Particle Image Velocimetry (PIV) Techniques Applied to Turbulence Studies in Helium II

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What will this talk cover?

- Brief introduction to modern flow visualization techniques
- Unique features of helium II visualization
  - Phenomena to be studied
  - Particle selection and seeding techniques
  - Experimental system components
- Examples of PIV experiments in helium II
  - Counterflow in channels and around bluff bodies
  - Forced flow helium II
  - Superfluid vortex line trapping
- Summary

Particle Imaging Techniques

Techniques that involve introducing small tracer particles into the fluid stream and monitoring their motion.

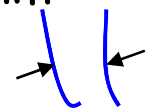
- Laser Doppler Velocimetry (LDV)
  - Point velocity measurement
  - Additional information (particle size, 3D)
- Pulsed Light Velocimetry (PLV)
  - Particle Image Velocimetry (PIV)
  - Whole velocity field measurement

Equipment to conduct these experiments is commercial available from a number of manufacturers. For liquid helium application there are some special requirements (optical cryostat) and challenging issues (particle seeding).

See: R. J. Adrian, "Particle-Imaging Techniques in Experimental Fluid Mechanics", Annu. Rev. Fluid Mech. 1991, Vol. 23, pp. 261-304

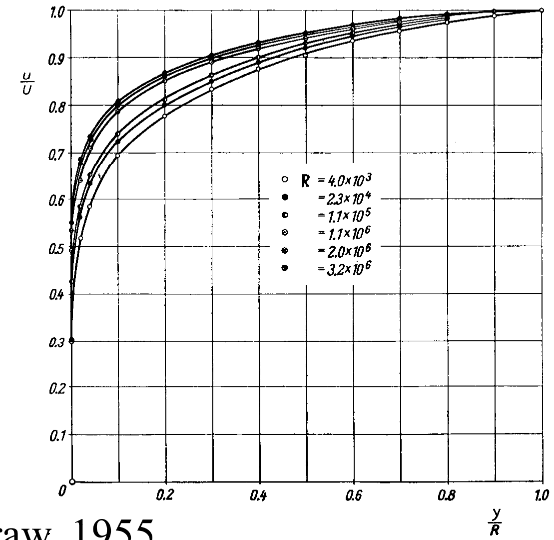
Turbulent fluid scaling issues

What is the dimension of the phenomenon to be studied and how does that compare to particle size? For example,

- Superfluid vortex core ~ 1 nm
- Vortex line spacing ~ 1 μm 
- Turbulence scales: Kolmogorov: $\eta \sim \dfrac{L}{\mathrm{Re}^{3/4}} \sim 10^{-6}$ m
- Turbulent boundary layer:

$$\frac{u}{U} \sim \left(\frac{y}{R}\right)^{1/n}$$

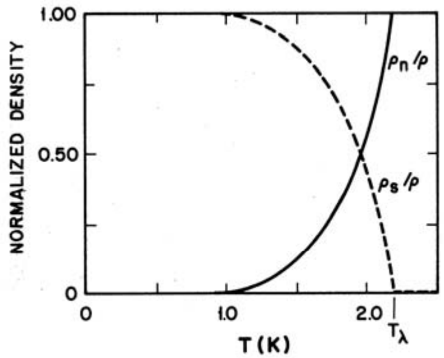
where $n \sim 7$

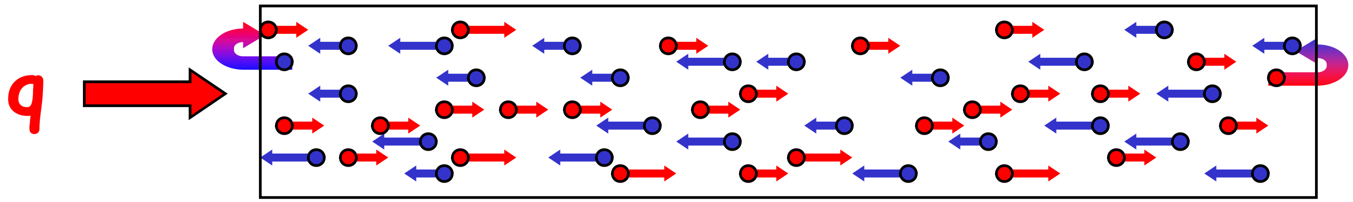


See: H. Schlichting, Boundary Layer Theory, McGraw, 1955

Two Fluid Model* for Helium II

- Helium II can be thought to consist of two interpenetrating fluids that are fully miscible and have temperature dependent densities (ρ_s and ρ_n)

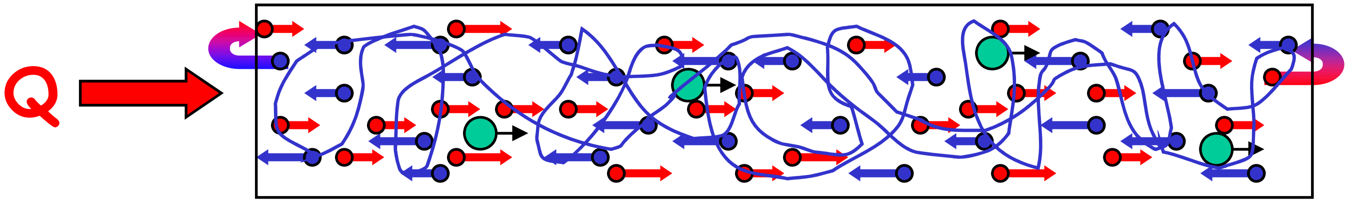




- These two components (• superfluid and • normal fluid) flow under influence of pressure and temperature gradients.
- Average heat current, $q = \rho s T \langle v_n \rangle$

* L. Landau, 1941

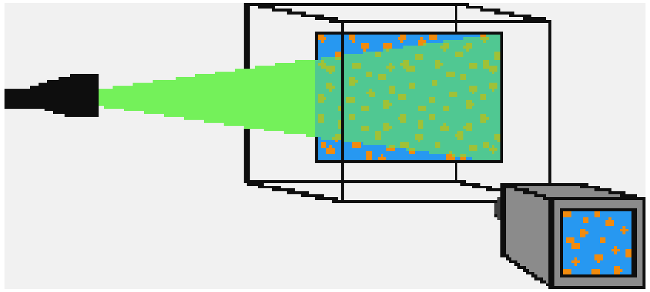
Particle –interaction with two fluid components



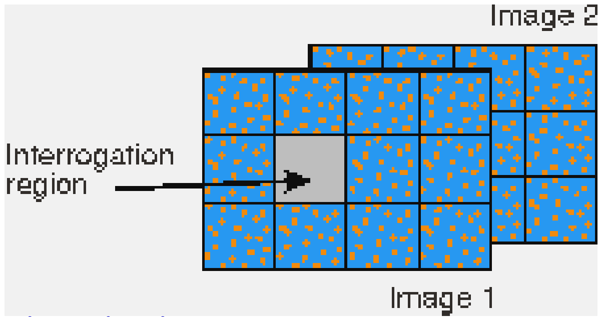
- Normal and superfluid components are not visible or separable. Need tracer particles
- Insert solid particles in He II channel
- Dimensional considerations
  - Particle diameter (~ 1 μm)
  - Vortex core (< 1 nm)
  - Vortex line spacing (δ ~ μm)
- How do these particles interact with the He II?

Potential flow around a sphere

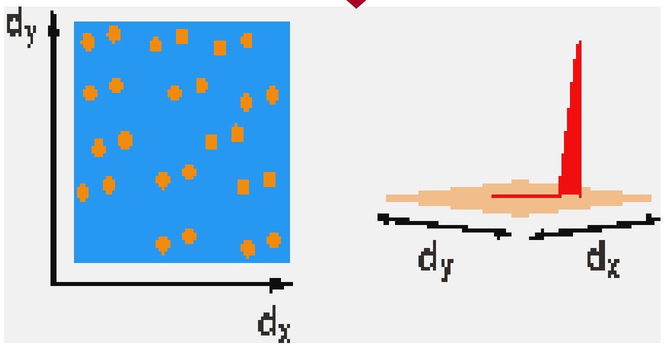
Particle Image Velocimetry (PIV) Technique



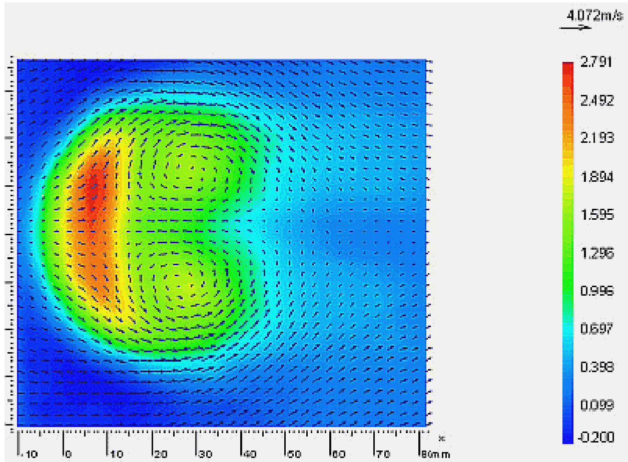
1. Flow seeding and image acquisition



2. Subdivided into interrogation areas



3. Cross correlation process ($N_p > 1$)



4. Result – velocity field

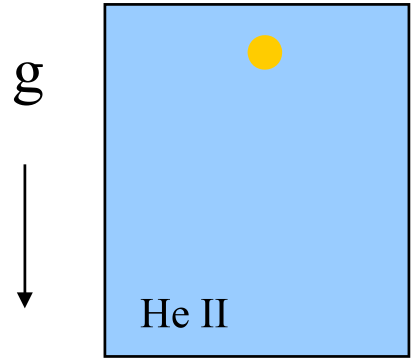
Velocity at x,t is defined as: $u(x,t) \equiv \dfrac{\Delta x(x,t)}{\Delta t}$

Particle Selection and Tracking

- Slip velocity between particles and fluid
  - small, neutral density particles, ρ_{HeII} = 145 kg/m^3

$$v_{slip} \approx \frac{(\rho_{HeII} - \rho_p) g d_p^2}{18\mu_n}$$

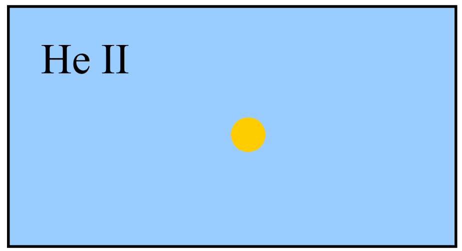
v_{slip} ~ mm/s for d_p ~ 1 μm & ρ = 1100 kg/m^3



- Response time (fidelity)

$$\tau \approx \frac{\rho_P d_p^2}{12\mu_f}$$

τ ~ 1 ms for d_p = 10 m



- It is best to minimize v_{slip} and τ: $\rho_p \sim \rho_{HeII}$ ~145 kg/m^3 and to have small size (d < 10 mm).

- Ideally v_{slip} < few % of v_{flow} for good measurements, but there is also some advantages experimentally to not have neutrally buoyant particles. For example, if bad seeding or particle agglomeration occurs, they leave the view field.

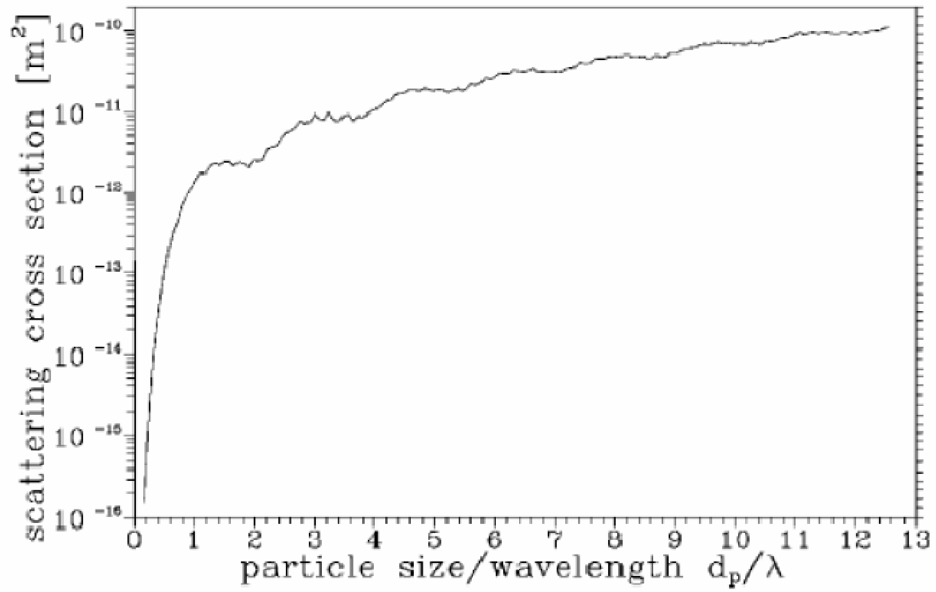
Properties of good tracer particles

- Particle concentration:
  - Statistics for velocity measurement
  - Differentiate between individual particles

} ~ 10 particles /integration area

- The lower limit on particle size: particles need to scatter enough light for image acquisition.

- $d_p > 1\ \mu m \sim 2\lambda$ (for green light with $\lambda = 532$ nm) is preferable.



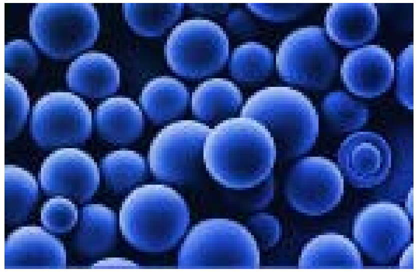
For best experiments: $1\ \mu m < d_p < 10\ \mu m$ with narrow size distribution

Introducing Solid Particles into He II

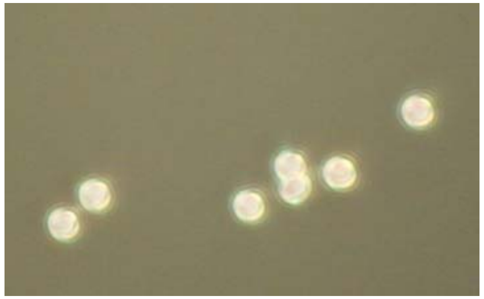
- Initial conditions:
  - Solid particles are stored at room temperature
    - in air (or other gases)
    - In liquids (water)
- Experimental conditions
  - $T_{op} \sim 2$ K
  - Partial vacuum: $p_{op} < 5$ kPa
- Issues of concern in He II application
  - Introducing particles into low pressure environment requires particle transport system
- Van der Waals attraction
  - Small particles will tend to agglomerate due to London dispersion forces

Commercial tracer particles

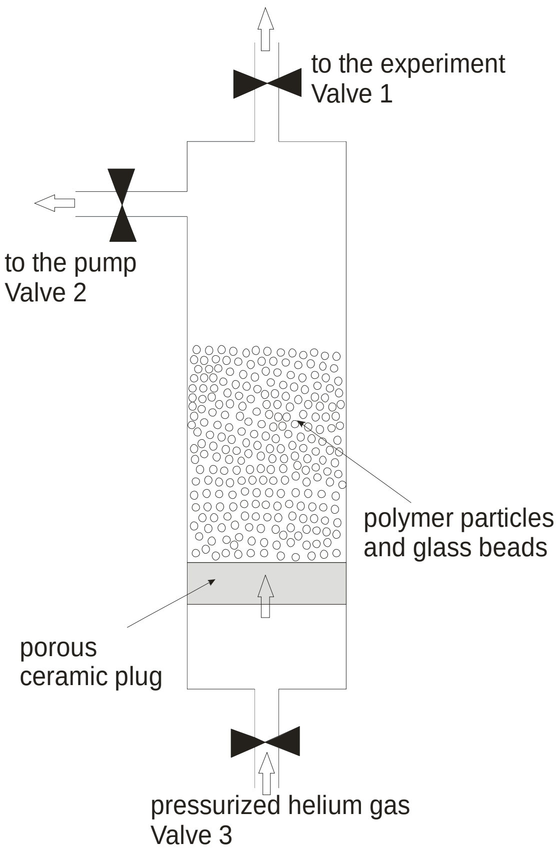
- Hollow glass spheres
  - PQ, 3M: d_p ~ 10 μm to hundreds μm
  - ρ_p between 140 to 200 kg/m^3
  - large size and density distribution per sample
  - only a small fraction of the particles are neutrally buoyant
  - large size -> large settling velocity (5 to 100 mm/s) and time constant (10 to 100 ms)
  - TSI: d_p = 8 to 12 μm, ρ_p = 1100 kg/m^3
    narrower size distribution but still large size and density



- Polymer micro spheres
  - Not neutrally buoyant but widely available in small sizes with narrow size distribution
    Bangs laboratory: d_p = 1.7 μm, ρ_p = 1100 kg/m^3
    Calculated: v_{slip} = 1.2 mm/s, τ_s = 0.15 ms at 1.8 K



Commercial tracer particles seeding into He II



- Goal: to remove air around the particles and disperse the particles as much as possible before and during the particle injection.

- Two phase fluidized bed technique: 1.7 μm polymer particles with 100 μm glass beads contained in a small vessel (particle ratio 2:1).
  - Pump overnight, purge ~ 10 times, possibly apply heat.
  - Use at most a few grams of tracer particles in the seeder.
  - Injection pressure of the He gas adjusted so the solid glass spheres are fluidized and the polymer particles are seeded into the liquid helium.

Solid hydrogen particles

- Advantages of sH_2 (sH_2/D_2) particles
  - Injection from gaseous or liquid state so no need to purge the particles
  - Particles can be removed from experimental system by warming to > 30 K and pumping vapor away

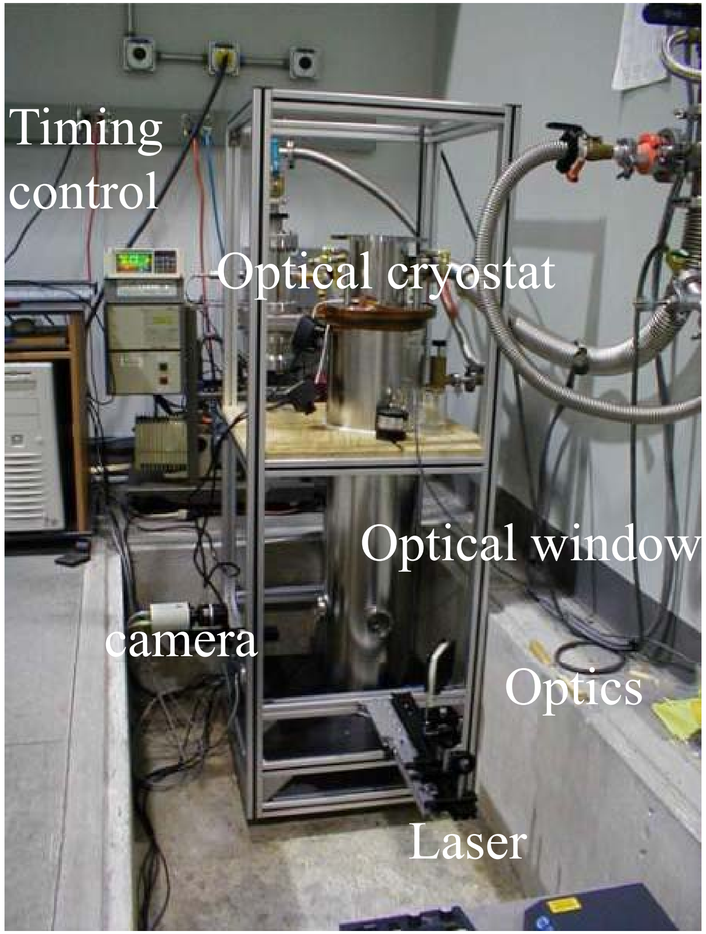
- Disadvantages
  - Particles are not stable and tend to agglomerate into large (d ~ mm) structures
  - Particles are not spherical or necessarily uniform in size, which can result in large variation in brightness.

Solidified H_2 tracer particles

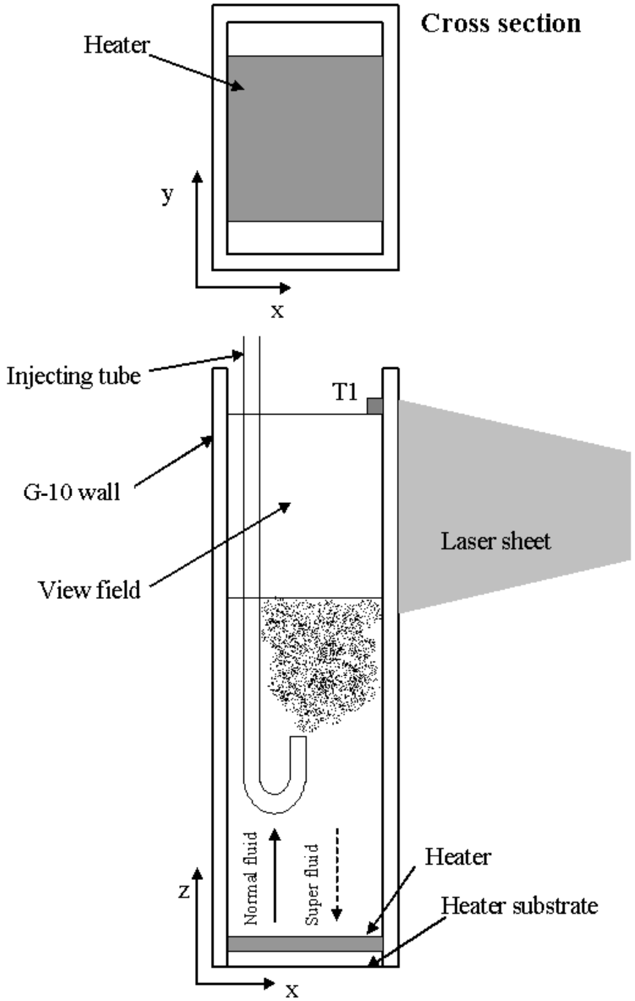
- Chopra & Brown (Phys. Rev. Vol. 108, 157 (1957))
  - –50-50 mixture by volume of hydrogen and deuterium injected into liquid through a 8 mm ϕ tube
  - –neutrally buoyant H_2/D_2 particles of diameter less than 1 mm
- Murakami (Cryogenics Vol. 29, 438 (1989))
  - –H_2/D_2 mixture injected through a heated tube in the gas phase. And sifted through a screen
  - –Initial stage: particles small ~ 1 μm then agglomerate to ~ 100 μm after passing through a wire screen.
- Gordon & Frossati (J. Low Temp. Phys. Vol. 130, 15 (2003))
  - –Solid particles from deuterium gas injected in the gas phase. Adding helium gas (ratio 1:20 to 1:1000) prevent the particles from sticking together before they enter the liquid helium phase.
  - –Deuterium particles of diameter less than 100 nm.

Helium II PIV experimental results

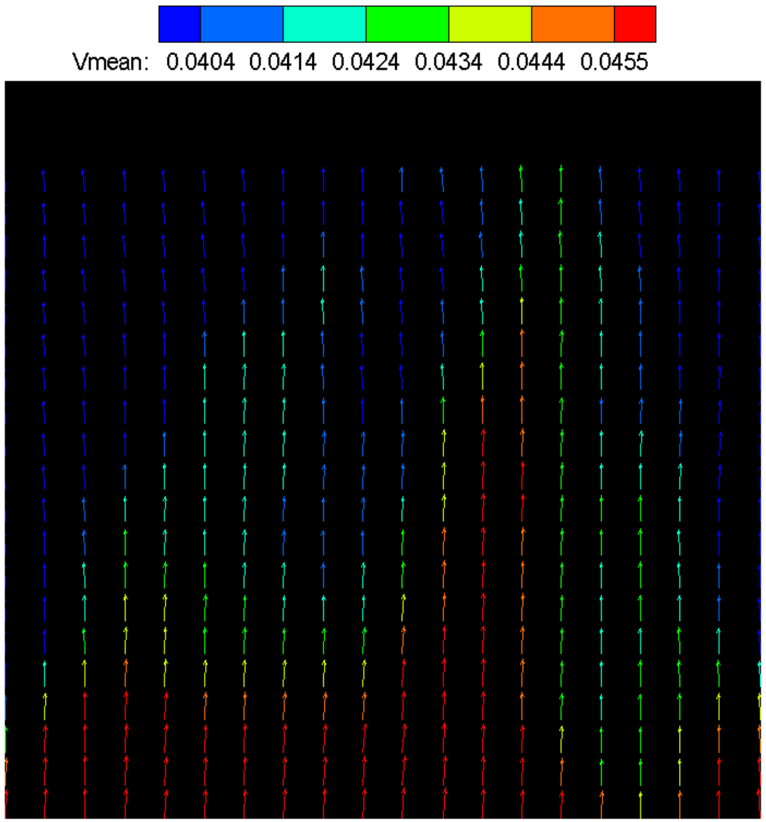
Counterflow PIV He II apparatus

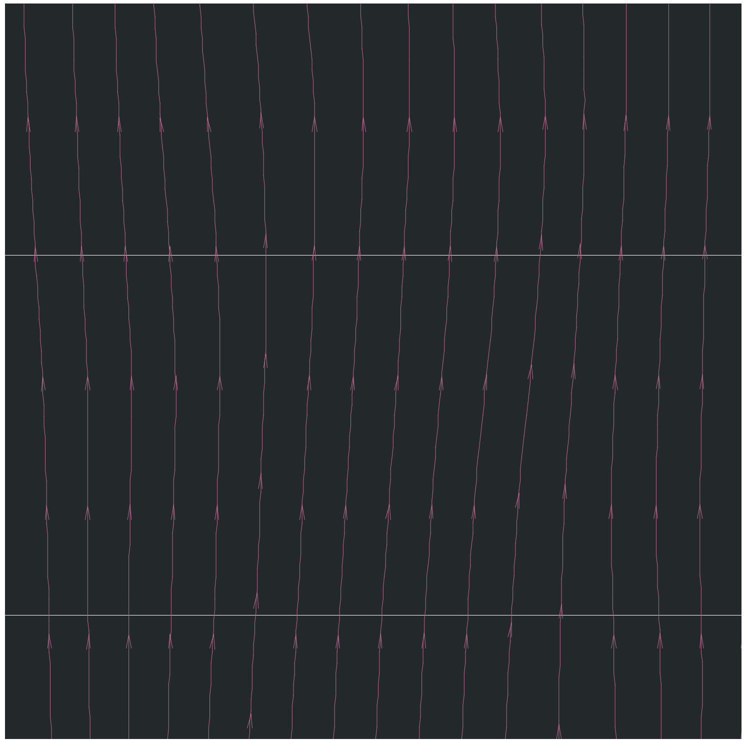


~ 2 m



Analysis of PIV in counterflow He II



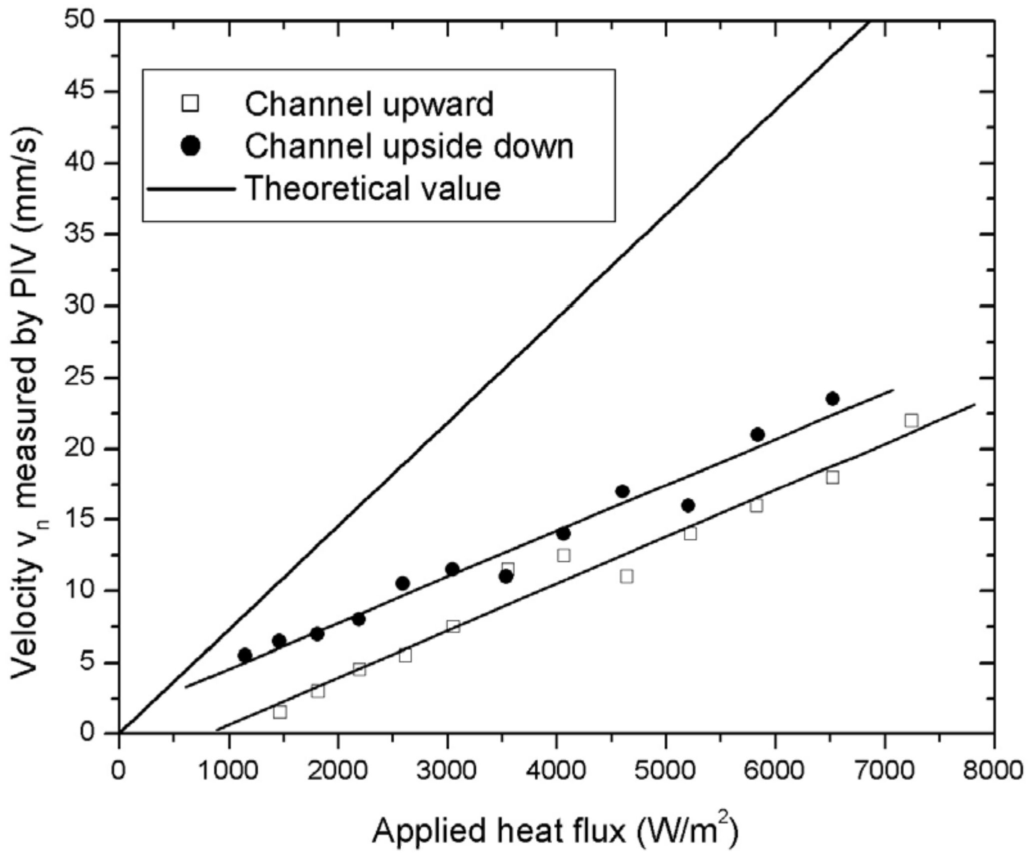


Averaged velocity field at 1.62 K and $q = 7.24\ \mathrm{kW/m^2}$

$\langle v \rangle \sim$ 40 - 45 mm/s while, $v_n = \dfrac{q}{\rho s T} \sim$ 100 mm/s

Comparison with theoretical results

T=1.80 K



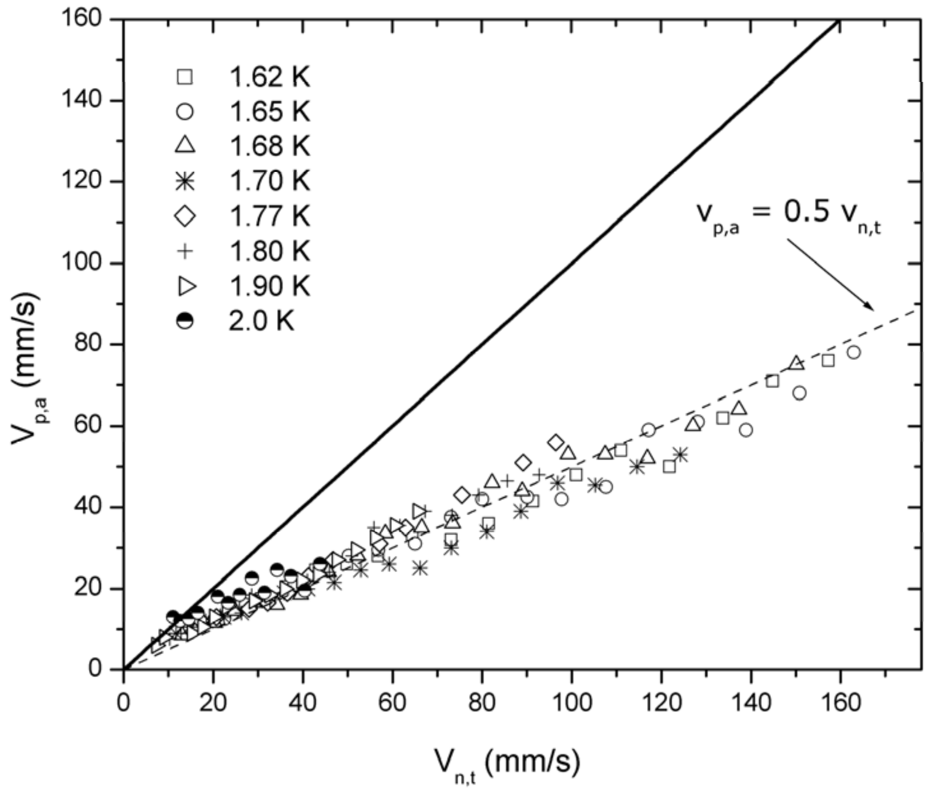
- PIV results represent the mean velocity of whole flow field.
- Theoretical value is calculated from

$$\bar{v}_n = \frac{q}{\rho s T}$$

- v_p is clearly less than v_n.
- Slip velocity can be eliminated by averaging two configurations (v_s ~ 5 mm/s)

Results at various temperatures

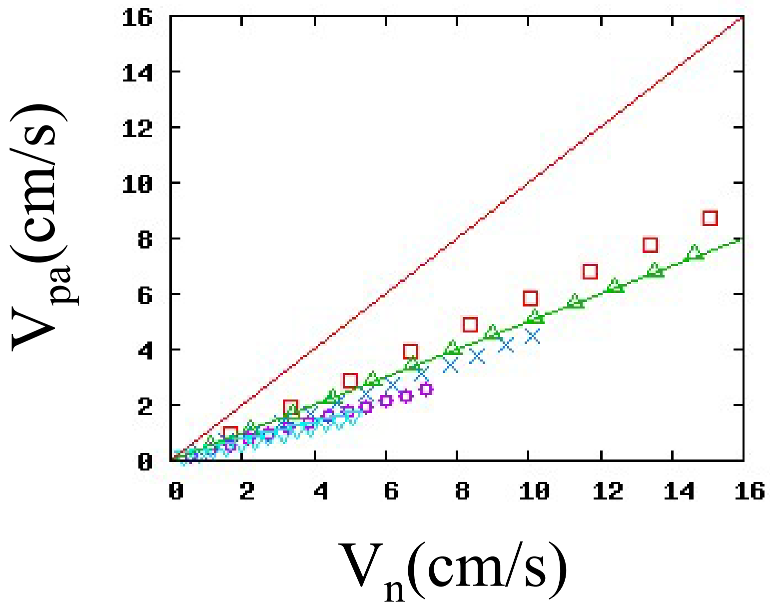
All temperatures



- Ratio of particle to normal fluid velocity ~ constant at all temperatures. $v_p/v_n \sim 0.5$
- Particle motion observed in pure superflow: Chung and Critchlow (PRL 14,892 (1965))
- Suggestion of effective viscosity of superfluid component: T. Zhang & S. Van Sciver, JLTP Vol. 138, 865 (2005)
- Recent theory by Sergeev, Barenghi and Kivotides

Motion of micron size particles in turbulent helium II
Y.A. Sergeev, C. F. Barenghi and D. Kivotides,
Phys. Rev. B74, 184506 (2006)

$$V_{pa} = \frac{(f)}{f} V_{slip} \left(\ldots \right)$$

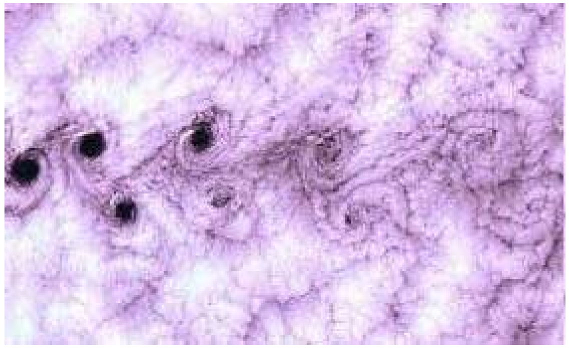


Theory agrees well with experiment: $V_{pa} \approx 0.5 V_n$

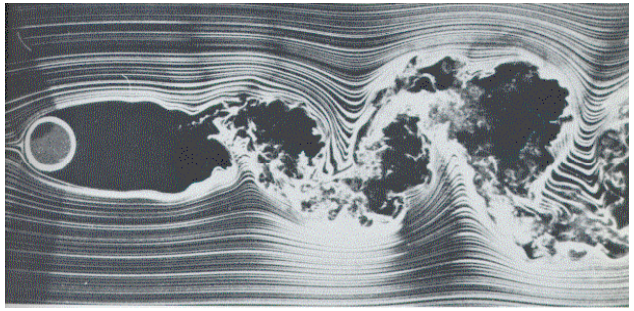
Counterflow around a cylinder

This is a classic problem of fluid mechanics.

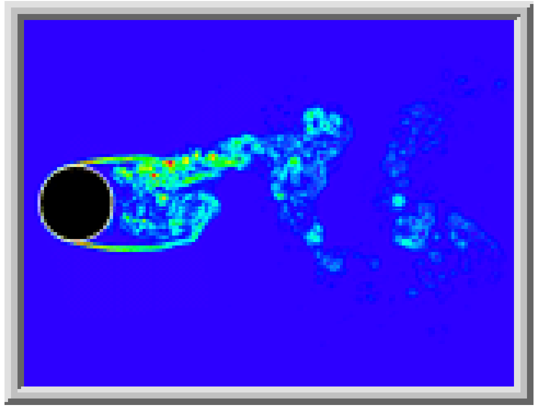
- Large scale vortex shedding occurs behind the cylinder
- Details scale with Re_d



Karman Vortex Street
Alejandro Selkirk Island



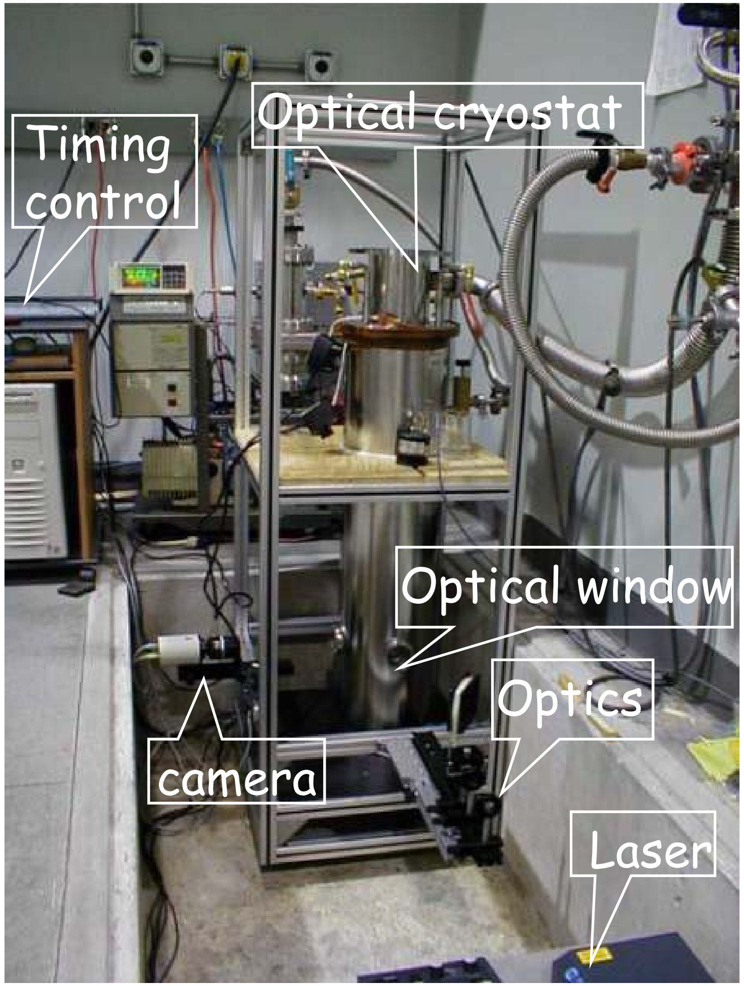
$$Re_d = \frac{\rho v d}{\mu} \sim 10000$$



Numerical codes (e.g. Fluent®) can model classical flow in some cases

How does counterflow helium II behave in this geometry?

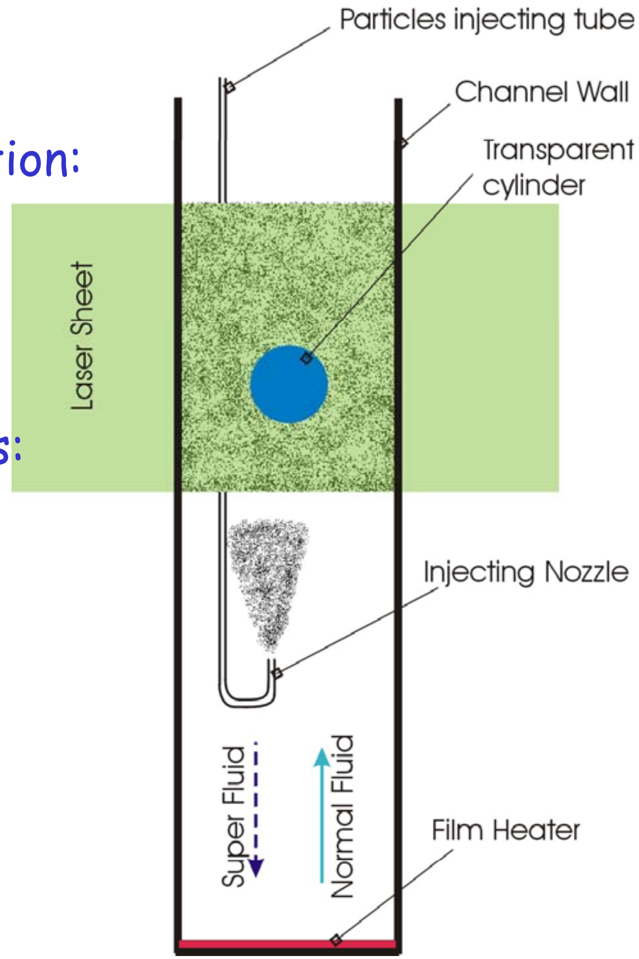
Cylinder He II counterflow experiment



Channel length:
200 mm
Channel cross section:
20×40 mm^2

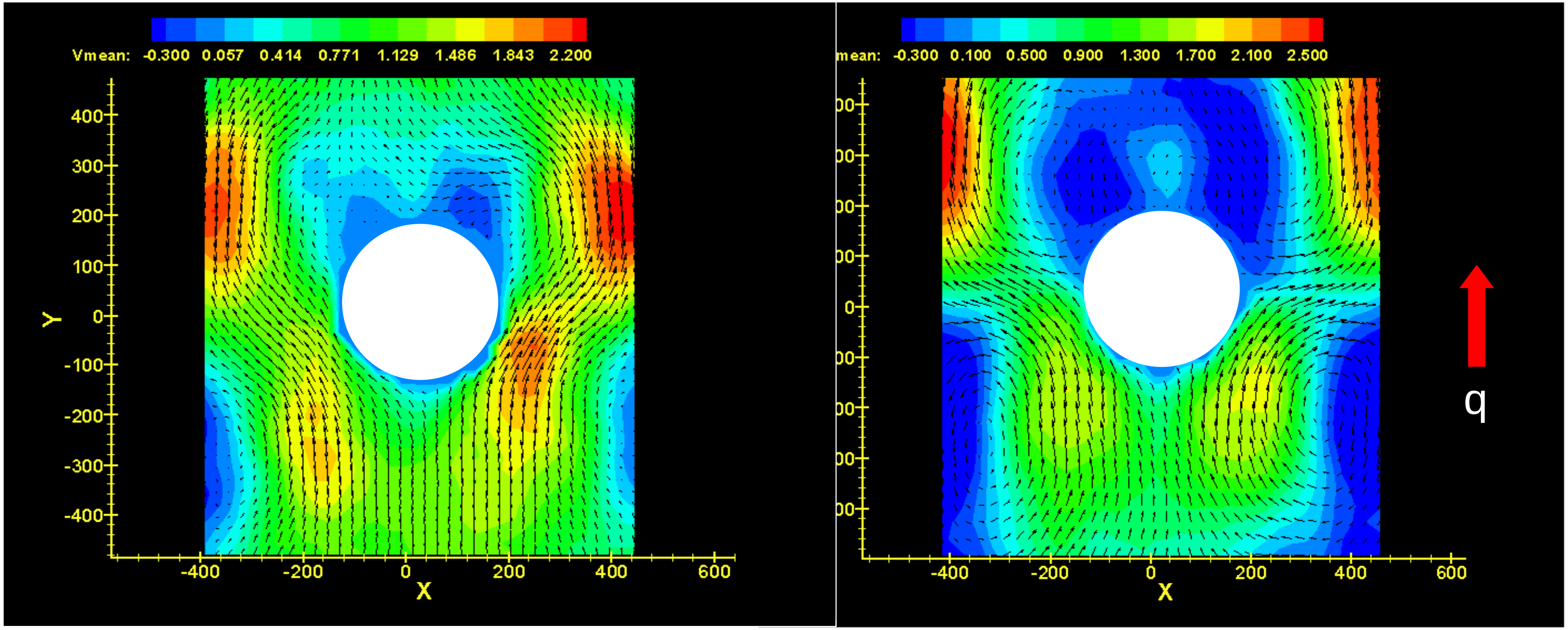
View field area:
20×30 mm^2
Cylinder diameters:
6.35 & 2 mm

Tracer particles:
d_p = 1.7 μm
sp = 1.1



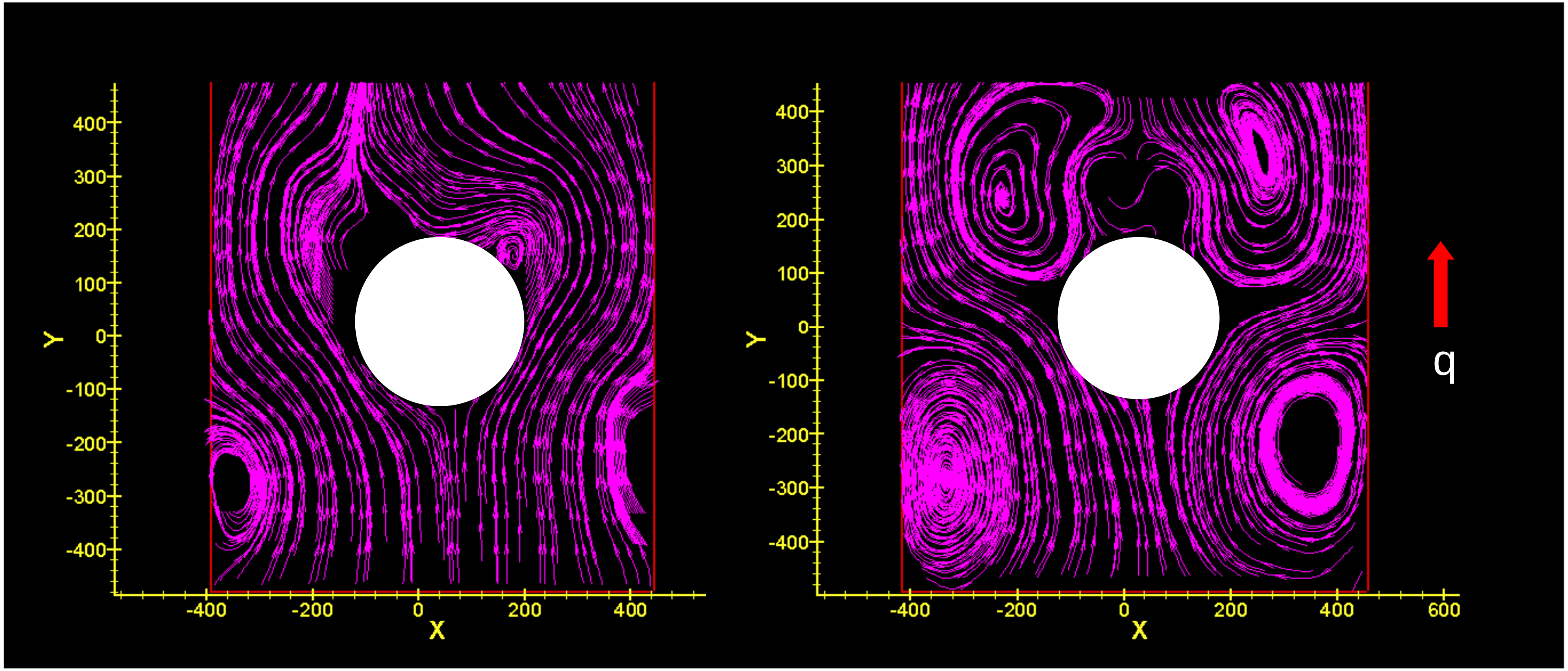
Convection in front of cylinder

Note: 1 pixel/ms = 22 mm/s



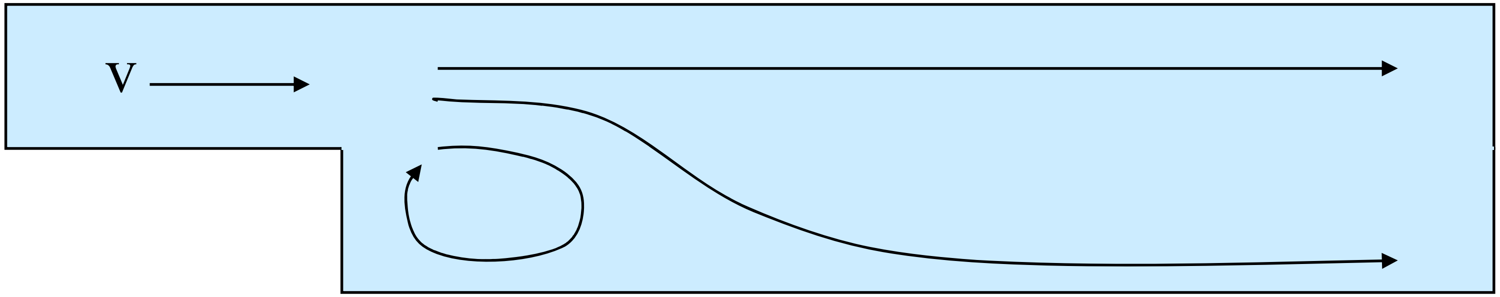
T = 1.60 K, q = 4.04 kW/m², Re = 40928   T = 2.03 K, q = 11.2 kW/m², Re = 20762

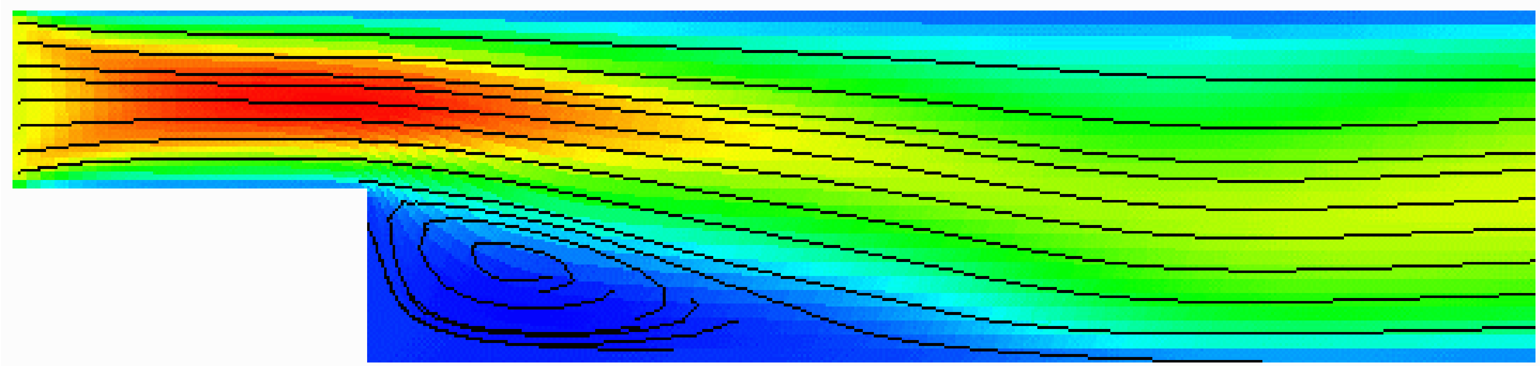
Streamlines confirm vorticity



T = 1.60 K, q = 4.04 kW/m^2, Re = 40928   T = 2.03 K, q = 11.2 kW/m^2, Re = 20762

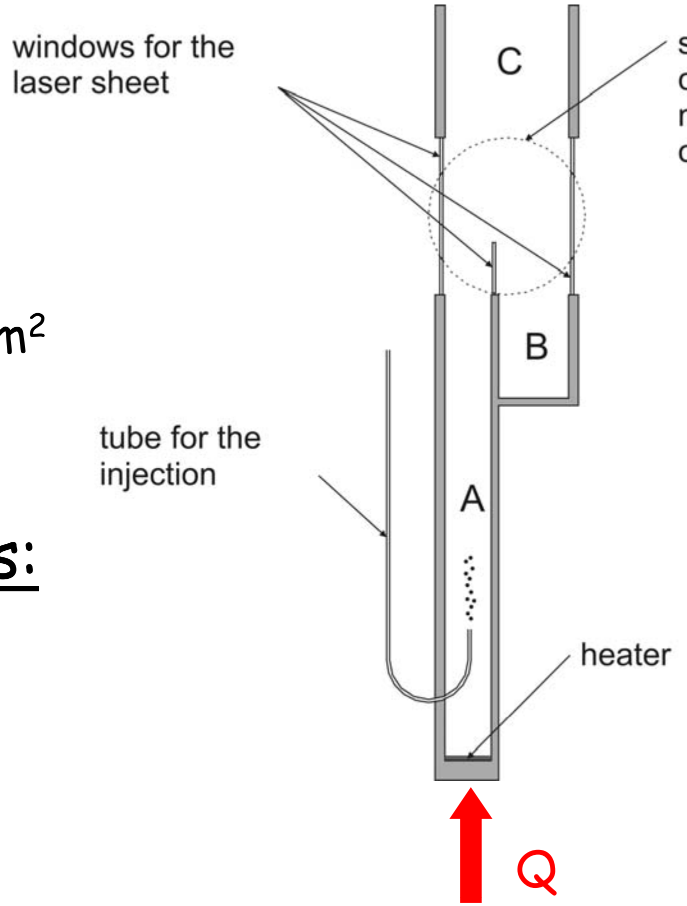
Flow over a backward facing step





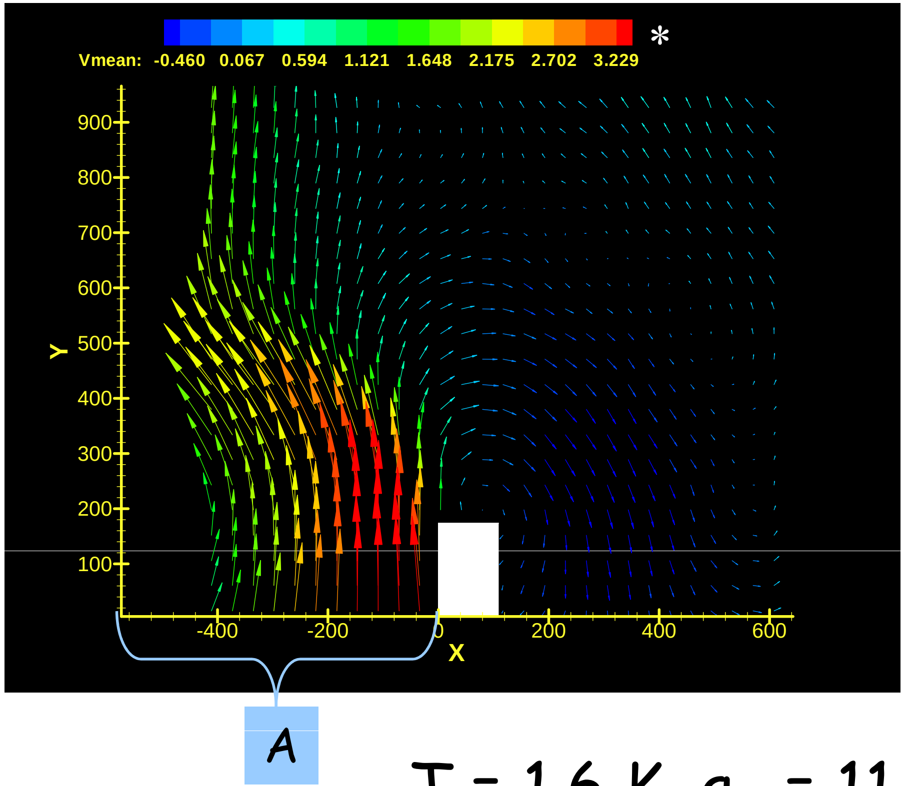
Helium II Counterflow Stepped Channel

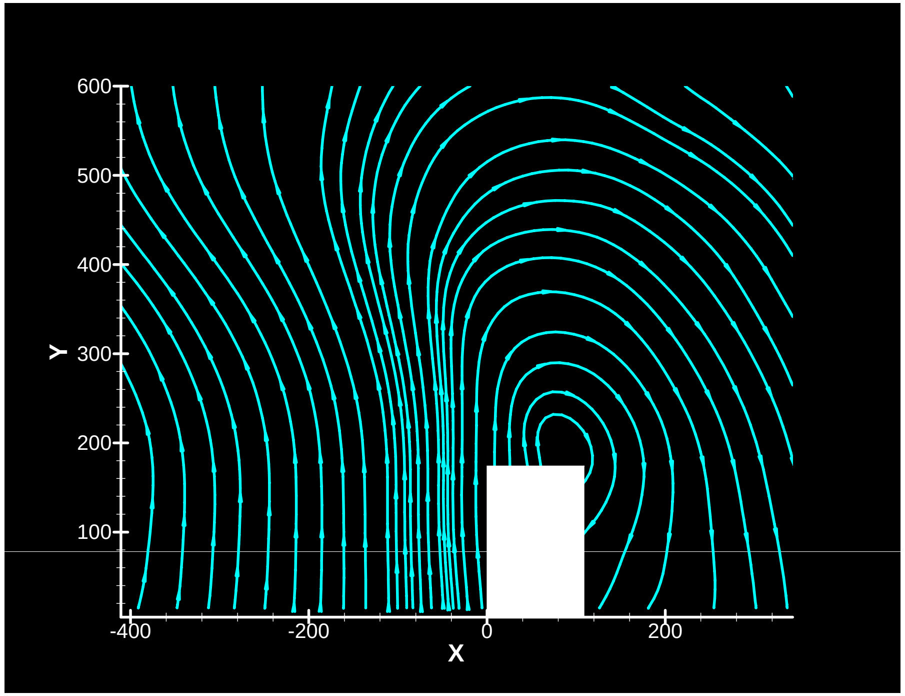
- <u>Test Section :</u>
  - A: 15 x 30 mm²
  - B: 23 x 30 mm²
  - C: 40 x 30 mm²
  - view field area = 50 × 40 mm²
  - Nichrome film heater
- <u>Polymer tracer particles:</u>
  - d_p = 1.7 μm
  - sp gravity = 1.1



Particle tracks using PIV (T = 1.6 K)

*1 pixel/s = 24 mm/s

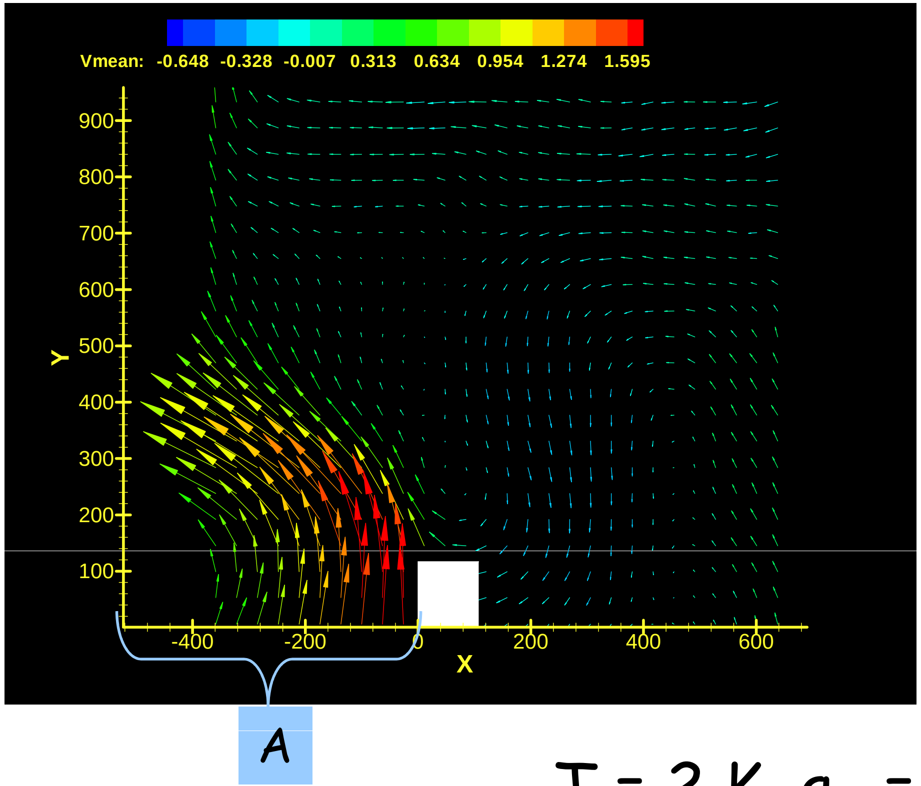


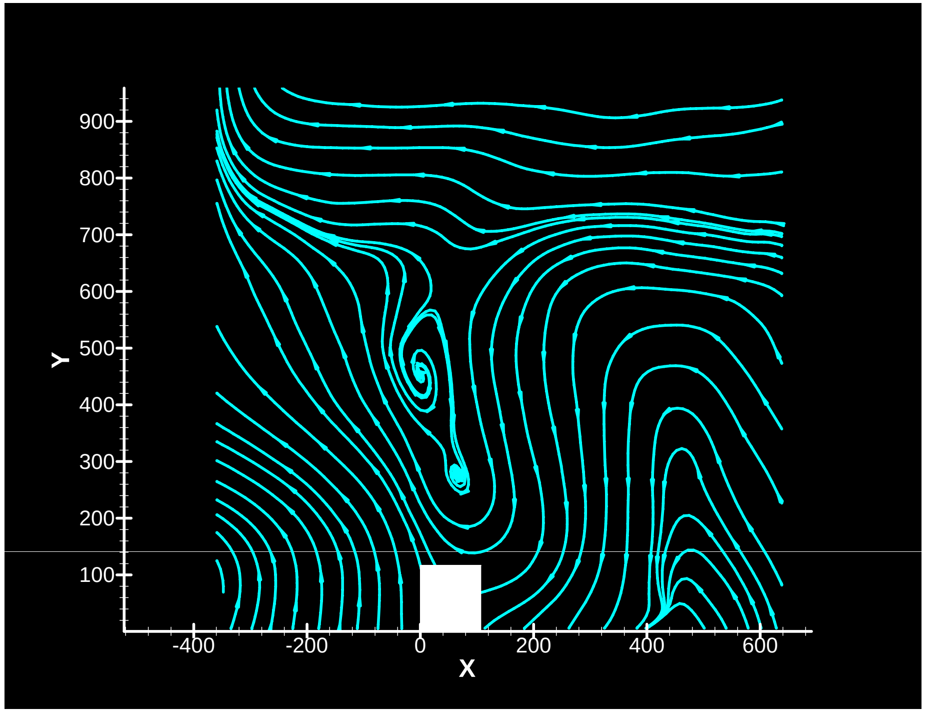


$T = 1.6\ K,\ q_A = 11.8\ kW/m^2$

$v_n = 182\ mm/s;\ Re = 37600$

Particle tracks using PIV (T = 2 K)

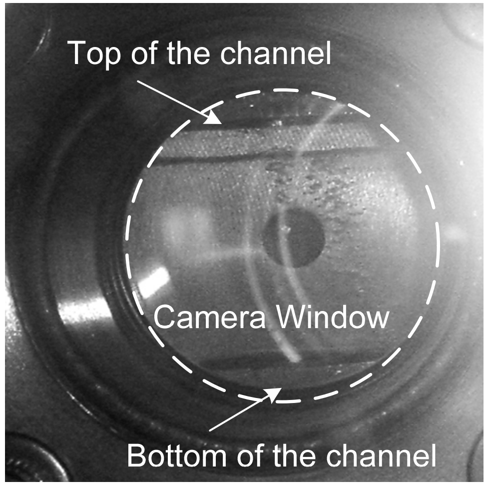


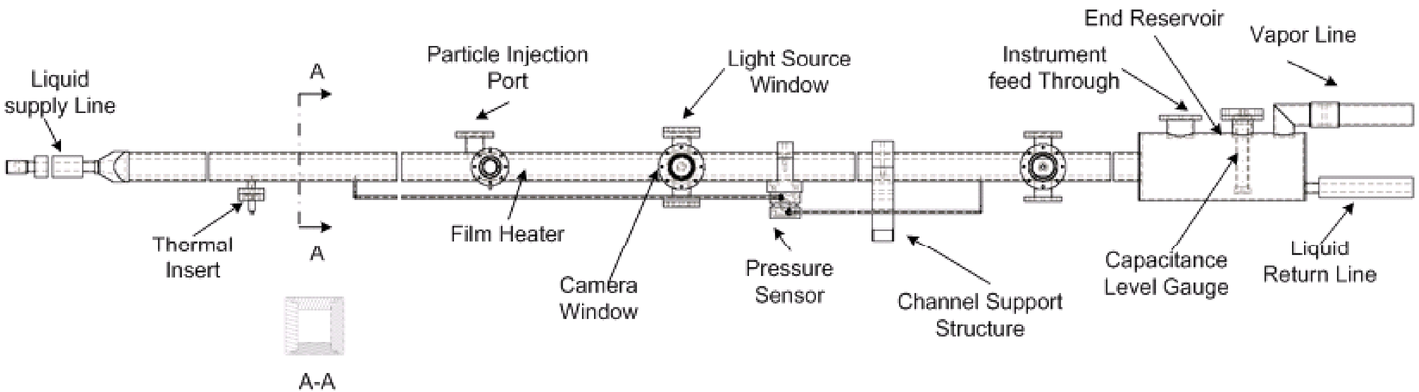


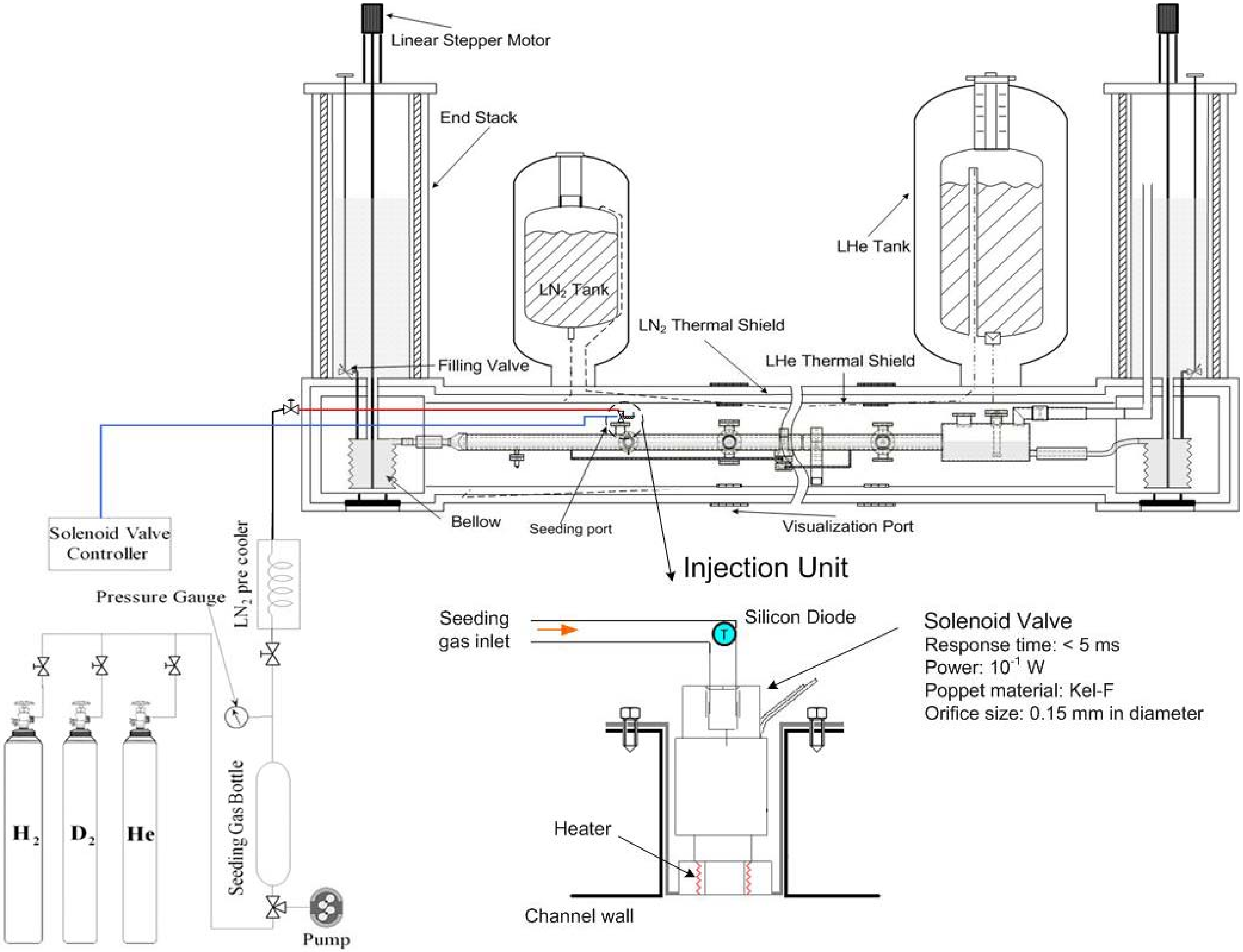
$T = 2$ K, $q_A = 11.8$ kW/m^2

$v_n = 42$ mm/s Re = 8000

Forced flow helium PIV apparatus

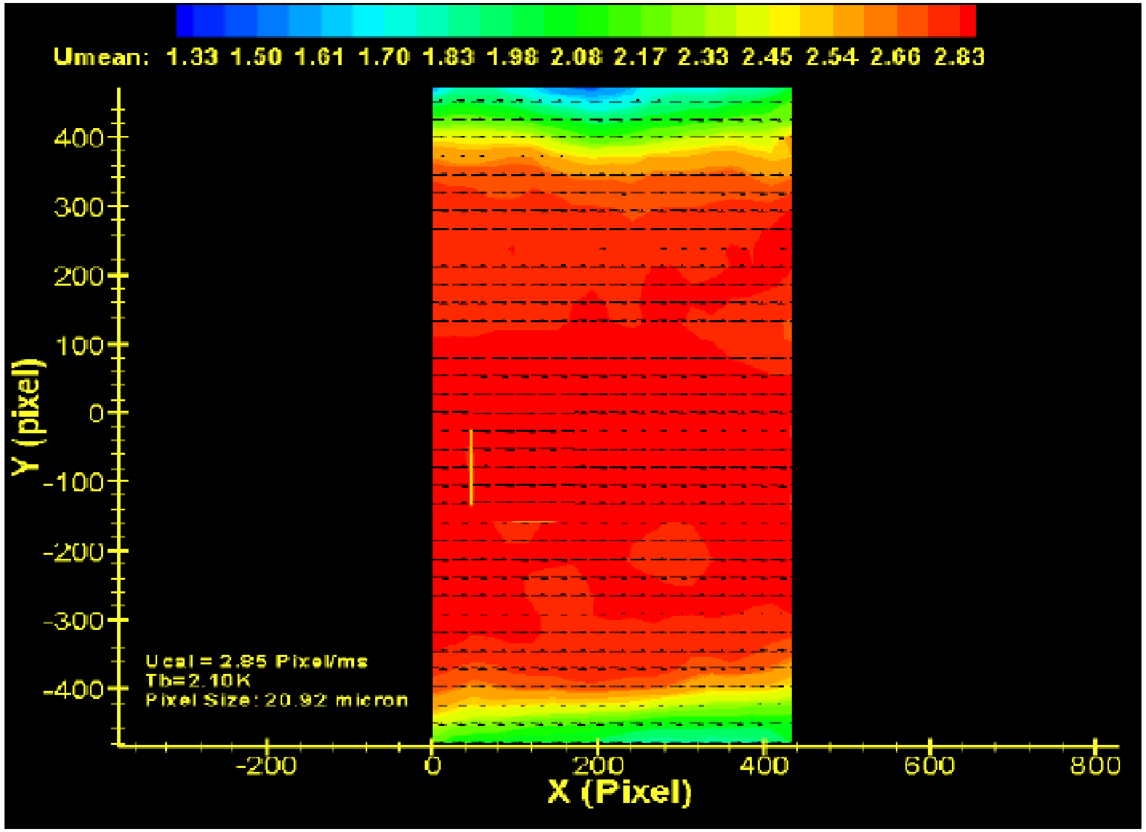






Linear Stepper Motor
End Stack
LN$_2$ Tank
LHe Tank
LN$_2$ Thermal Shield
LHe Thermal Shield
Filling Valve
Solenoid Valve Controller
Bellow
Seeding port
Visualization Port
Injection Unit
LN$_2$ pre cooler
Pressure Gauge
Seeding Gas Bottle
Pump
H$_2$
D$_2$
He
Seeding gas inlet
Silicon Diode
T
Solenoid Valve
Response time: < 5 ms
Power: 10^{-1} W
Poppet material: Kel-F
Orifice size: 0.15 mm in diameter
Heater
Channel wall

Forced flow velocity field

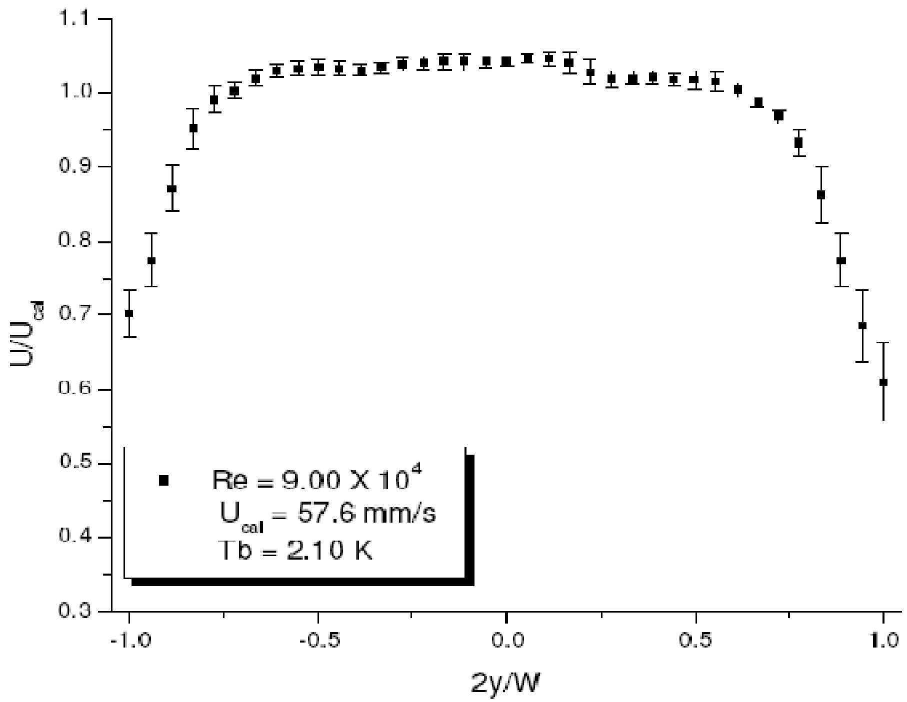


T_b = 2.1 K
U_{cal} = 57.6 mm/s

- Large uniform velocity region in center of channel (U ~ U_{cal})

- Velocity profile near the wall suggests the existence of boundary layer

Forced flow helium II boundary layer



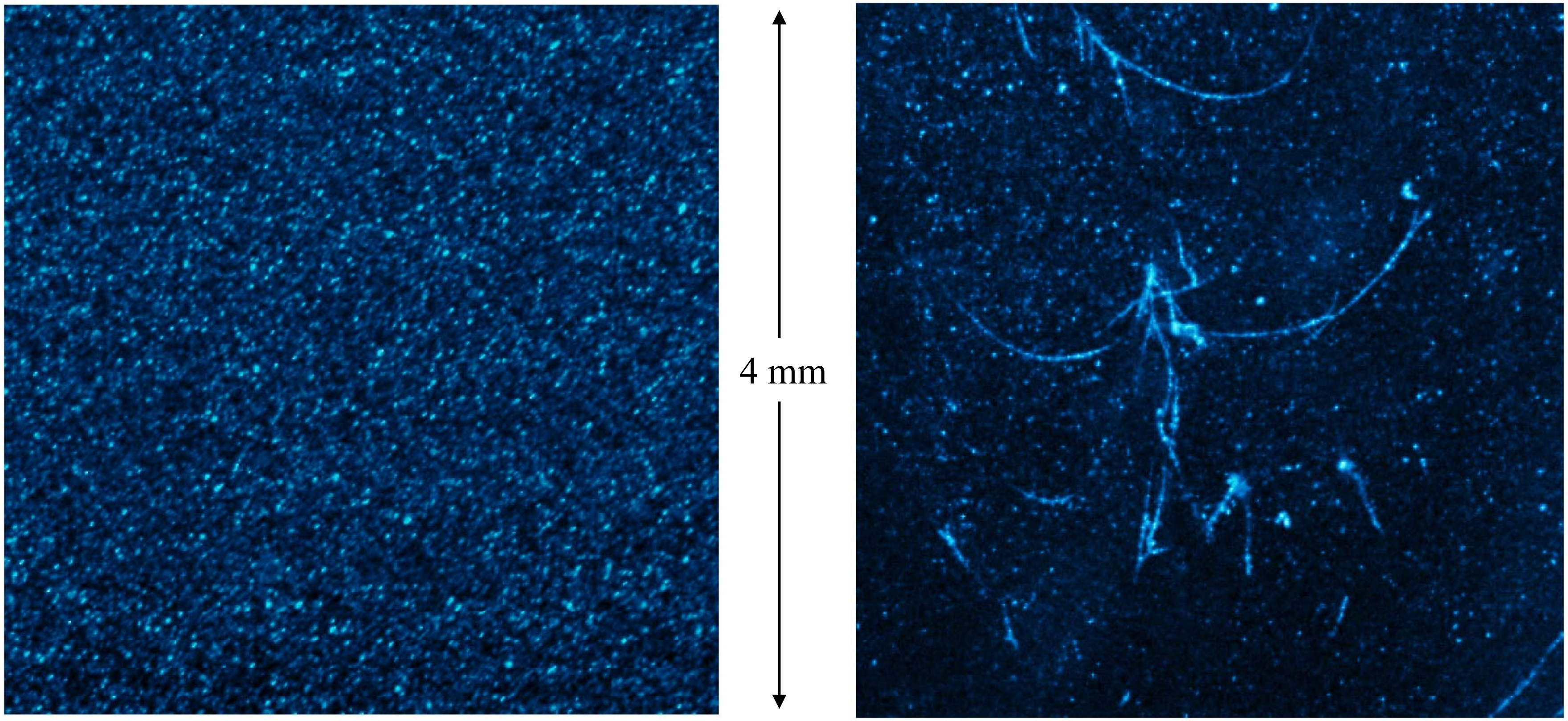
For classical turbulence flow in smooth round pipe, the velocity profile can be written in the following form:

$$\frac{U}{U_{\max}} = \left(\frac{y}{R}\right)^{\frac{1}{n}}$$

However, this channel is of square cross section so some modification of the above form is expected.

U_{mean}*: Calculated average velocity; W: Channel width; y: location of the data point along the vertical axis, zero sets to be bottom of the channel.

sH_2 particle trapping (Bewley, et al)

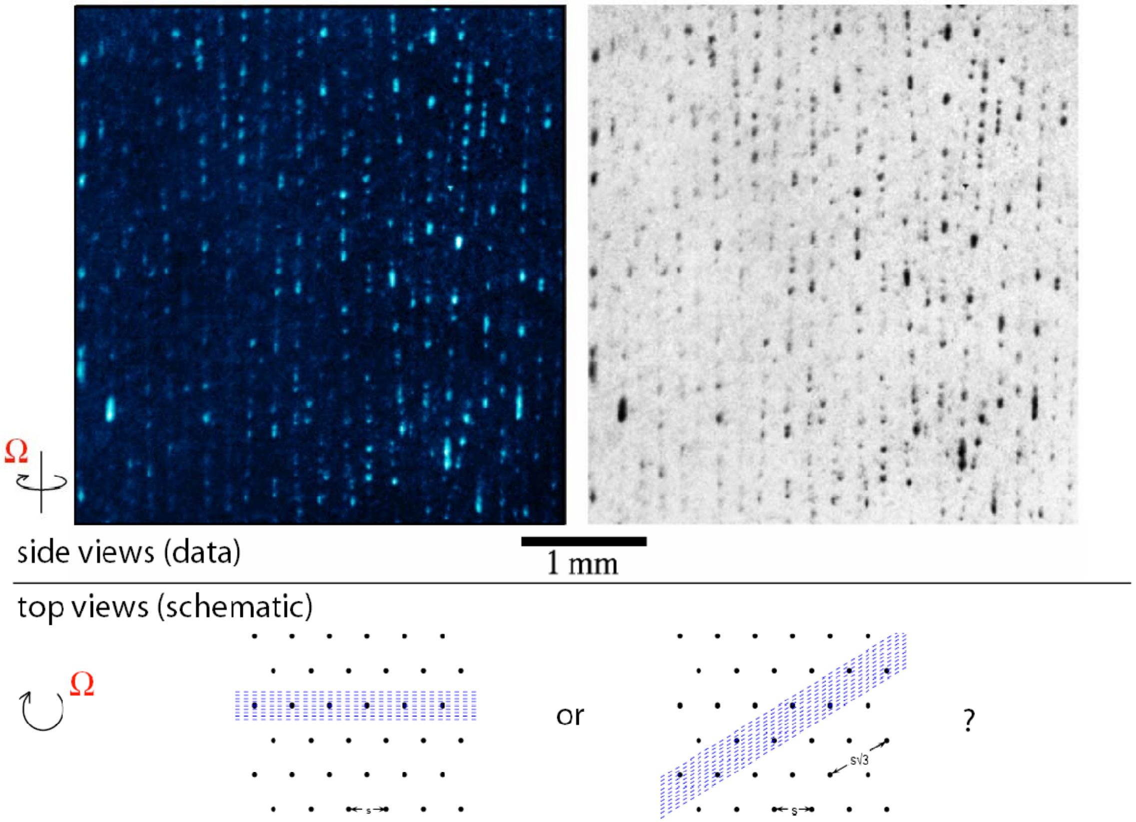


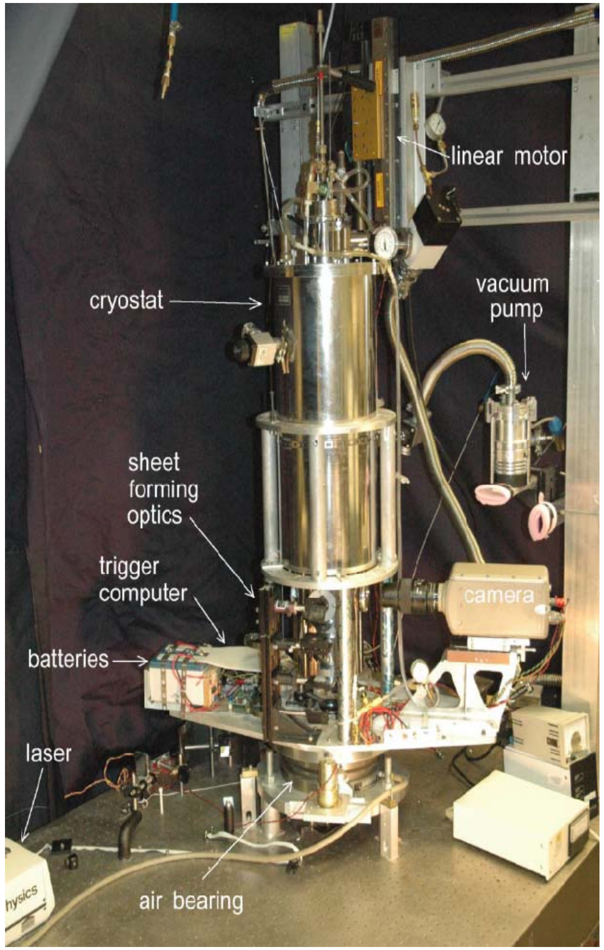
Normal He I, $T > T_\lambda$

Superfluid He II, $T < T_\lambda$

G. P. Bewley, D. Lathrop and K. Sreenivasan, Nature Vol. 441, 588 (2006)

Vortex lines in rotating helium II





Further Reading

1. R. J. Adrian, "Particle Imaging Techniques for Experimental Fluid Mechanics", Annu. Rev. Fluid Mech., Vol. 23, 261-304 (1991)
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Interaction of sphere and quantised vortex

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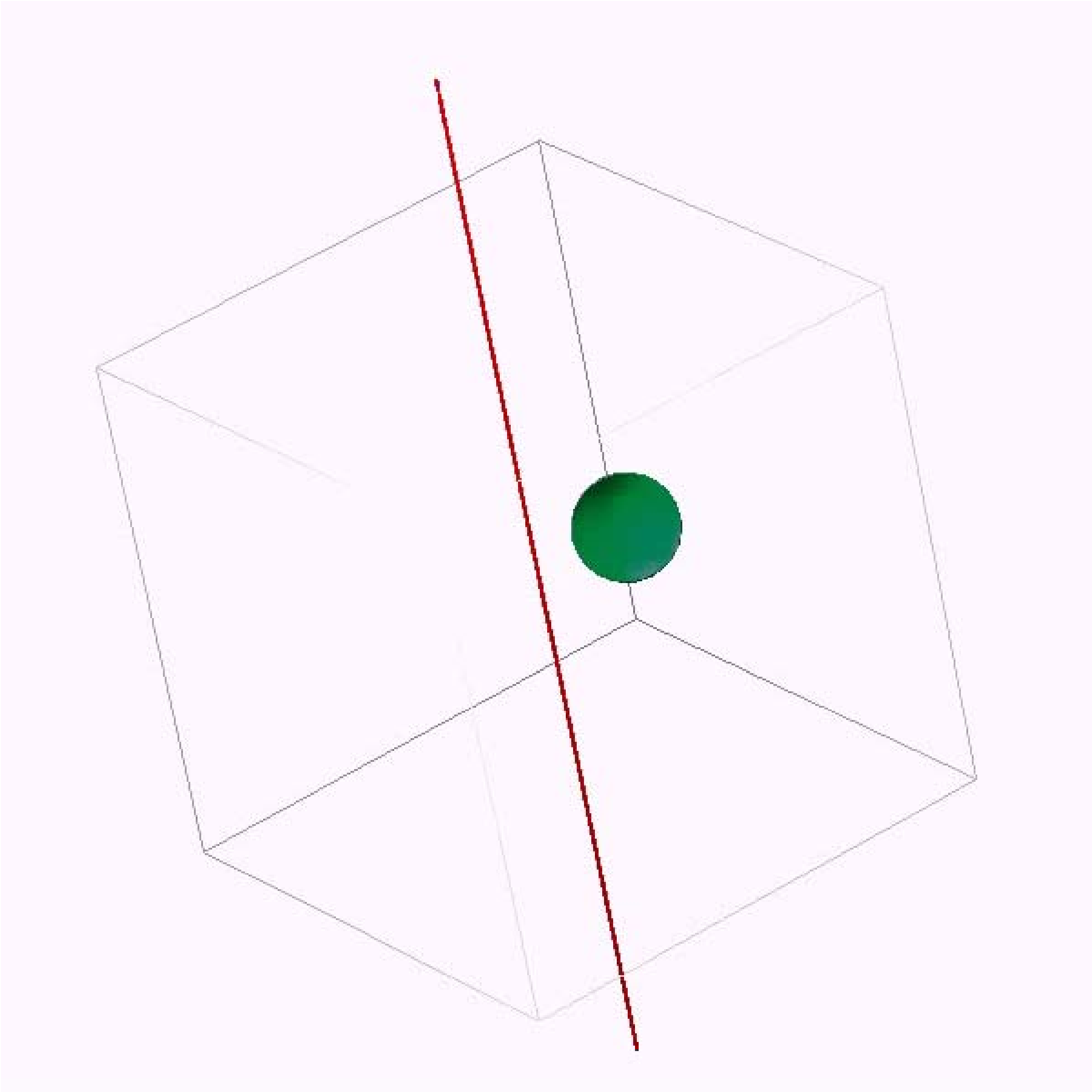
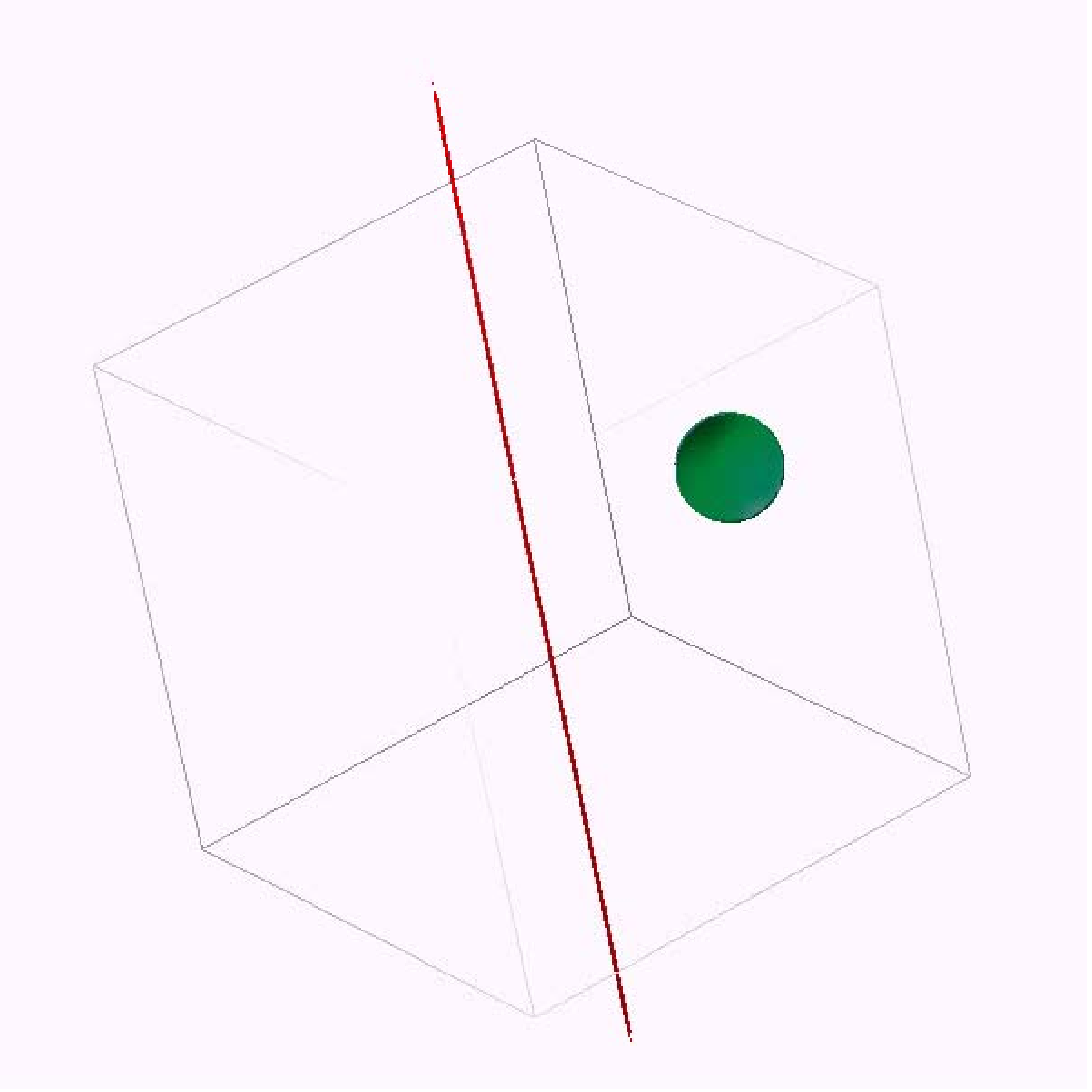
The velocity of each point X along the vortex depends on the Biot-Savart law, the presence of the spherical boundary, the potential superflow induced by the moving sphere and the friction with the normal fluid:

$$\frac{d\vec{X}}{dt} = \vec{V}_s + \vec{V}_\phi + \vec{V}_b + \vec{V}_f$$

The acceleration of the sphere depends on the presence of the boundary, the time-varying superflow and the drag with the normal fluid:

$$m_{eff} \frac{d\vec{v}}{dt} = \vec{f}_d + \vec{f}_t + \vec{f}_b$$





Another possible PIV method:
(Dan McKinsey, Yale)

Laser-induced fluorescence of He2 molecules in liquid helium