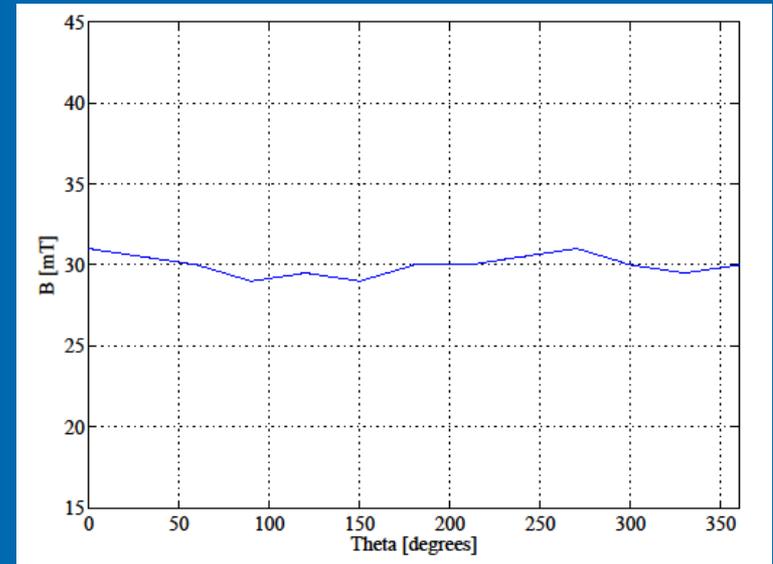
Axial magnetic field

Axial magnetic field

Bottom of the container at $z = 7$ cm

• Almost constant dependence on r

• Almost constant dependence on z

Constant magnetic field at the edge of the container as a function of the poloidal angle

Markers of the Flow:
1- Dye with uniform white light
## 2-Glass beads with a laser sheet

Glass beads:

- Neutrally buoyant spherical glass beads (40-60μm diameter)
- Seeding the fluid with beads and using a laser sheet follow their dynamics with time

Electro-magnets

Container

Laser

Cylindrical lens
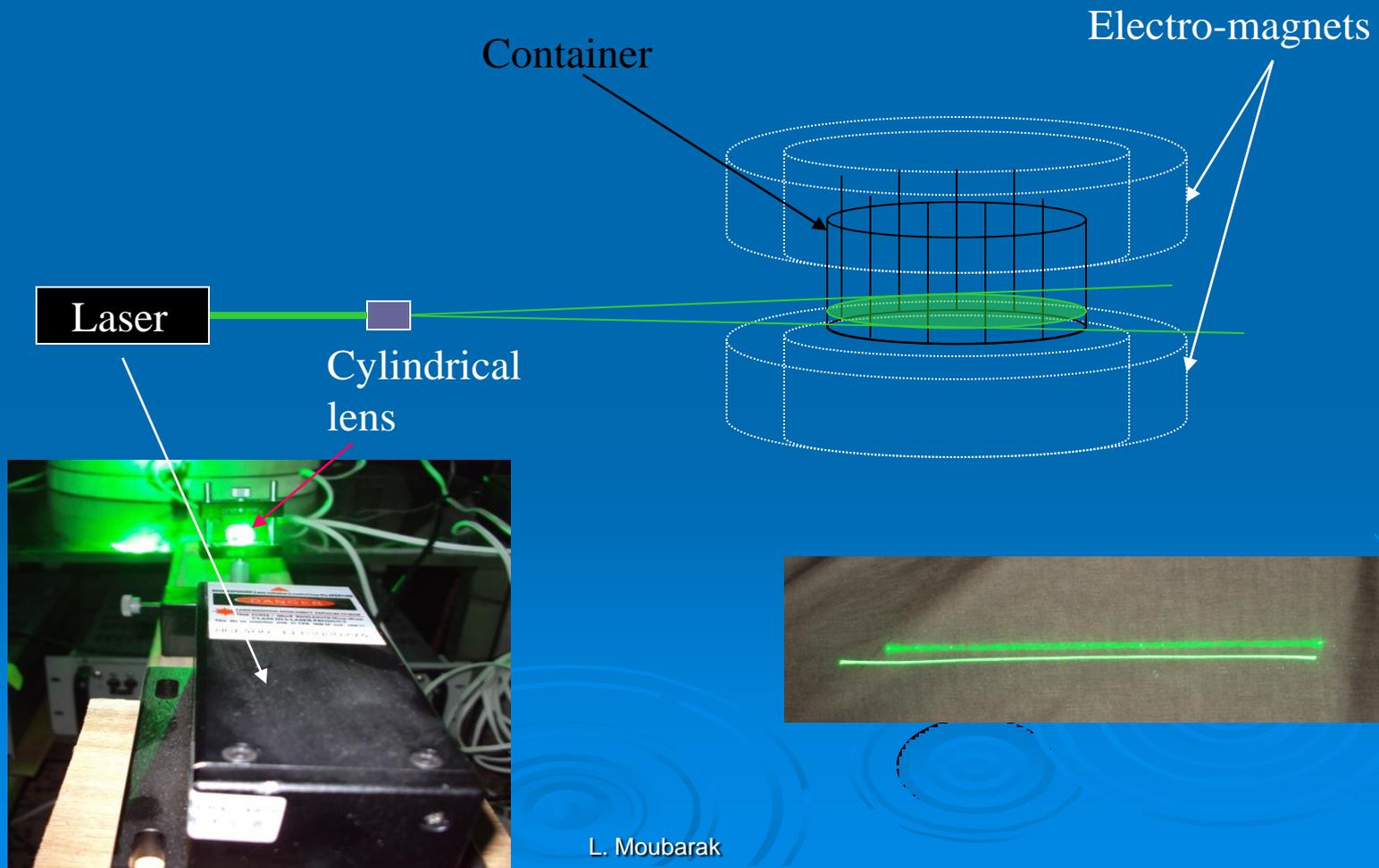
Velocity Field Measurement (PIV) when using Glass beads + laser sheet

1. Area selection, for example 50x50 pixels

2. Filter the selected area in the two frames.

3. Select the maxima from each frame

4. Select distances that are smaller than D_{max} and greater than D_{min}

5. Get the velocity from the travelled distance
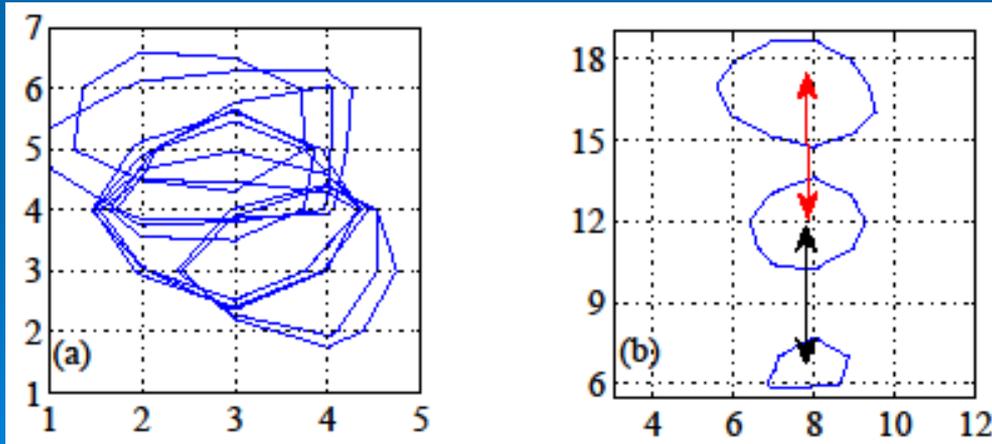
Minimum distance, D_{min}, is determined from the light fluctuations without motion.

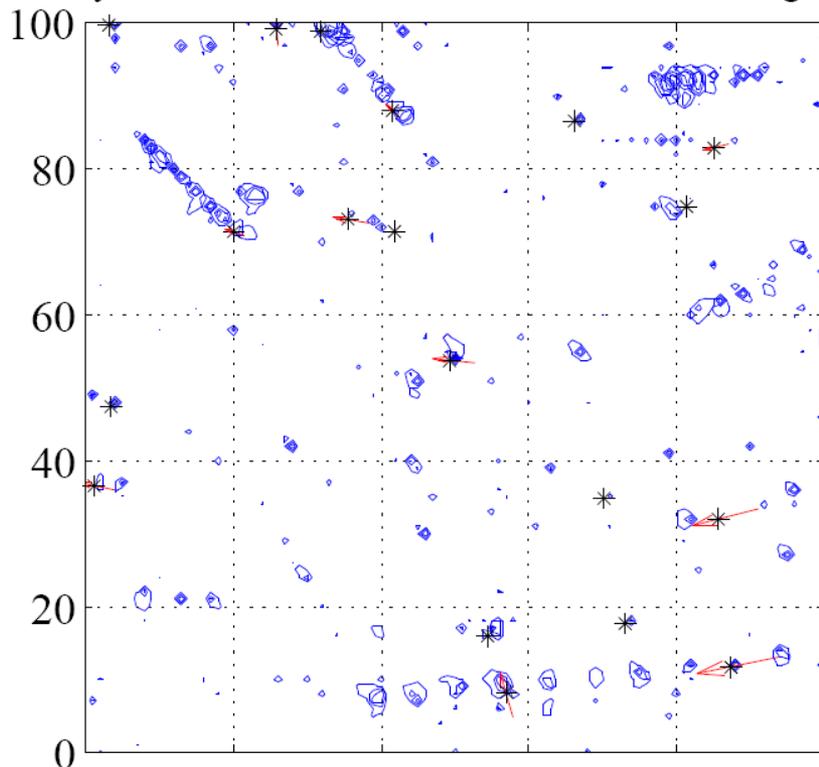Maximum distance, D_{max}, is obtained by the visual inspection of the motion.

(1), 10 contour plots (blue)

(2) Maxima of the second image (black *) and

(3) the velocity field between the first and the second image (red arrows)


- The number of maxima in the second frame is 19. We got 9 velocity vectors for the beads of the first two frames, thus almost half of the maxima selected contribute to the velocity measurement

- After setting the values of D_{max} and D_{min} we measure the velocity field between consecutive frames.

- Only one vector is pointing in a direction different than the others

Validation with and without External Forcing

Velocity field with $I = 0$:

• Overlay of 30 contour plots

• Velocity vectors scattered in all directions

• Average velocity components $= 0$

• Noise velocity due to light fluctuations caused by dust and impurities
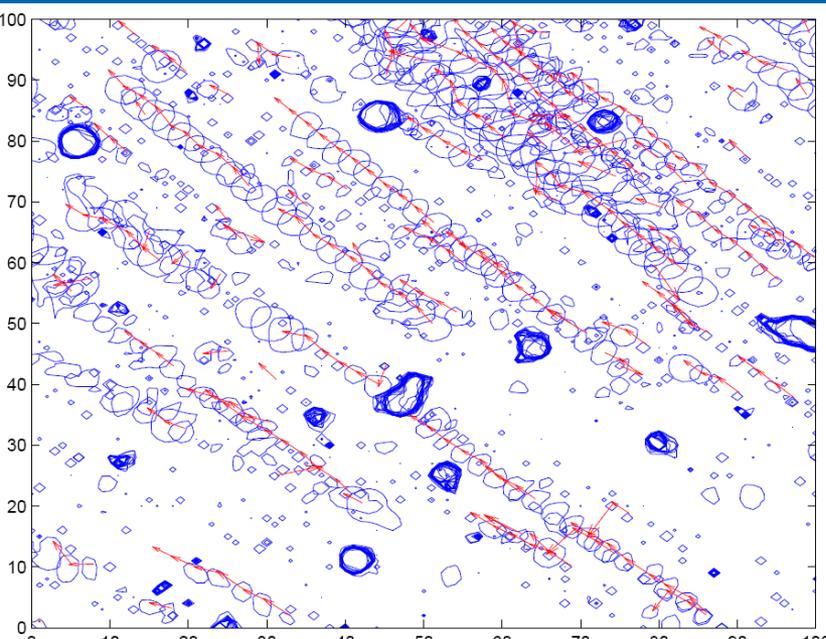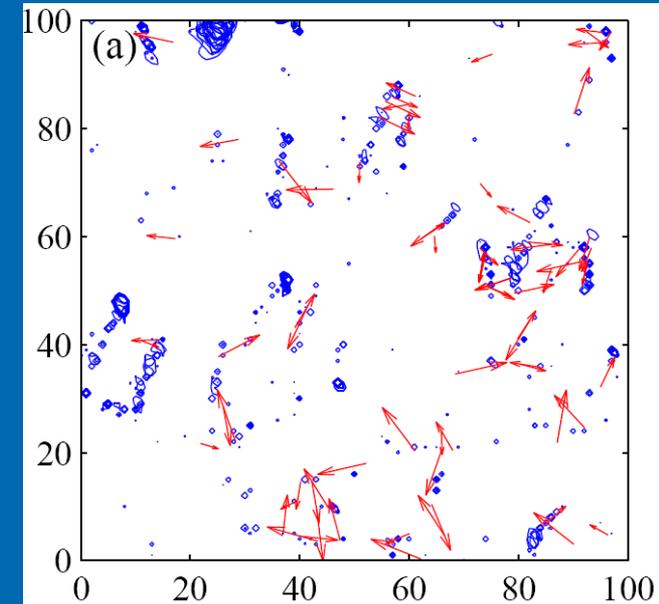
Velocity field with I different than 0:

• Overlay of 20 contour plots and the corresponding velocity field

• Almost 5% of the velocity vectors are deviated from the general trajectory of the beads

• Average velocity different from 0

incompressible Navier-Stokes equations

$$\vec{\nabla}.\vec{v} = 0$$

$$\frac{d\vec{v}}{dt} = \frac{\partial \vec{v}}{\partial t} + \left(\vec{v}.\vec{\nabla}\right)\vec{v} = -\frac{1}{\rho}\vec{\nabla}P + \frac{\eta}{\rho}\vec{\nabla}^2\vec{v} + \frac{\sigma}{\rho}(\vec{E} + \vec{v}\times\vec{B})\times\vec{B}$$

The interaction parameter N:

$$N = \frac{\sigma(\vec{E} + \vec{v}\times\vec{B})\times\vec{B}}{\rho\vec{v}.(\vec{\nabla}\vec{v})}$$

$$N \sim \frac{\sigma B(\Delta V)}{\rho v^2} + \frac{\sigma L B^2}{\rho v} \sim 1650 >> 1$$

The Hartmann number Ha:

$$Ha = \sqrt{\frac{\sigma(\vec{E} + \vec{v}\times\vec{B})\times\vec{B}}{\eta\Delta\vec{v}}} \sim \sqrt{\frac{\sigma L\, B(\Delta V)}{\eta v} + \frac{\sigma B^2 L^2}{\eta}} \sim (400 - 500) >> 1$$

The magnetic diffusion equation:

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla}\times(\vec{v}\times\vec{B}) + \frac{1}{\sigma\mu}\Delta\vec{B}$$

The magnetic Reynolds number Rm:

$$R_m = \sigma\mu\,\frac{\vec{\nabla}\times(\vec{v}\times\vec{B})}{\Delta\vec{B}}$$

$$R_m \sim \sigma\mu L v \sim 10^{-8}$$

Conclusion:

Lorenz force is the dominant force in the flow. The applied magnetic field dominates the induced magnetic field.
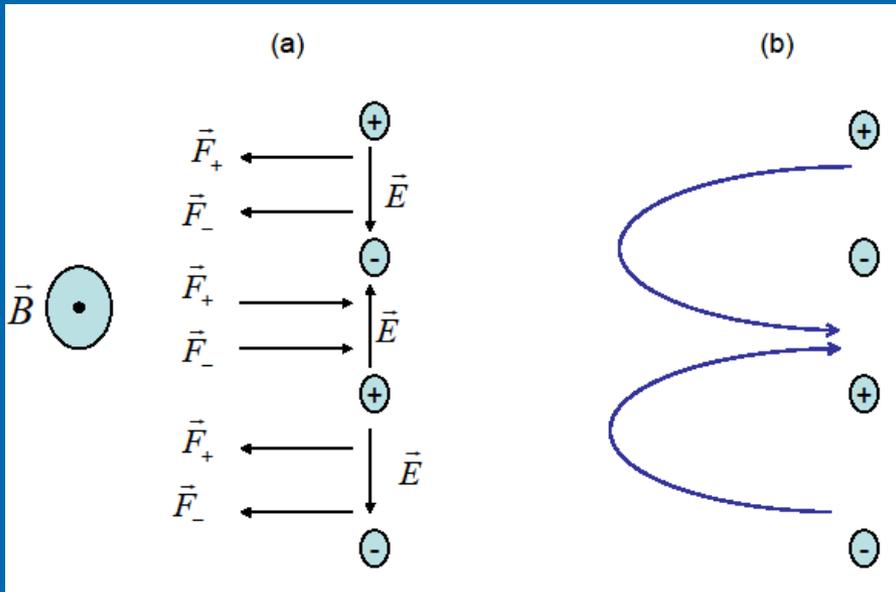
Square container: The Flow dynamics using Dye and a uniform white light source

➤ KOH Concentration: 27% of water mass

➤ KOH solution thickness = 1

➤ Driving current: 1 Ampere
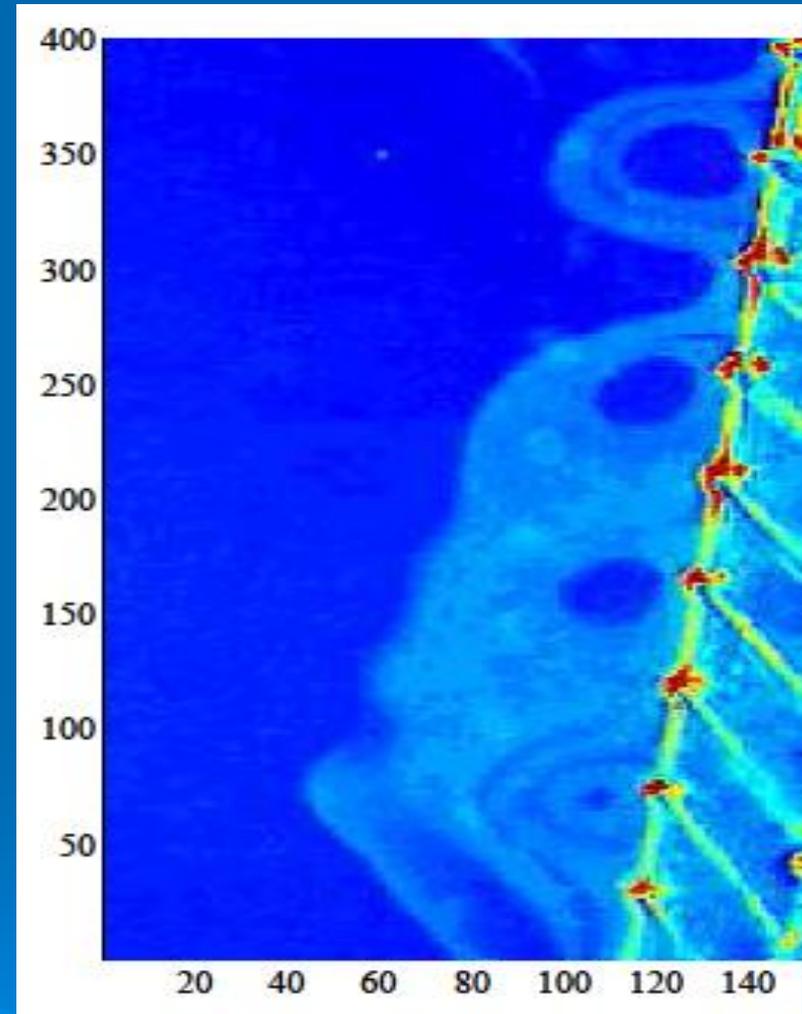
➤ Tracer: Dye

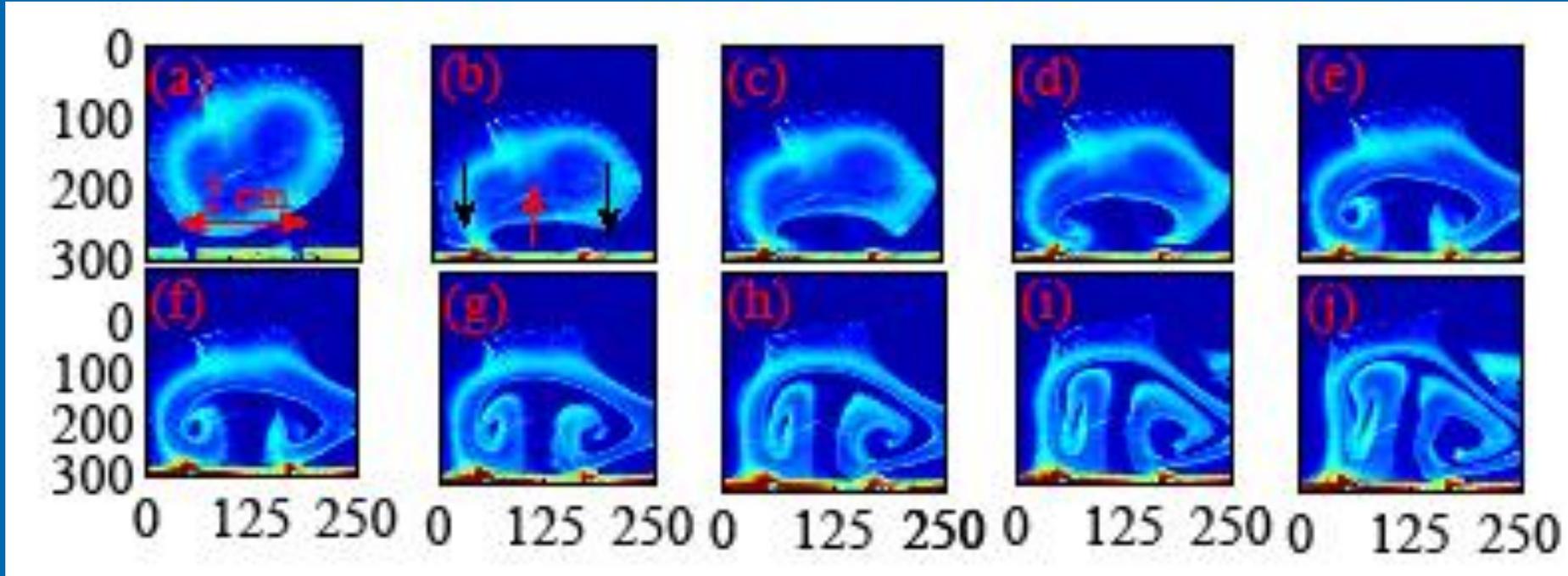➤ Camera 25 frames/second

The square container: Primary structures

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

When the Lorenz Force dominate the motion, the velocity is mainly caused by **ExB**, hence, the two charges move in the same direction
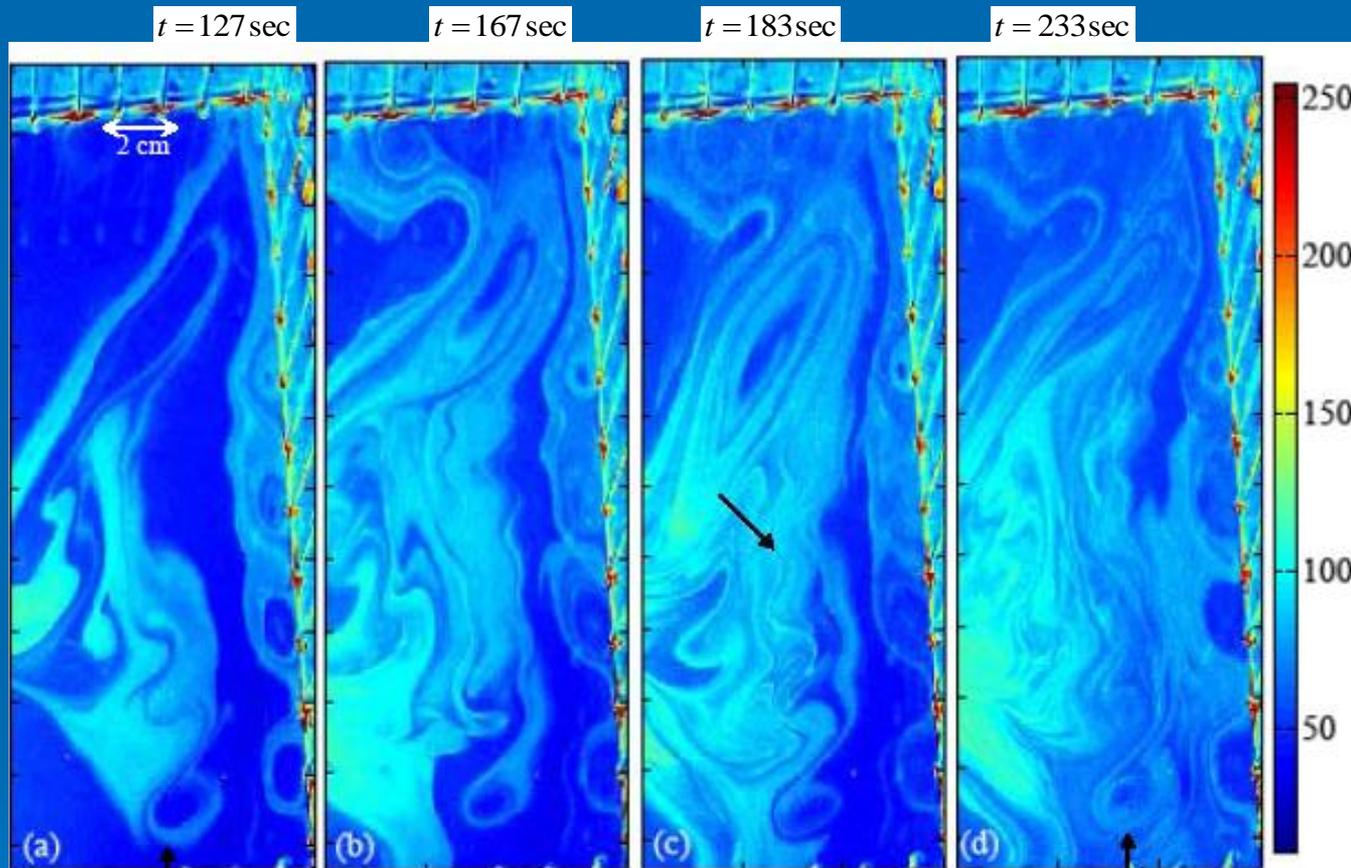

Primary vortices in front of the electrodes

Primary Structure Formation

- (a), No current.

- (b), start-up with forces toward and away from the containers edge.

- (c) - (e), the formation of two counter-rotating vortices.

- (f) - (j), vortex deformation due to non-linear interaction with neighboring vortices.

# Secondary vortices and complex motion

- Secondary vortices are formed away from the container edge

- They result from viscous interaction of the fluid with primary vortices

- They rotate in the counter-direction as the primary vortices

Unexpected dynamics: The diagonal jet
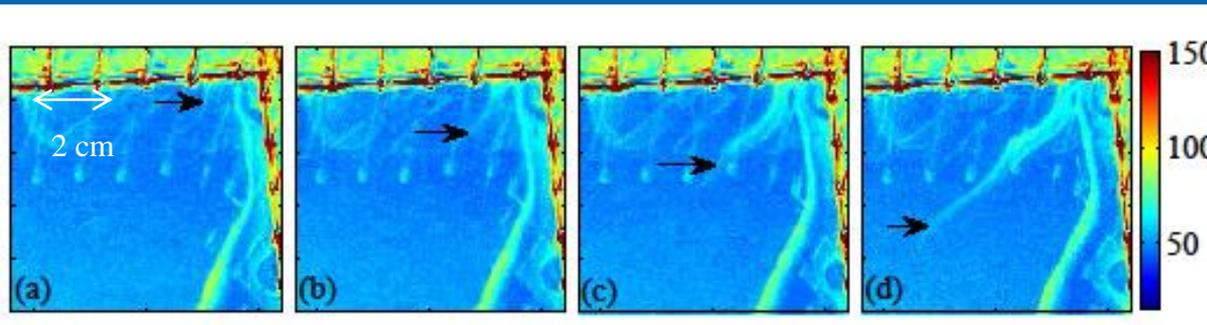
A jet moves from the upper right corner to the middle of the container. The time between consecutive images is 2sec.
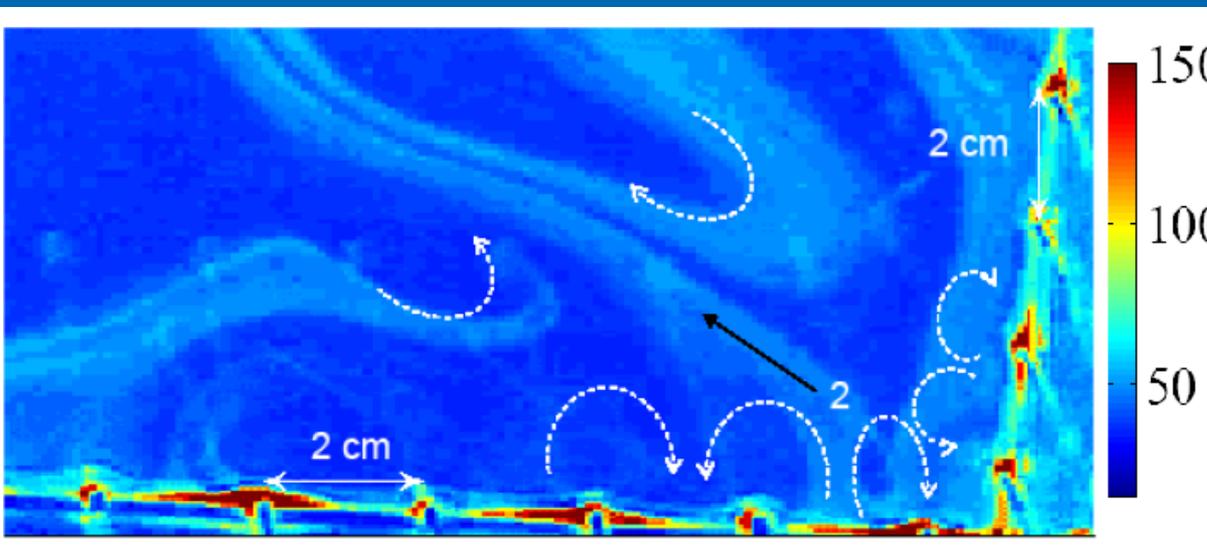
• At point 2, the outward force generates the jet $\vec{j} \times \vec{B}$ (indicated by the black arrow).

• The jet interacts with large vortices.

• The jet is driven to the middle of the container by the large vortices.

The emergence of vertical jets
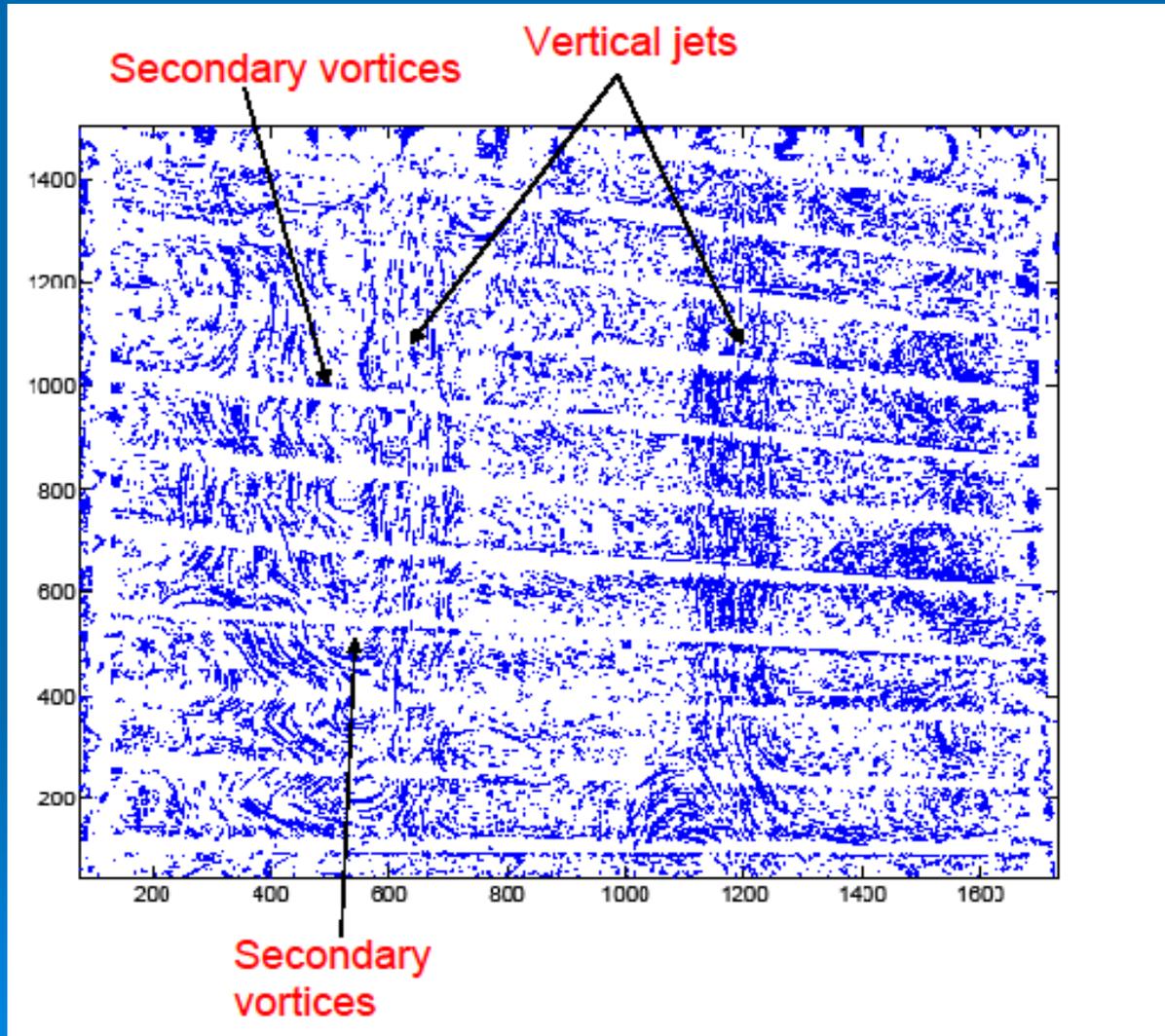
Observations:

• Secondary vortices

• Two jets heading from top to bottom in the same direction.
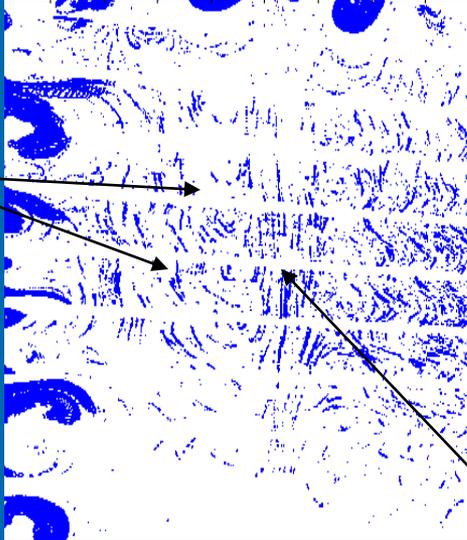
Interpretation:

The magnets position below the container and the magnetic field distribution reflecting a strong *magnetic field gradients* between adjacent drawers could be the reason behind the observation of the vertical jets.
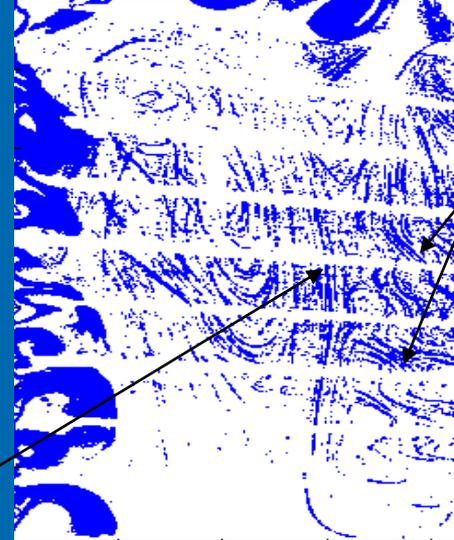
Jet formation as a function of time

Secondary vortices
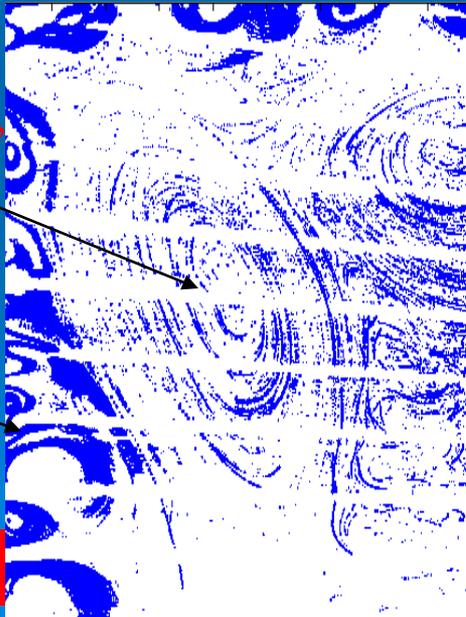
t = 2-8sec

Secondary vortices

t = 10-20sec

Jets

Secondary vortices merging. Large vortex
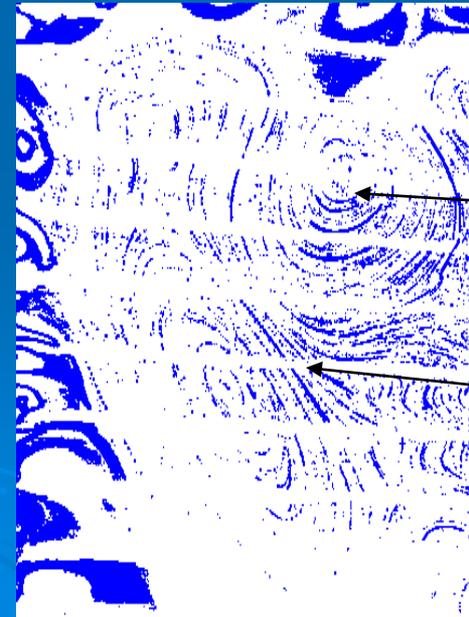
Primary vortices

t = 30-40sec

Secondary vortices merging. Large vortex
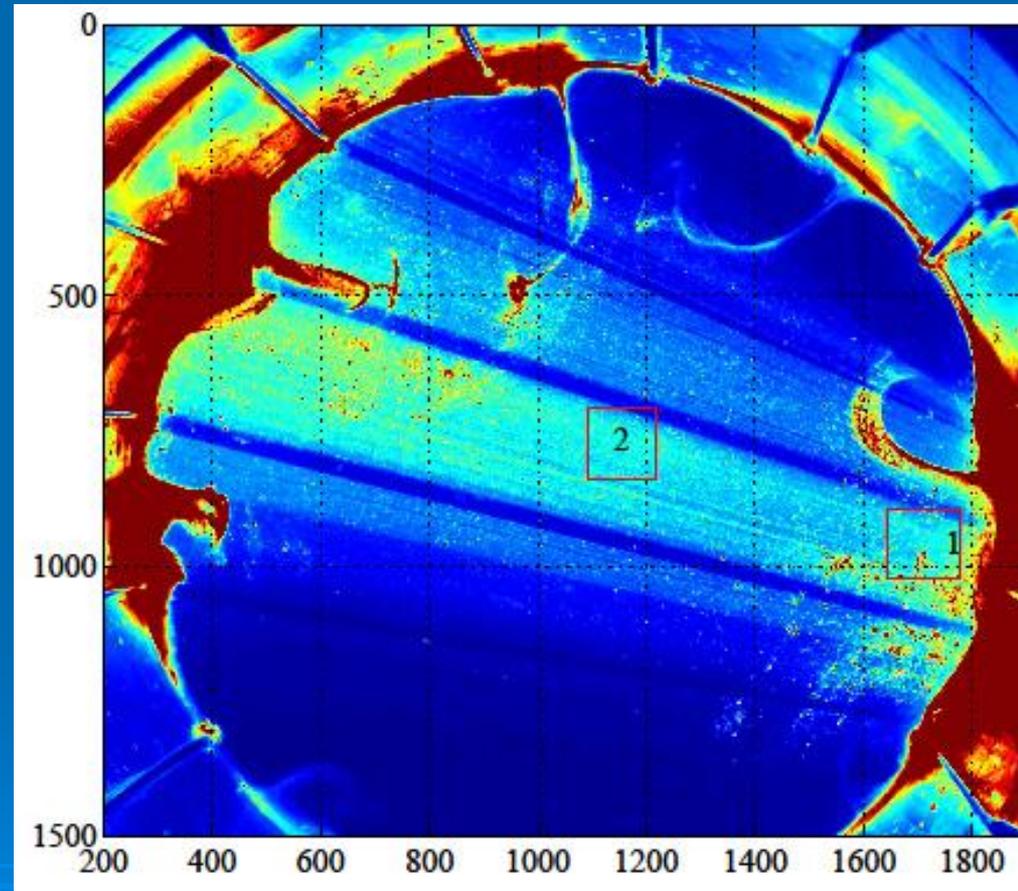
Diagonal jet

t = 116-122sec

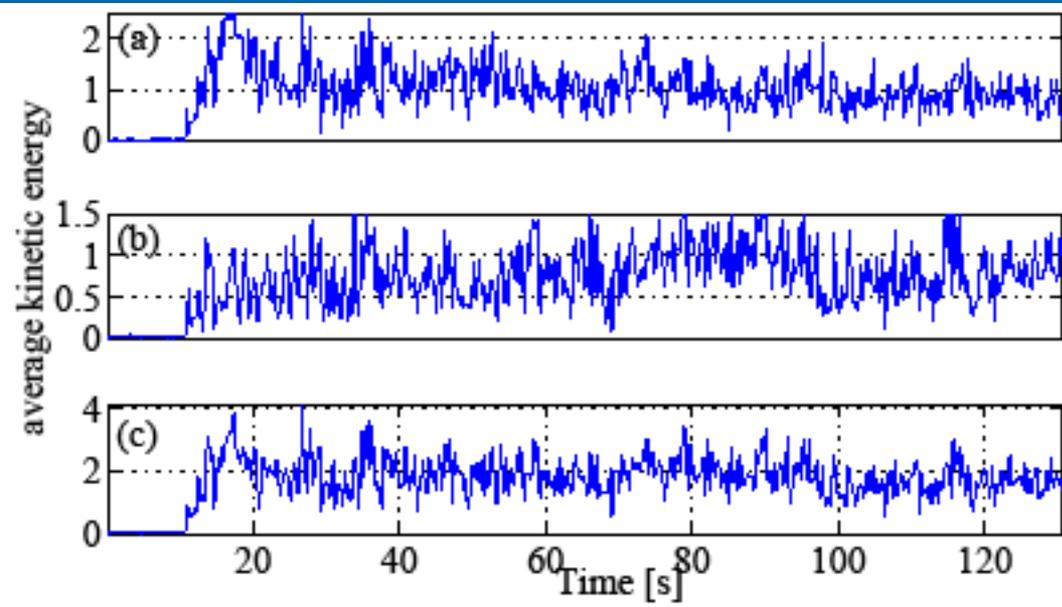We calculate the average kinetic energy per frame:

$$\overline{E}_{frame} = \frac{1}{2N} \rho \Sigma \left(v^2_x + v^2_y \right)$$

N is the total number of maxima in the area chosen per frame.

• Tracer: glass beads; Lighting source: Laser sheet.

• Start recording for almost 9-10seconds, then turn on the current, FPS= 4.
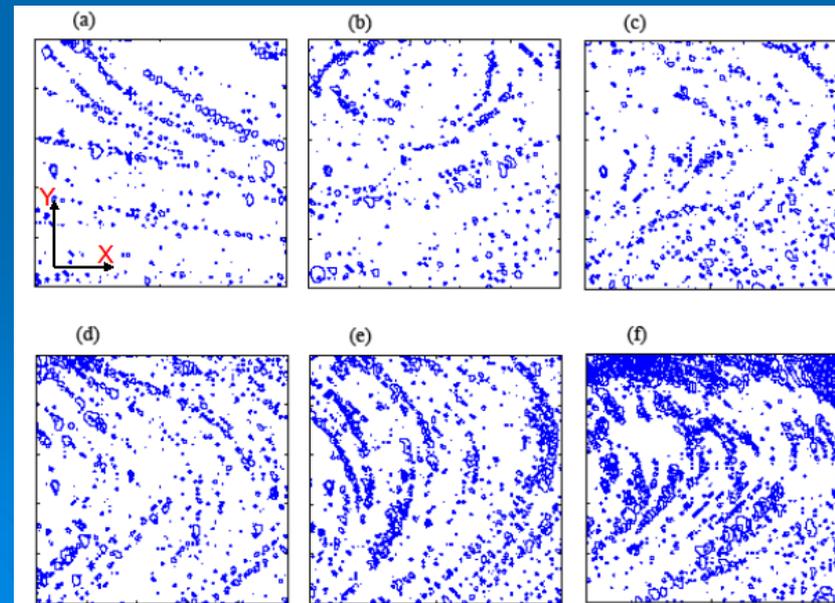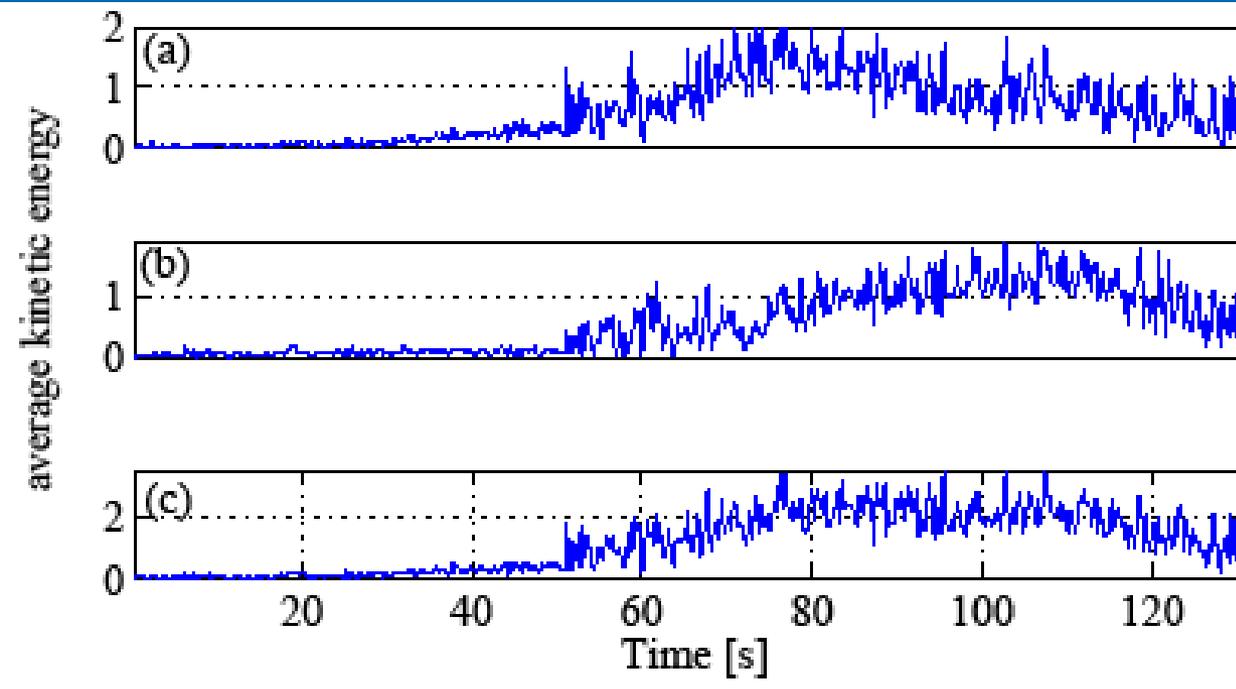
Evolution of the flow near the edge

• The energy increases in the x direction after turning the current on.

• The same time dependence in E_x and E_y reflects a diagonal path of the beads, caused by a vortex formation.

• The stationary state is reached after ~10sec.

(a), t =13-21sec (b), t =40-48sec.

(c), t =53-64sec (d), t =69-80sec.

(e), t =83-91sec (f), t =101-107sec.

Evolution of the flow around the middle

- The energy in the x and y directions are of equal magnitudes. This is an indicator for the diagonal trajectories followed by the beads.

- The persistence of the diagonal trajectories indicates that a large vortex and the area chosen covers a small part of this vortex.

- Stationary state reached after ~65 seconds.
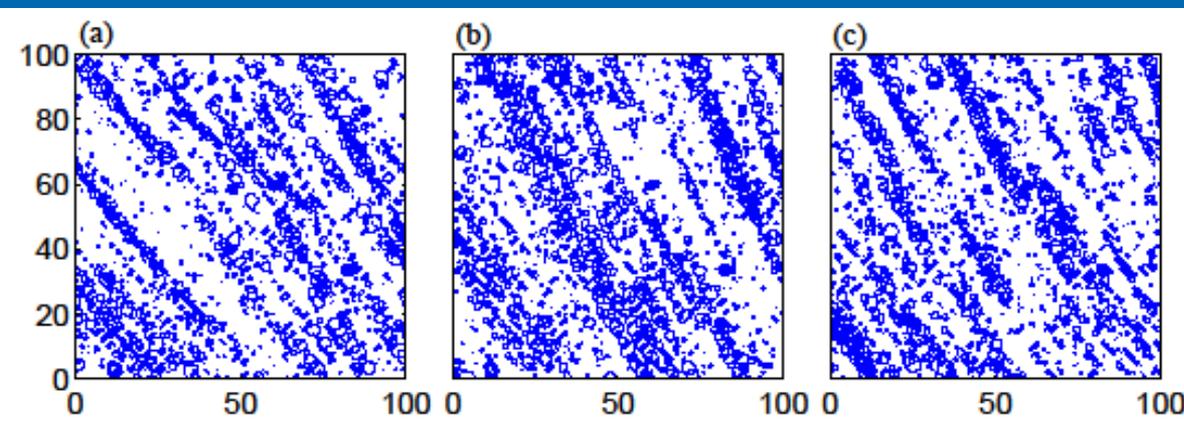
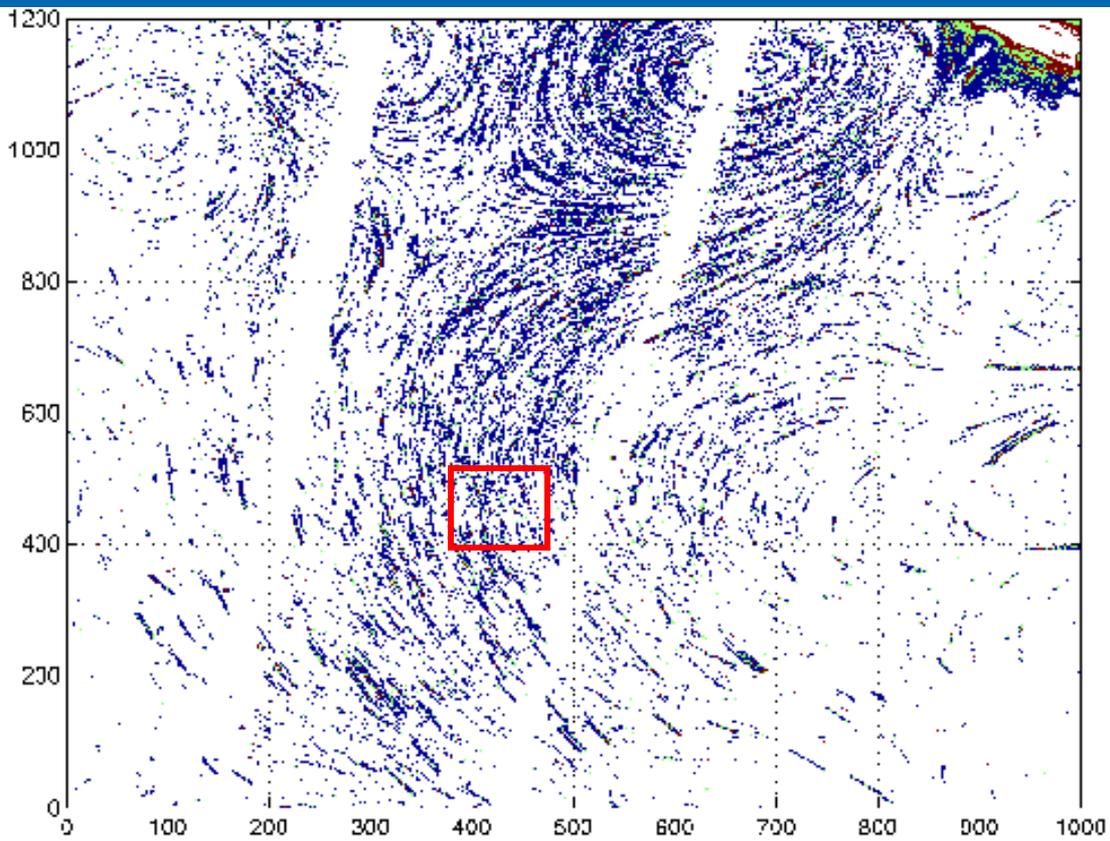(a), $t = 93$-107sec

(b), $t = 107$-120sec

(c), $t = 120$-133sec

The probability distribution function of the two components of the velocity field
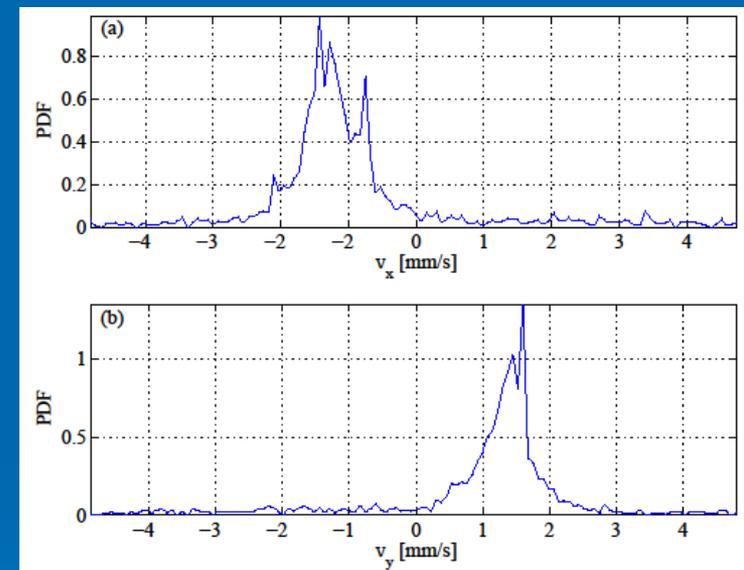
• The coherent structures are distributed around the edge of the container.

• A large scale vortex is observed in the middle.

• Kurtosis = 8.5, 8

• Skewness = 0.5, -0.4

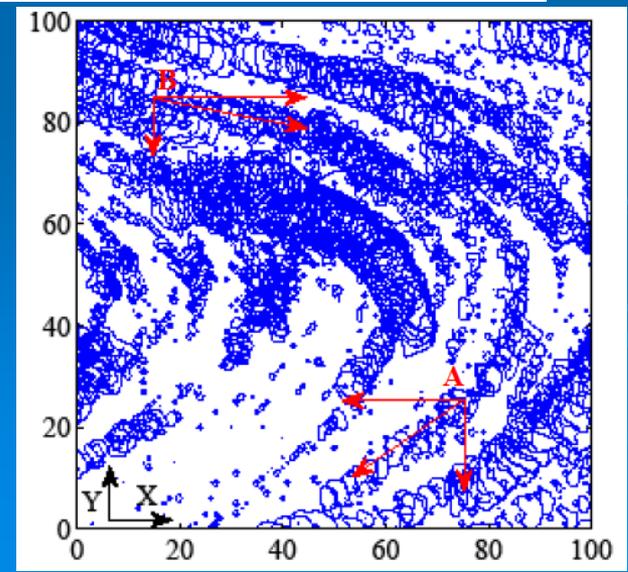The velocity distributions are non-Gaussian.

- Kurtosis = 4.4, 5.2

- Skewness = -0.02, 0.3
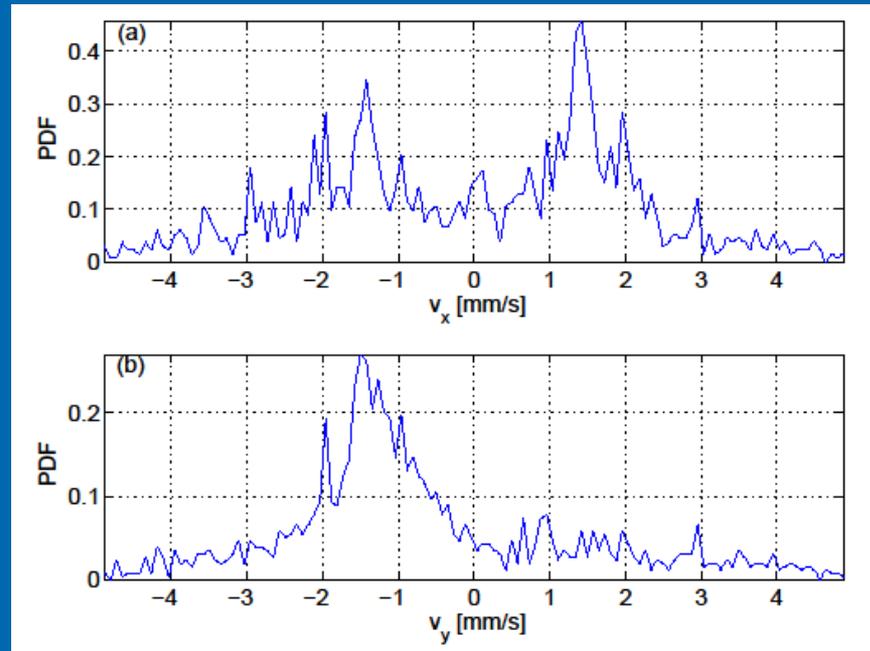
- The projection of the velocity vector in the *x* direction gives positive and negative values.

- The projection in the *y* direction gives only negative values.

Conclusion

➤ We constructed several experiments to understand the properties of quasi-2D coherent structures.

➤ We also developed the adequate diagnostics to evaluate both the quantitative and qualitative nature of the flow's motion

➤ We developed a numerical code to determine the two components of the velocity and initiated the determination of the statistical properties

➤ We verified the onset of primary vortices and described their main properties

➤ The existence of secondary vortices is put forward making the flow's dynamics more complex far from the edge

➤ The onset of a diagonal jet was studied in detail, a phenomena linked to the geometry of the square container and the magnetic field

Future work

• Build a cylindrical container with electrodes separation equal to 1cm. The size of the edge coherent vortices becomes smaller

• Build a square container of smaller size to be used with electromagnets generating homogeneous axial magnetic field in the flow.

•Increase the intensity of the magnetic field and reduce that of the electric current.

• Perform experiments with different heights to investigate the effect of the depth of the KOH solution layer on the dynamics.

• Perform parametric dependence on the current and/or the magnetic field strength