Visualizing Counterflow Heat Transport in Superfluid Helium (He II)*

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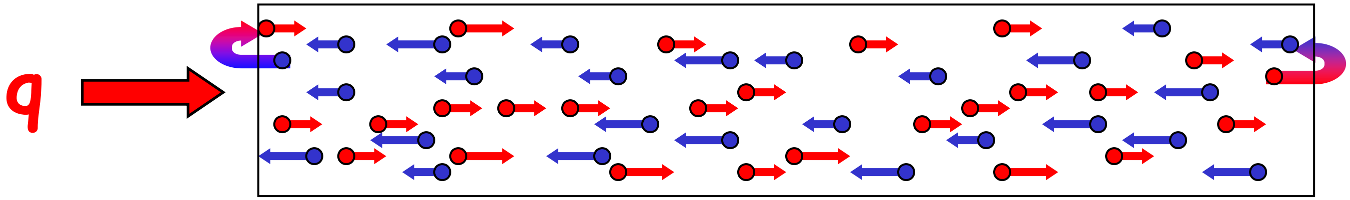
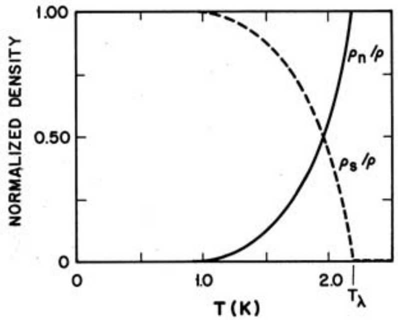
Two Fluid Model for He II

- The model (developed by Landau and Tisza) is similar to the two fluid model for superconductivity
- Semi-empirical fluid dynamics model for describing the dynamic behavior of He II.
- He 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 a heat current that produces pressure and temperature gradients ($q = \rho s T \langle v_n \rangle$)

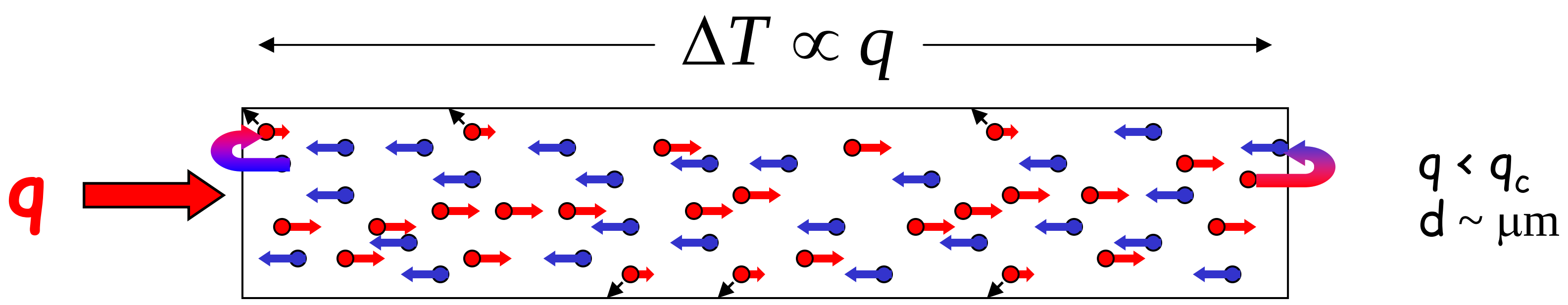
"It should, however, be most decidedly emphasized that regarding the liquid (He II) as a mixture of normal and superfluid parts is no more than a convenient description of the phenomena which occur in a quantum fluid"

L. D. Landau & E. M. Lifshitz

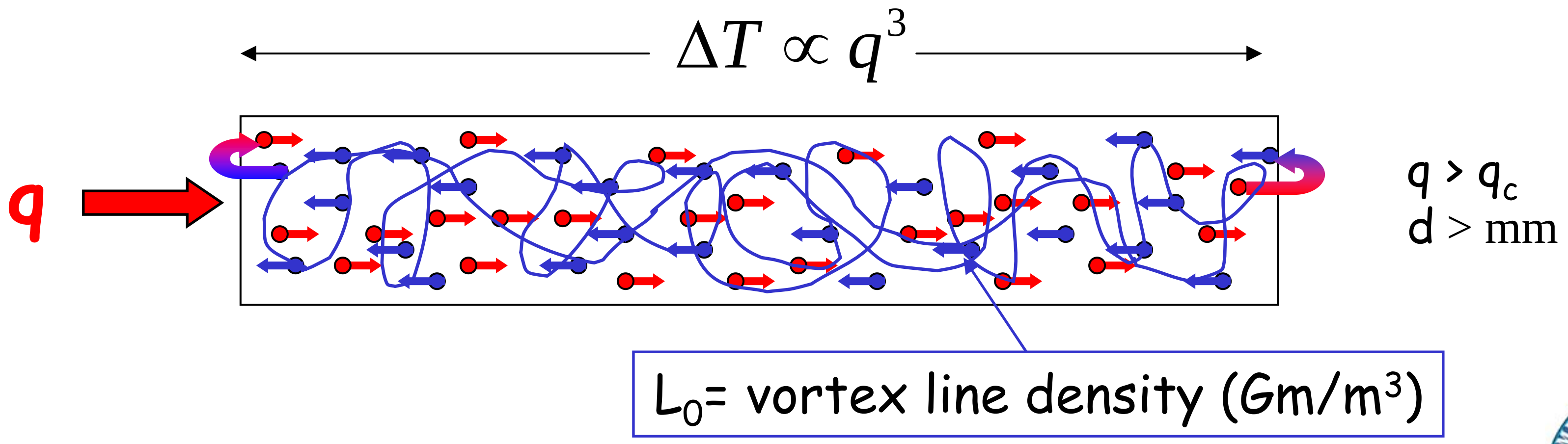
Fluid Mechanics, p. 515

Counterflow heat transport in He II

- Normal fluid viscous interaction with channel walls (laminar flow)

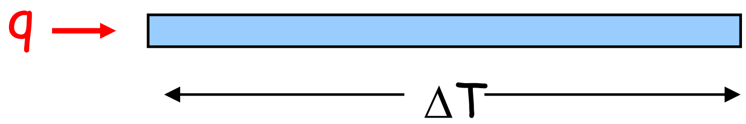


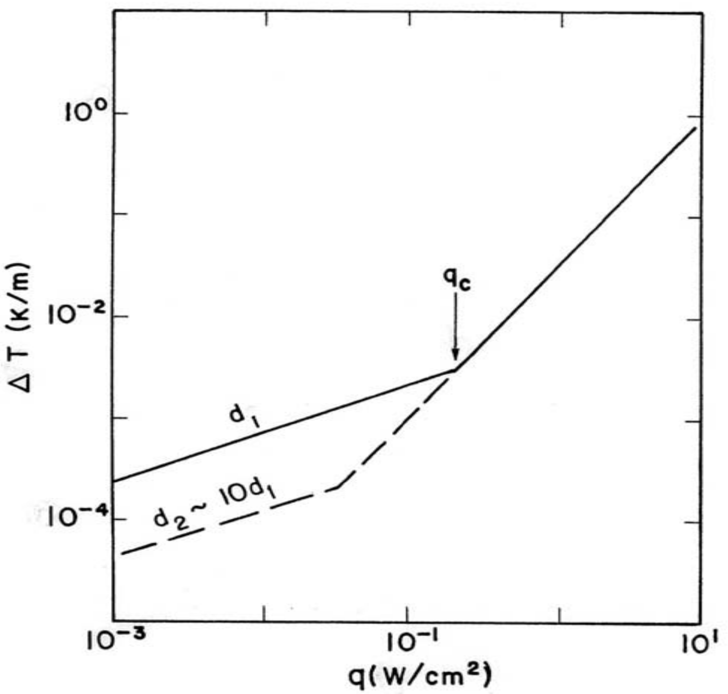
- Mutual friction between normal fluid and turbulent superfluid



Steady state heat transport in He II

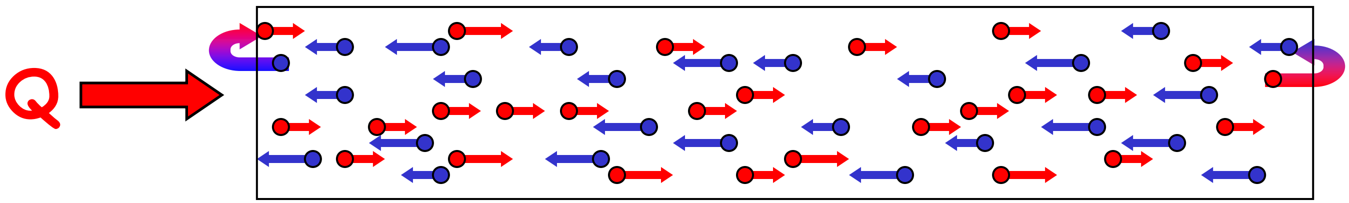
- Anomalous heat transport
  - Effective heat conductivity comparable to that of high purity metals
  - Low flux, laminar regime
    $dT/dx \sim q$
  - High flux, turbulent regime
    $dT/dx \sim q^3$
  - Transition between two regimes marks onset of quantum turbulence and depends on diameter of channel



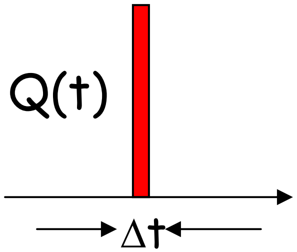


Transient Heat Transport (2^{nd} sound)

- He II can sustain ordinary first sound (pressure waves, $\rho(p)$) and "second sound" (entropy waves, $\rho_s/\rho_n(T)$).
- Second sound can propagate as a standing wave or a pulse that carries entropy



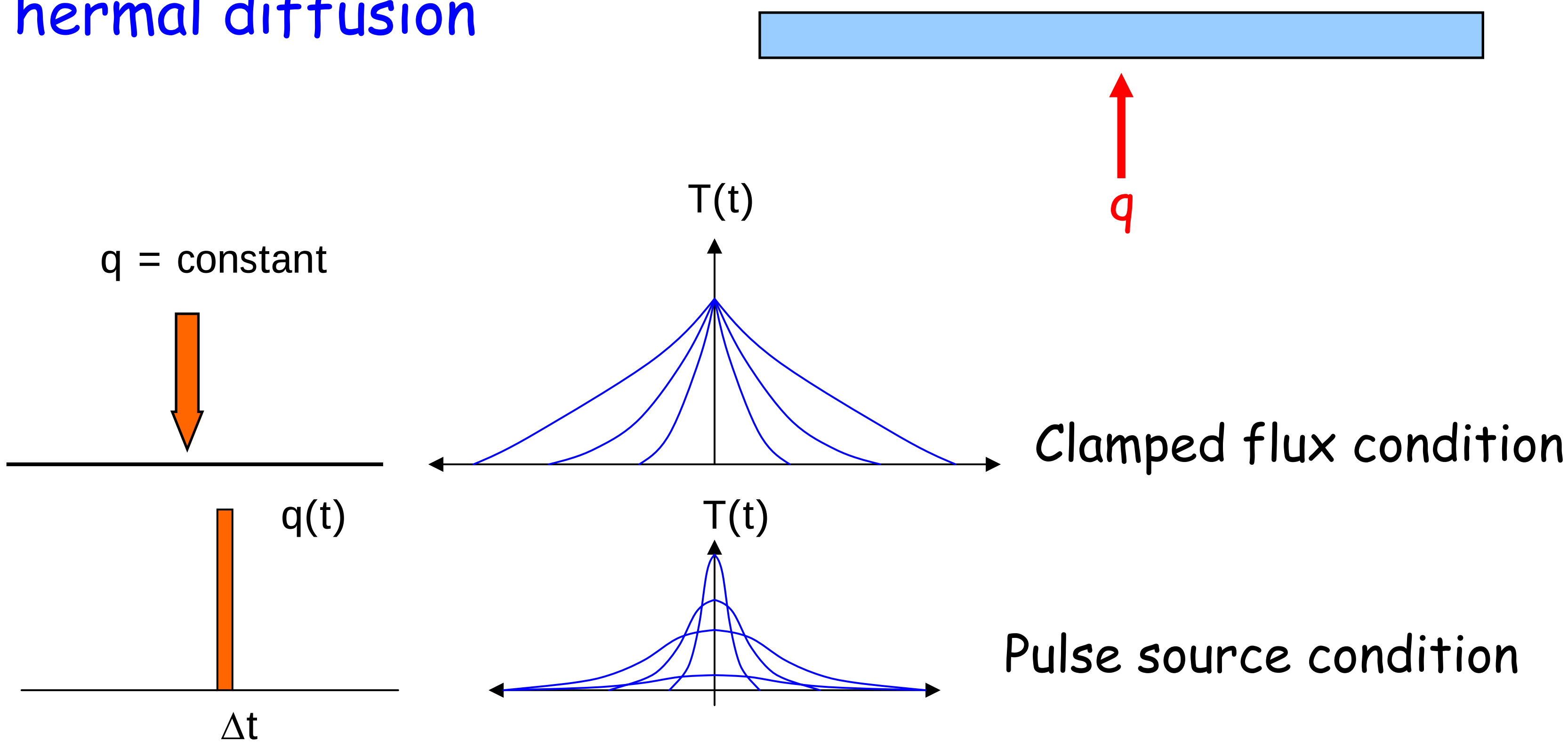
- Characteristic velocity of second sound C_2 ~ 20 m/s (~1/12 that of first sound, C_1)
- High intensity second sound pulses create turbulence and thermal shock



$Q > 10\ \mathrm{W/cm^2}$
$\Delta t < 1\ \mathrm{ms}$

Transient Heat Transport: Diffusion

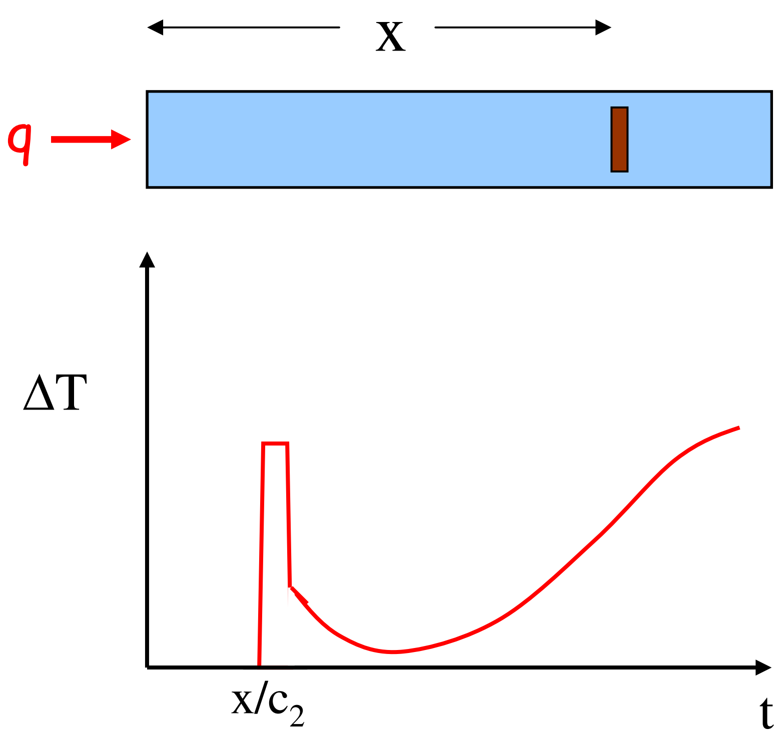
- Thermal diffusion



These processes are described by the He II non-linear diffusion equation

Summary: He II diffusion + 2nd sound shock

- Short, intense pulses carried by second sound
- Longer, less intense pulses diffuse from heat source into bulk He II
- Both processes are described in terms of average values of v_n and v_s.
- Previous work limited to counterflow in 1D
  - dv_n/dx is small

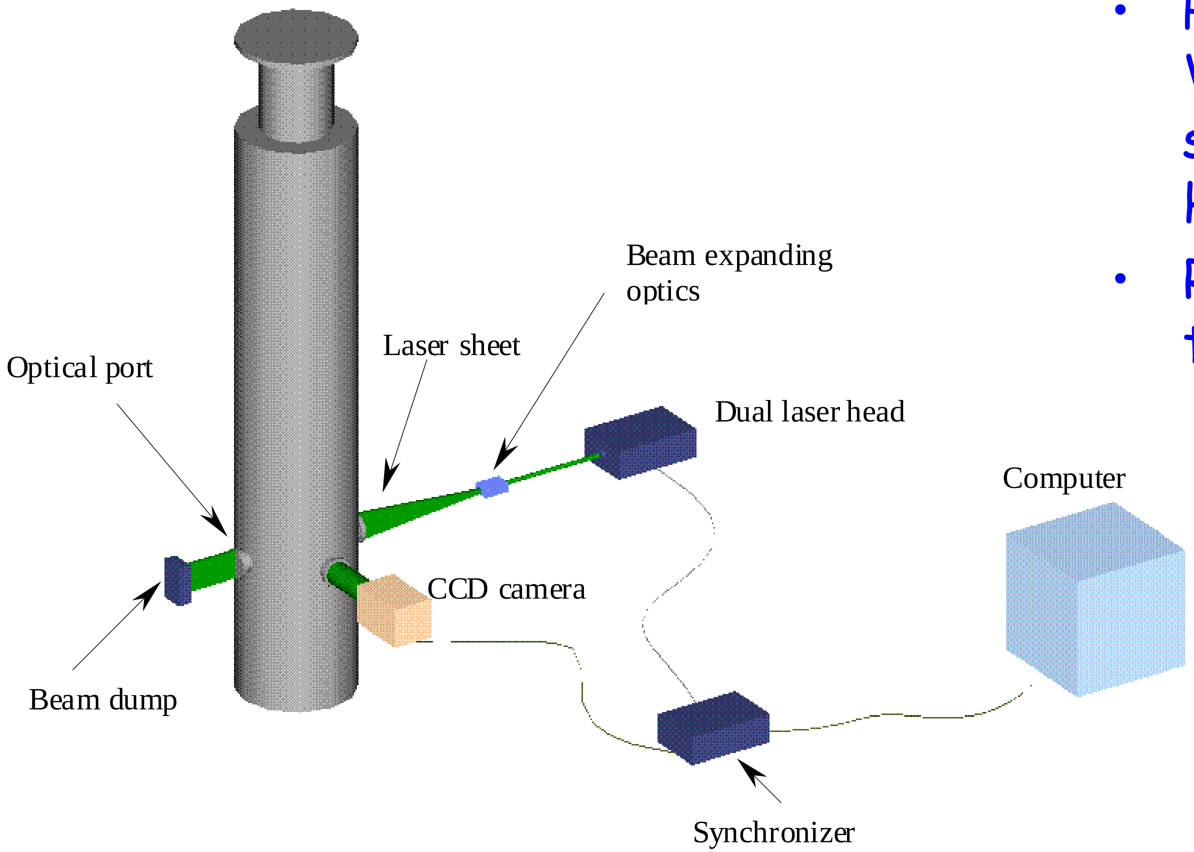


How do we visualize these phenomena?

- Previous attempts to visualize motion of the fluid components in He II
  - Tagging with ions (Schwarz, et al)
  - Droplets of ^{3}He (Lucas, et al)
  - Laser Doppler Velocimetry (Murakami, et al)
    - H_2/D_2 solid particles d ~ 10 μm
    - Glass spheres 20 μm < d < 100 μm, Re ~ 8000
- Particle Image Velocimetry (PIV)
  - Insert neutral density particles (d ~ 1μm)
  - Monitor motion of particles to determine if they follow the normal fluid component
  - Whole field measurement
  - Study complex geometries and transient effects

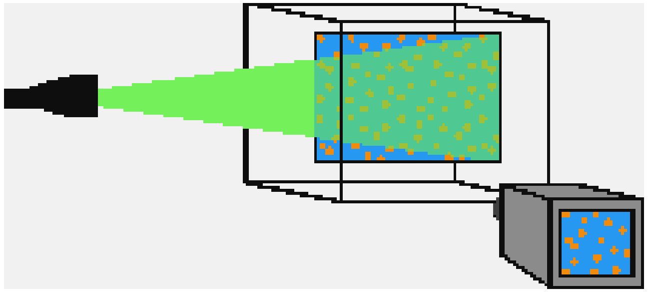
Counterflow Jet

Particle-Image-Velocimetry Measurement in He II

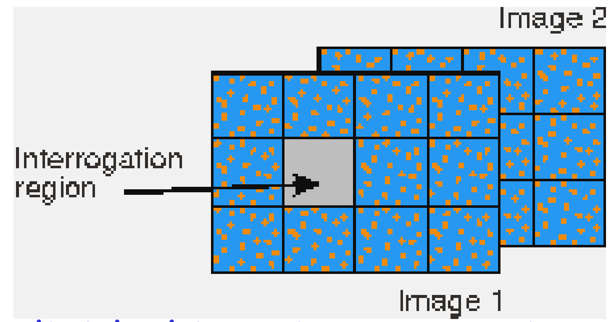


- Particle Image Velocimetry (PIV) studies of flow fields in He II
- Requirements of technique
  - Pulse laser
    - Nd:YAG: (532 nm)
    - Diode (795 nm)
  - Optical cryostat with image collection system
  - Neutral density particles (d < 10 μm)

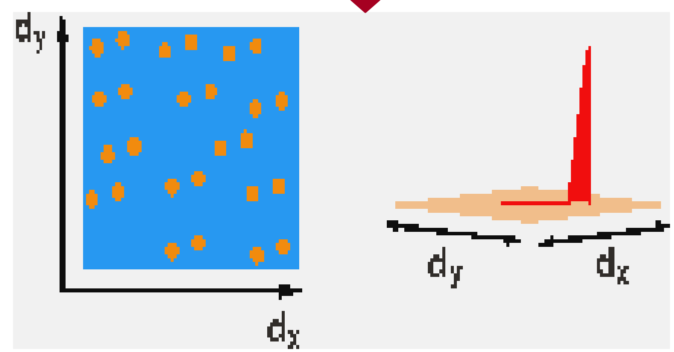
Particle Image Velocimetry Technique



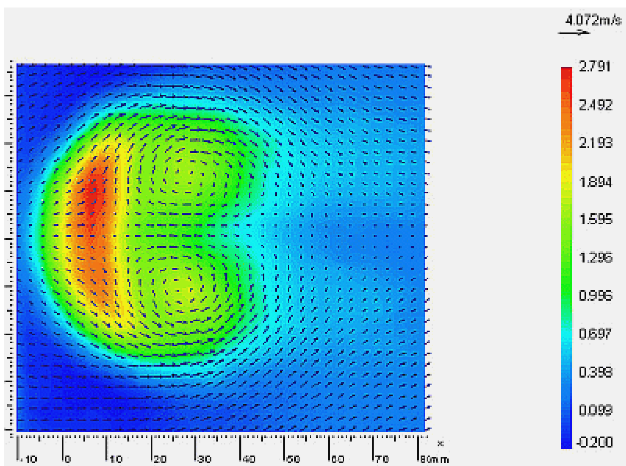
1. Flow seeding and image acquisition



2. Subdivided into interrogation windows

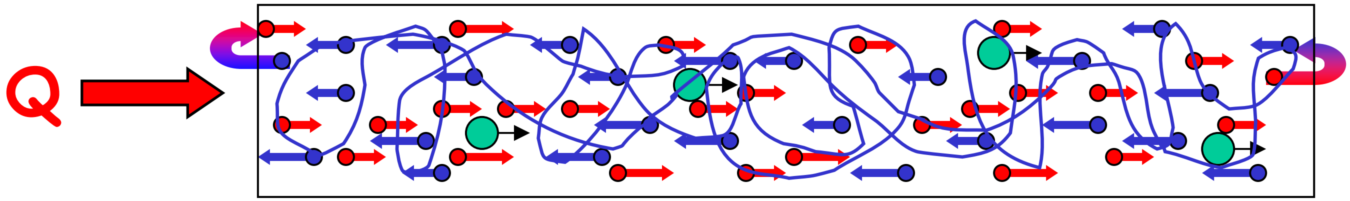


3. Correlation process



4. Result – velocity field

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 Tracking Characteristics

- Concentration
  - Statistics for velocity measurement
  - Particle-fluid interaction affect dynamics

  } $C \sim 10^9/m^3$, $d_p \sim 10\ \mu m$

- Slip velocity between particles and fluid

$$v_n - v_p = \frac{(\rho_p - \rho_{HeII}) d_p^2 g}{18 \phi \mu_n}$$

$$\phi = 1 + f(\mathrm{Re}_p)$$

For deviation from Stokes law

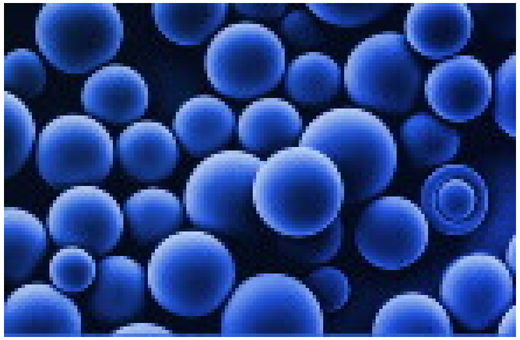
  - Small viscosity (~ 1.4 μPa.s) makes slip a significant issue
  - Particle density should be ~ $\rho_{He\ II}$ ~ 145 kg/m^3
  - Extremely small particle size (d < 10 μm)

- Response time

$$\tau \equiv \frac{(\rho_p + \frac{1}{2}\rho_{HeII}) d_p^2}{18 \phi \mu_n}$$

τ ~ 1 ms for d_p = 10 μm

Candidate particles for seeding



- Hollow glass spheres
  - Density around 160 kg/m^3
  - Particle size distributed from 30 to 120 μm
- Polymer micro-spheres
  - High density around 1100 kg/m^3
  - Small uniform diameter ~ 1.7 μm
- Solidified H_2/D_2 particles (condensed from gas phase)
  - Density around that of LHe (125 to 145 kg/m^3)

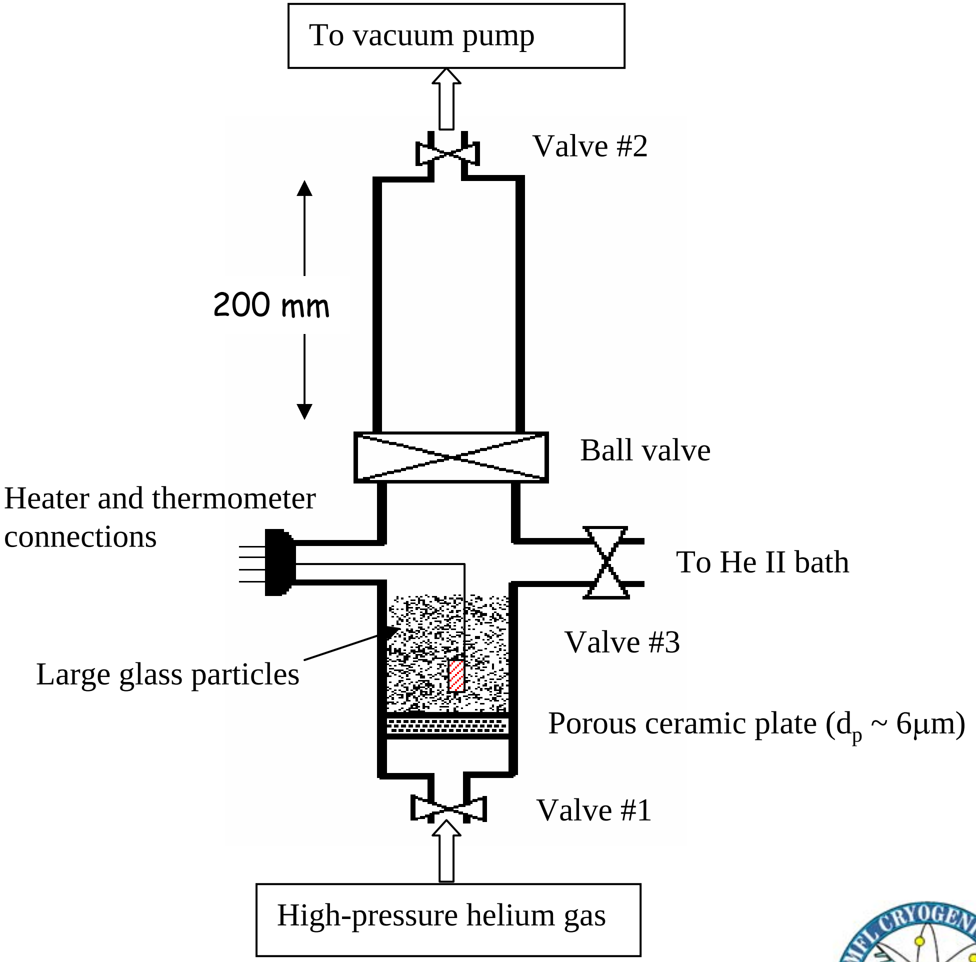
Type of particles	Size	Slip velocity	Relaxation time
Hollow glass spheres	30 μm	3.12 mm/s	8.1 ms
	120 μm	13.8 mm/s	130 ms
Polymer micro-spheres	1.7 μm	1.0 mm/s	0.13 ms
Solid H_2/D_2 particles	~ 10 μm	~ 0.2 mm/s	~ 0.9 ms

Introducing Particles into He II

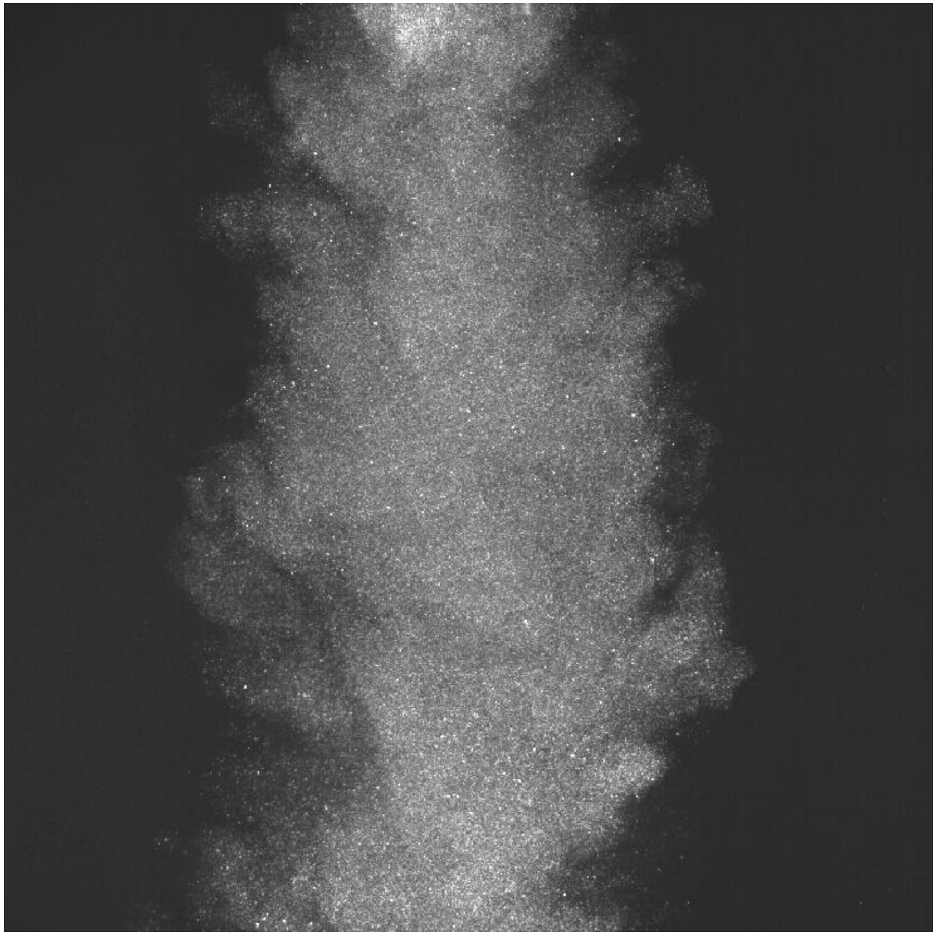
- Initial conditions:
  - Solid particles are stored at room temperature in air (or other gas)
  - H_2 & D_2 is in gaseous state at room temperature
- Experimental conditions
  - $T_{op} \sim 2$ K
  - $P_{op} < 0.05$ atm
- Issues of concern in He II application
  - Since all gases (except He) freeze at 2 K, careful purging with He gas is necessary prior to injection into He II
  - Introducing particles into low pressure environment requires particle transport system

Seeding solid particles

- Seeding requirements
  - Adequate seeding concentration
  - Minimize coagulation of particles
- Method
  - Seeding by fluidized bed technique to reduce aggregation :
    - large glass particles mixed with visualization particles
    - Purging with pure helium gas
    - Suspended particles transported in He gas stream

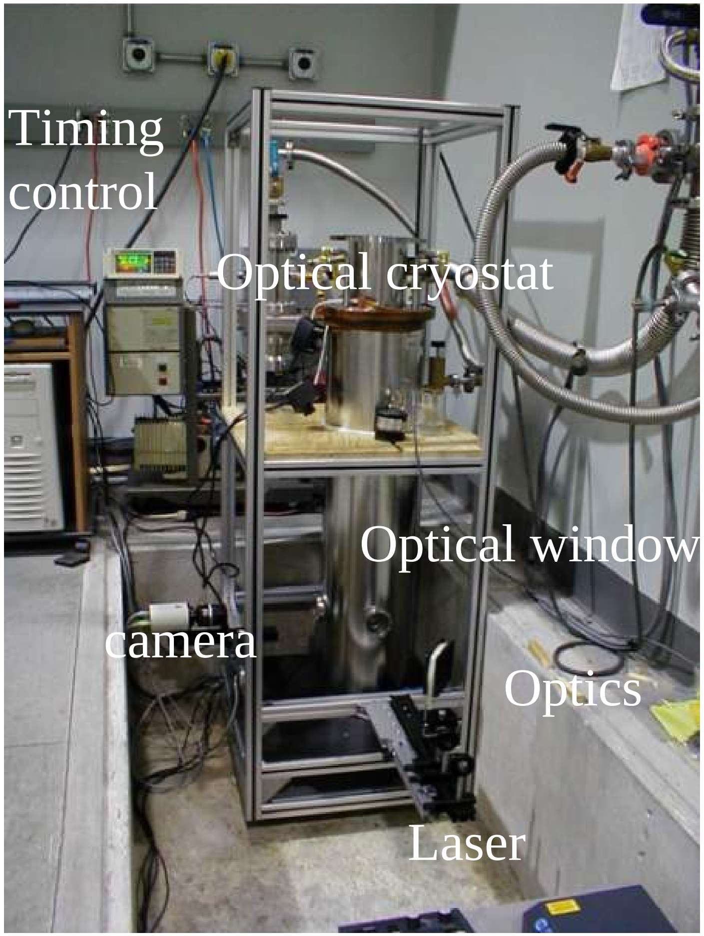


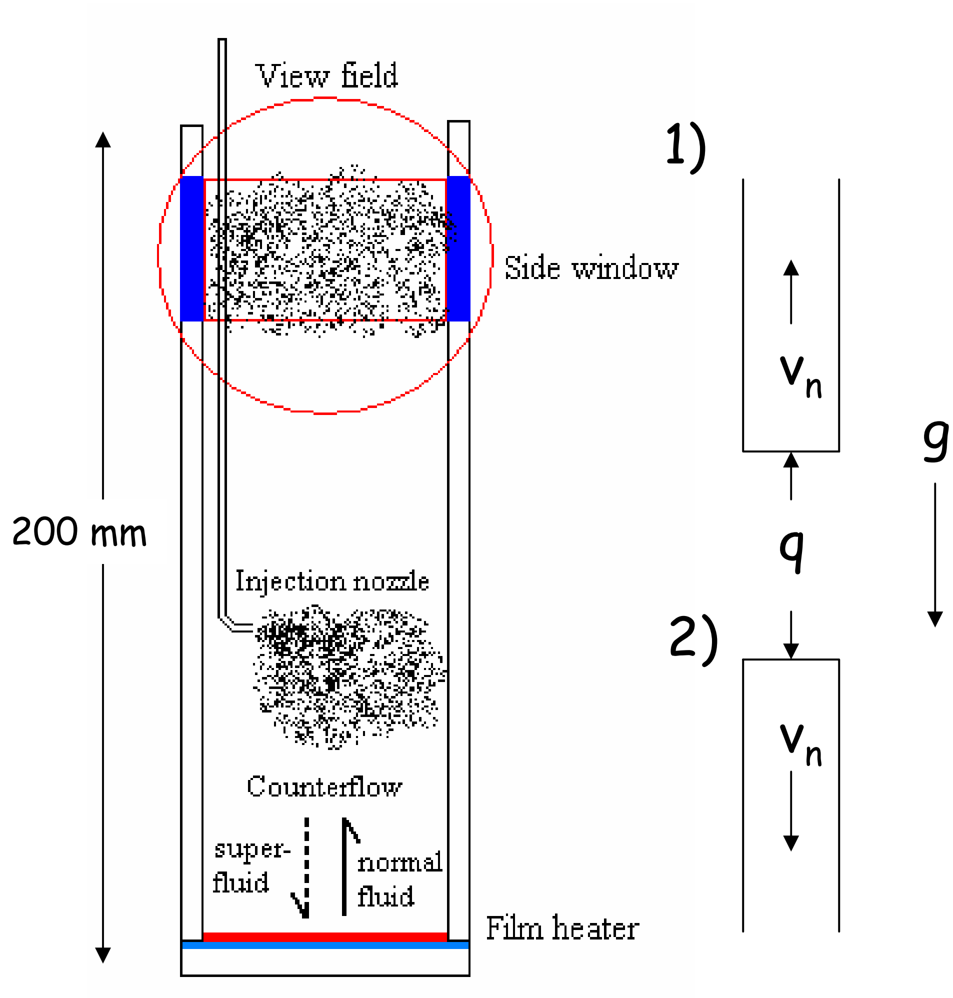
Particle seeding results



- Stable delivery of particles.
- Adequate seeding concentration.
- Aggregation of particles is reduced.
- The size of seeded particle is more uniform.
- See: T. Zhang, D. Celik and S. van Sciver, JLTP Vol. 134, 985 (2004)

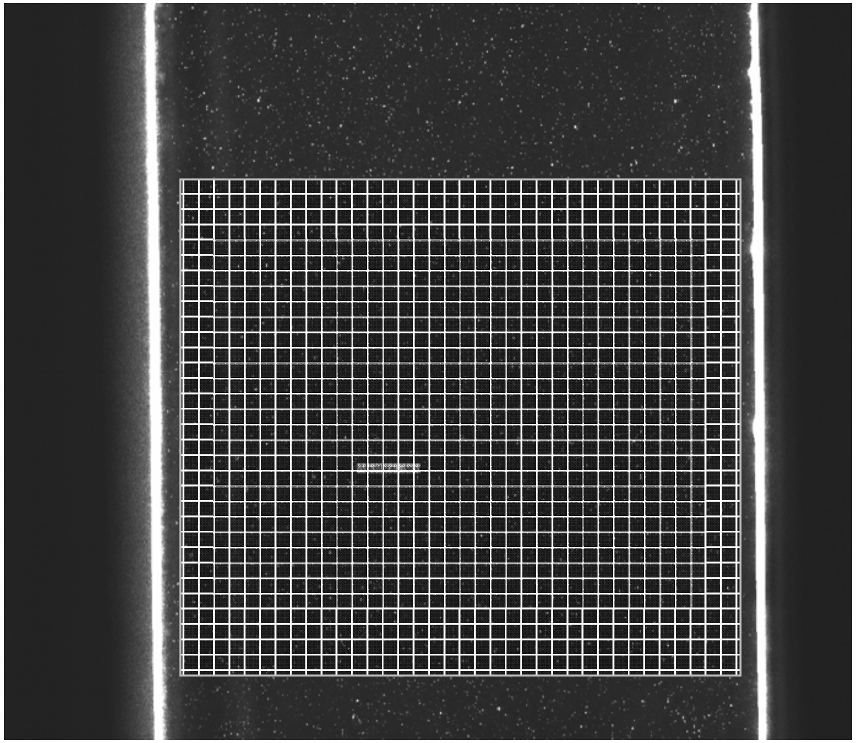
PIV He II Counterflow Experiment





43 x 19.5 mm rectangular channel

Steady State Results



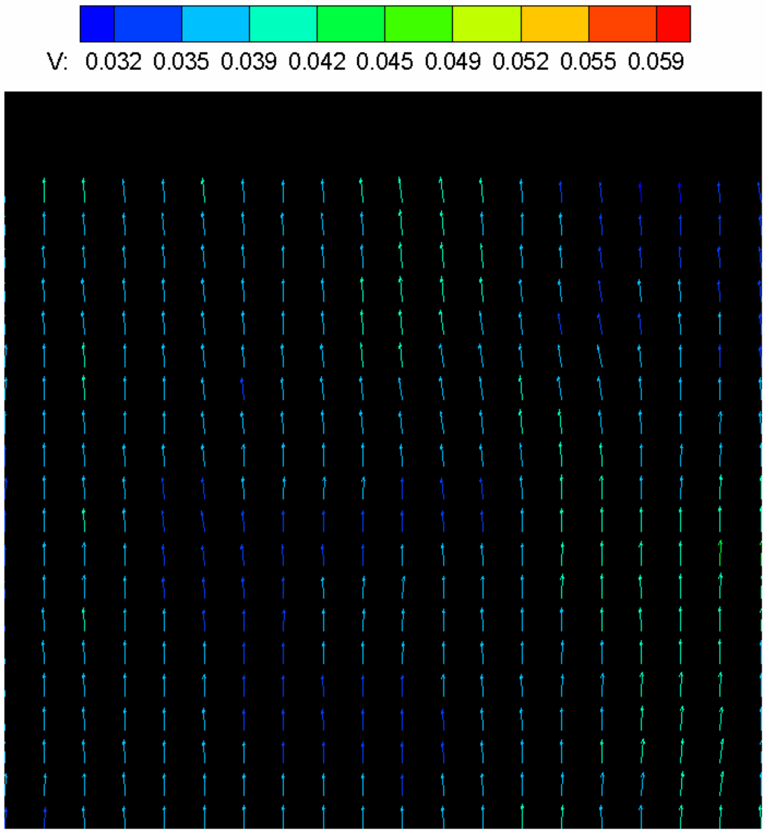


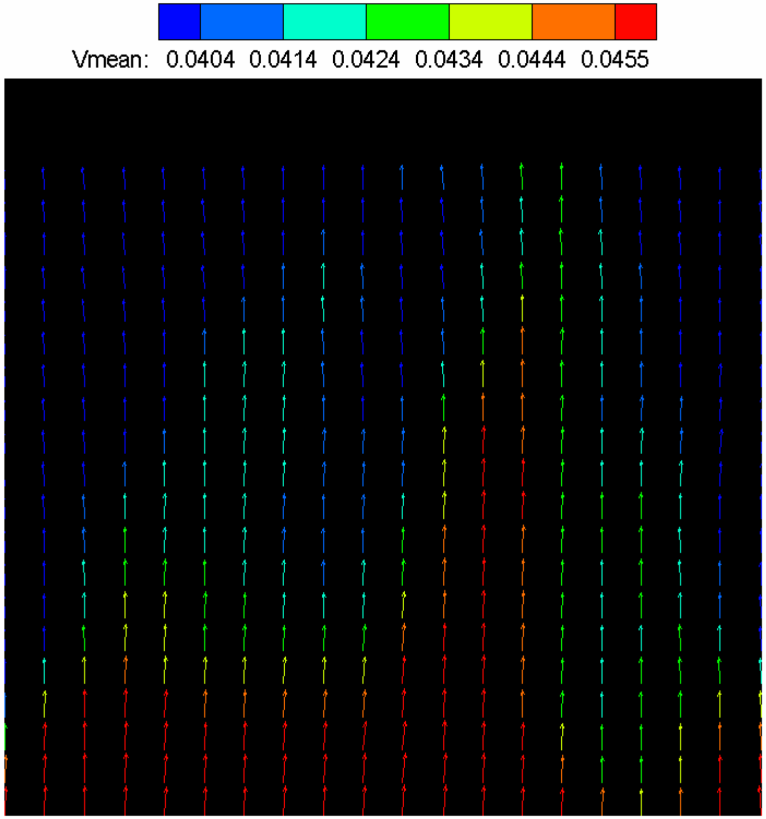
Image Acquisition Process

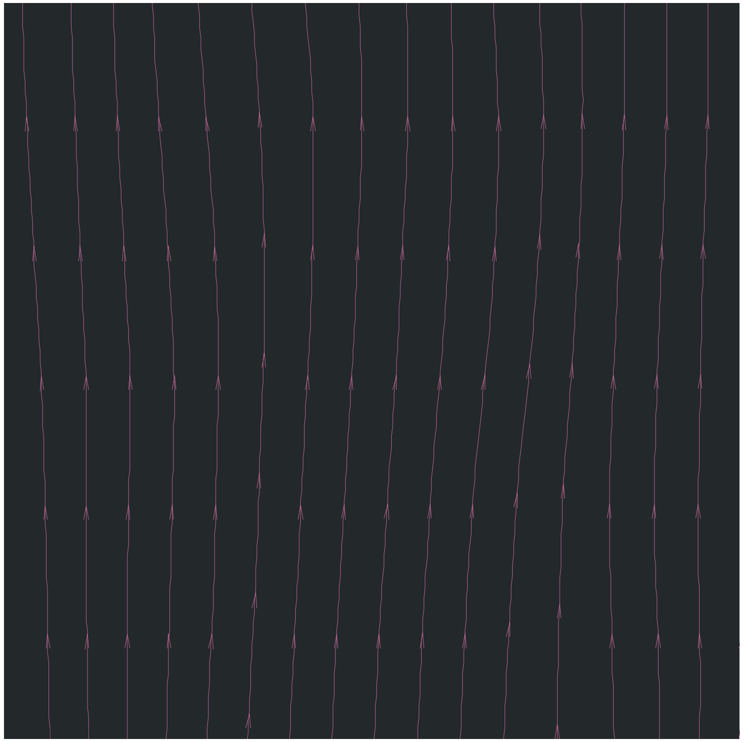
- Seeding particles are polymer spheres of ϕ = 1.7 μm, 1100 kg/m^3
- Calculated slip velocity ~ 1 mm/s
- Bright lines are channel walls

For each pair of images, the instant velocity field is obtained

- CCD camera operated at 5 Hz.
- 25 Pairs of images collected within around 5 seconds.

Analysis of PIV in counterflow He II



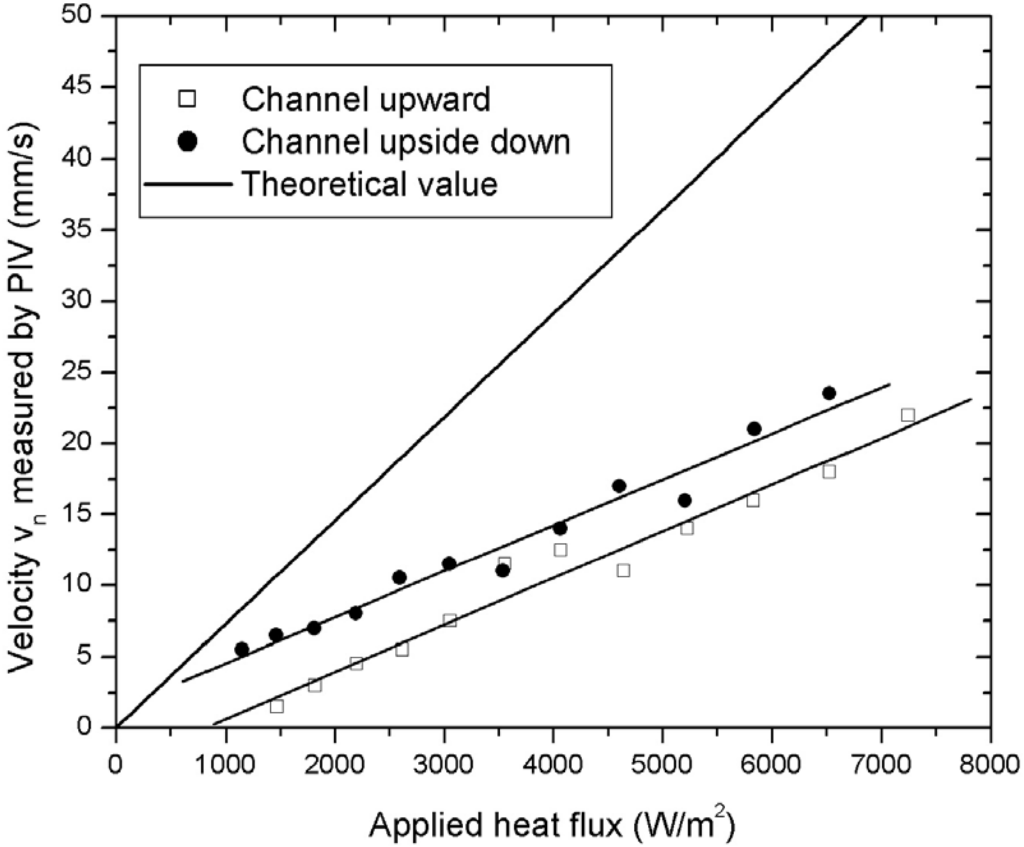


Averaged velocity field at 1.62 K and q = 7.24 kW/m^2

<v> ~ 40 - 45 mm/s while, $v_n = \dfrac{q}{\rho s T}$ ~ 100 mm/s

Comparison with theoretical results

T=1.80 K



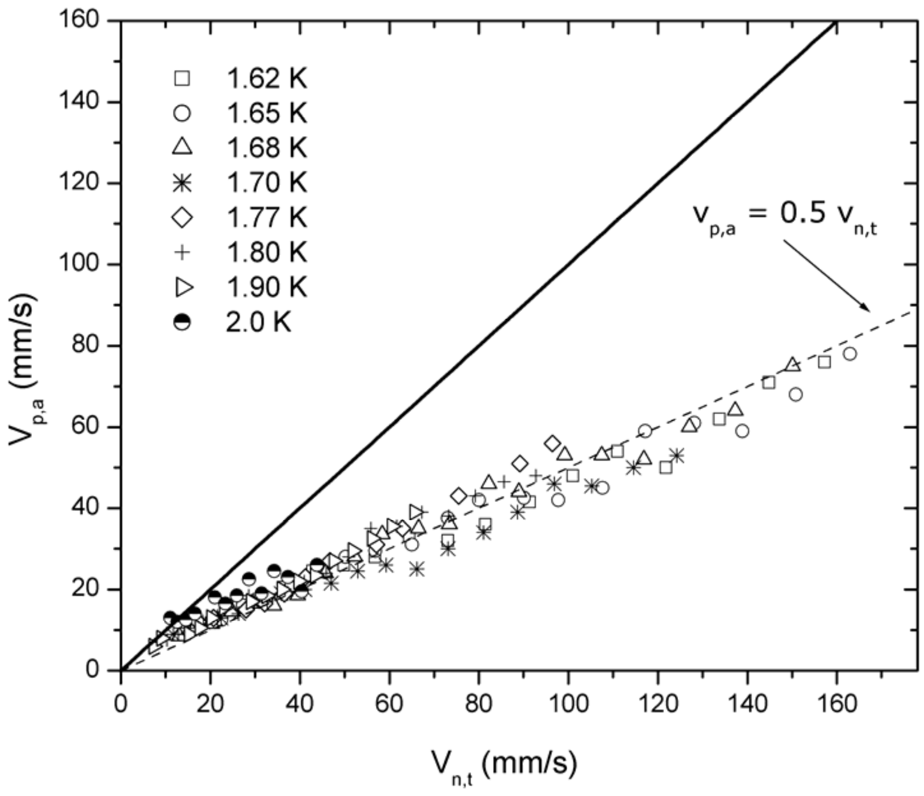
- PIV results represent the mean velocity of whole flow field.
- Theoretical value is calculated from

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

- A disagreement is clearly shown.
- Slip velocity can be eliminated by averaging two configurations

Results at various temperatures

All temperatures

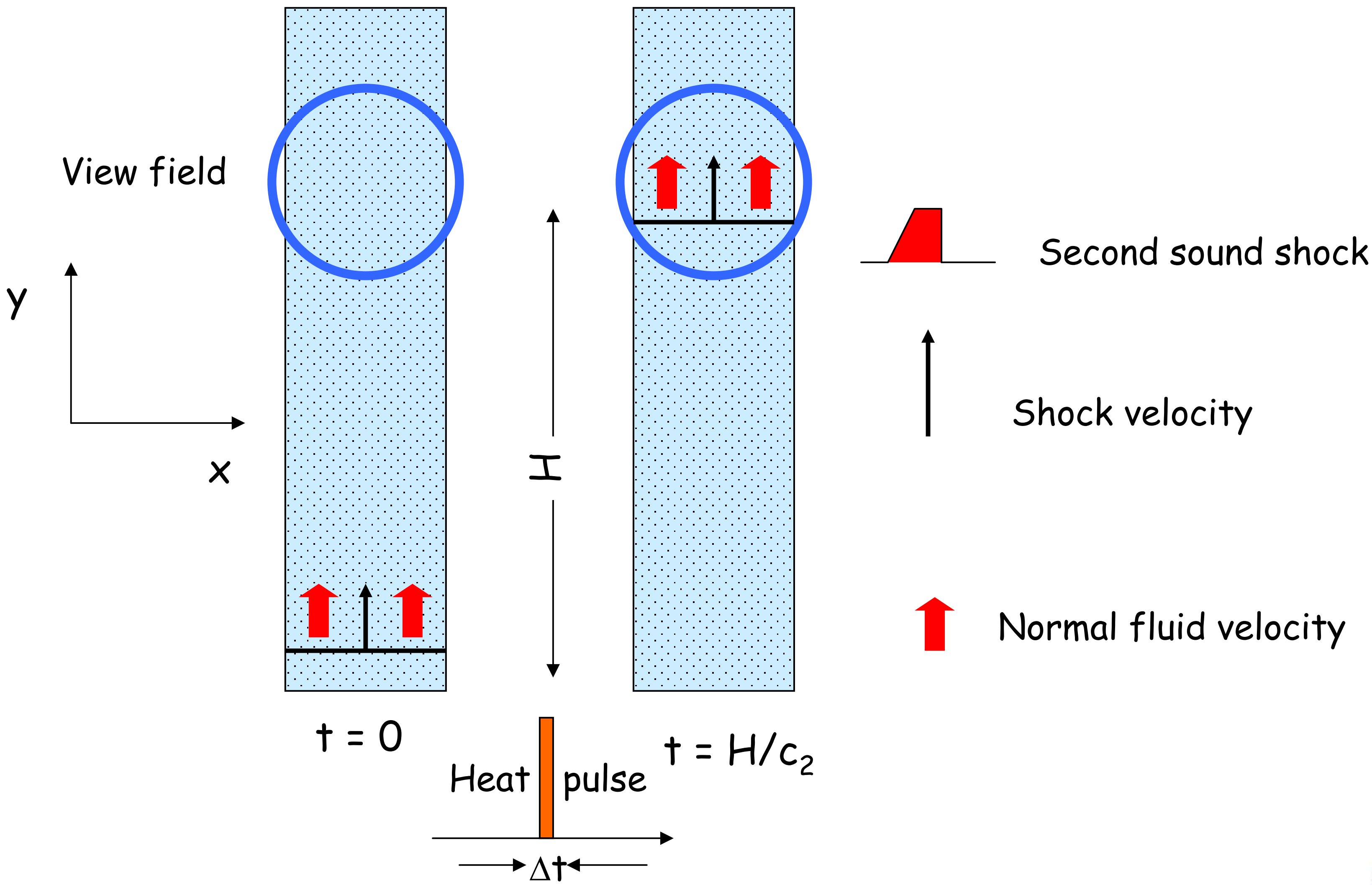


- Disagreement exists at all temperatures. $v_p/v_n \sim 0.5$
- Different result from Nakano and Murakami (Cryogenics, 34, 179 (1994))

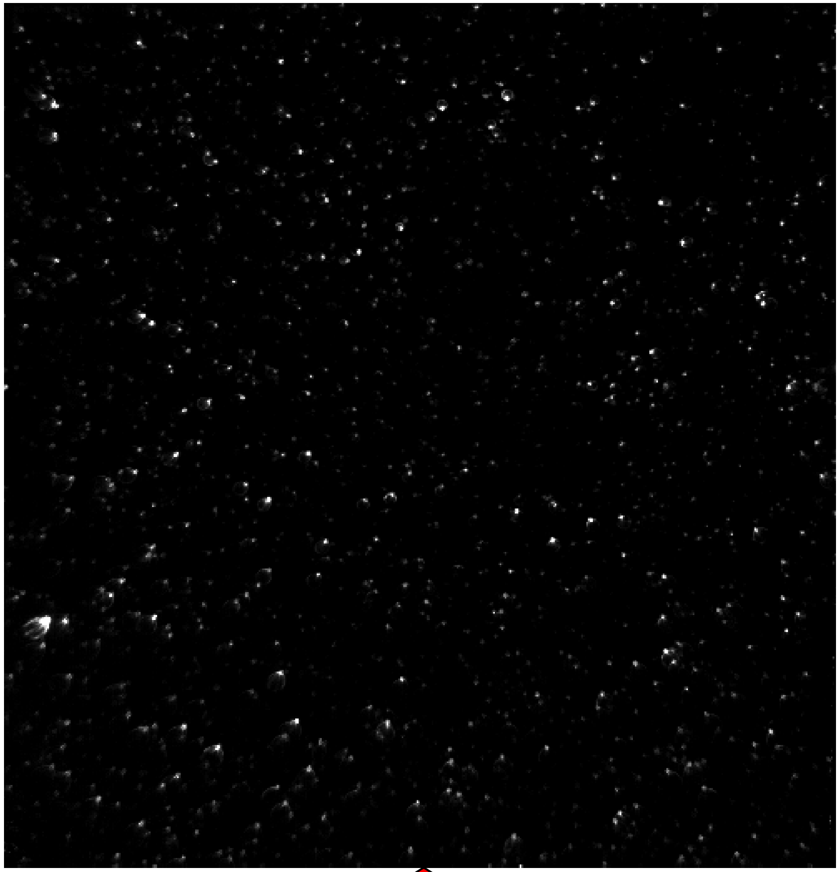
$$v_{n,measurement} = \frac{\rho_n}{\rho} v_{n,theory}$$

- Chung and Critchlow (PRL 14,892 (1965)) observed particle motion in pure superflow
- See T. Zhang & S. van Sciver, JLTP Vol. 138, 865 (2005)

PIV Measurement of Transient Counterflow



Motion of tracer particles in the He II counterflow field



Bath temperature: 1.61 K.

Pulse width: 1 second.

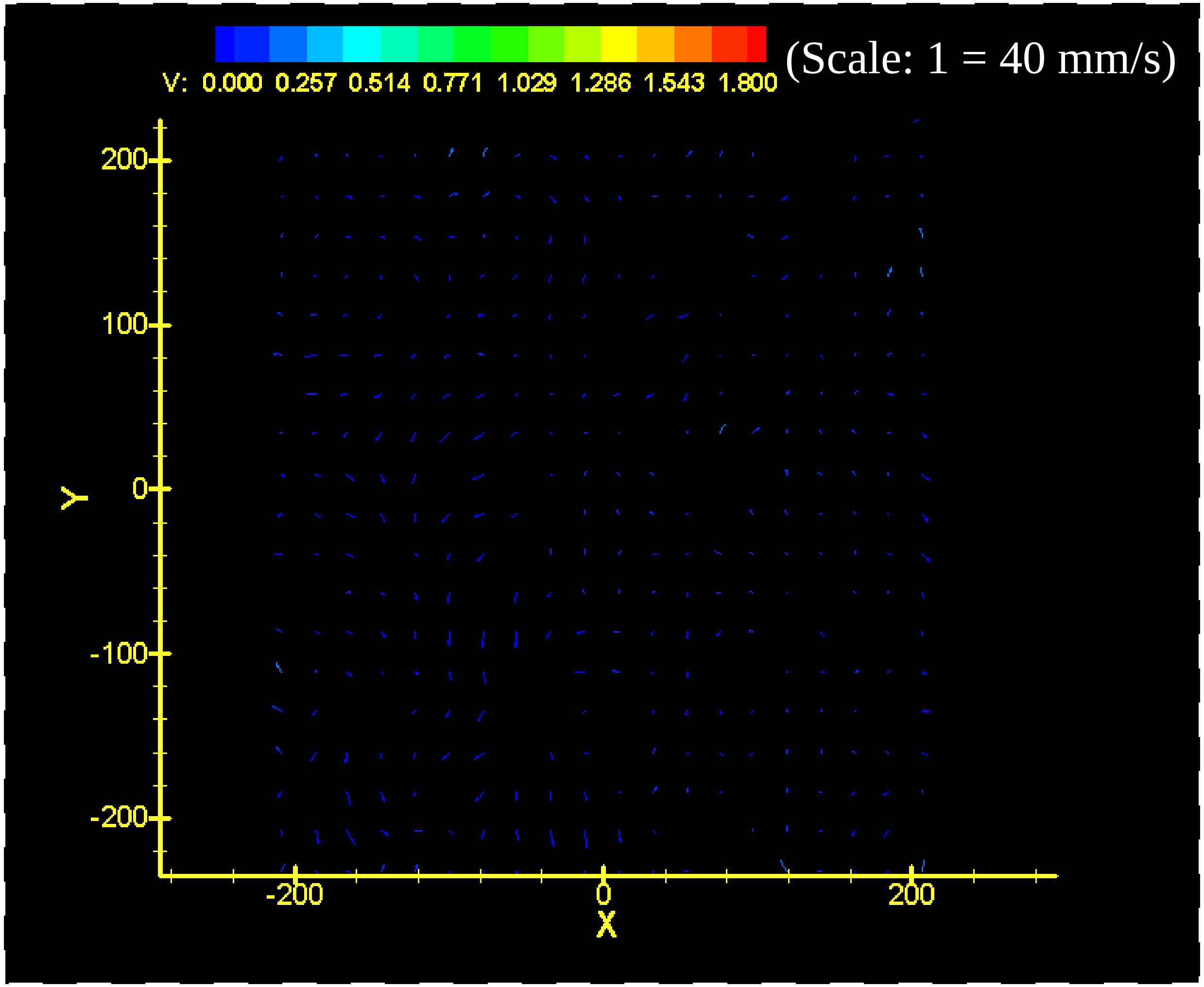
Camera operating rate: 1200 Hz.

Time interval: 0.883 ms.

Total time: 883 ms.

$Q = 11.2\ kW/m^2$

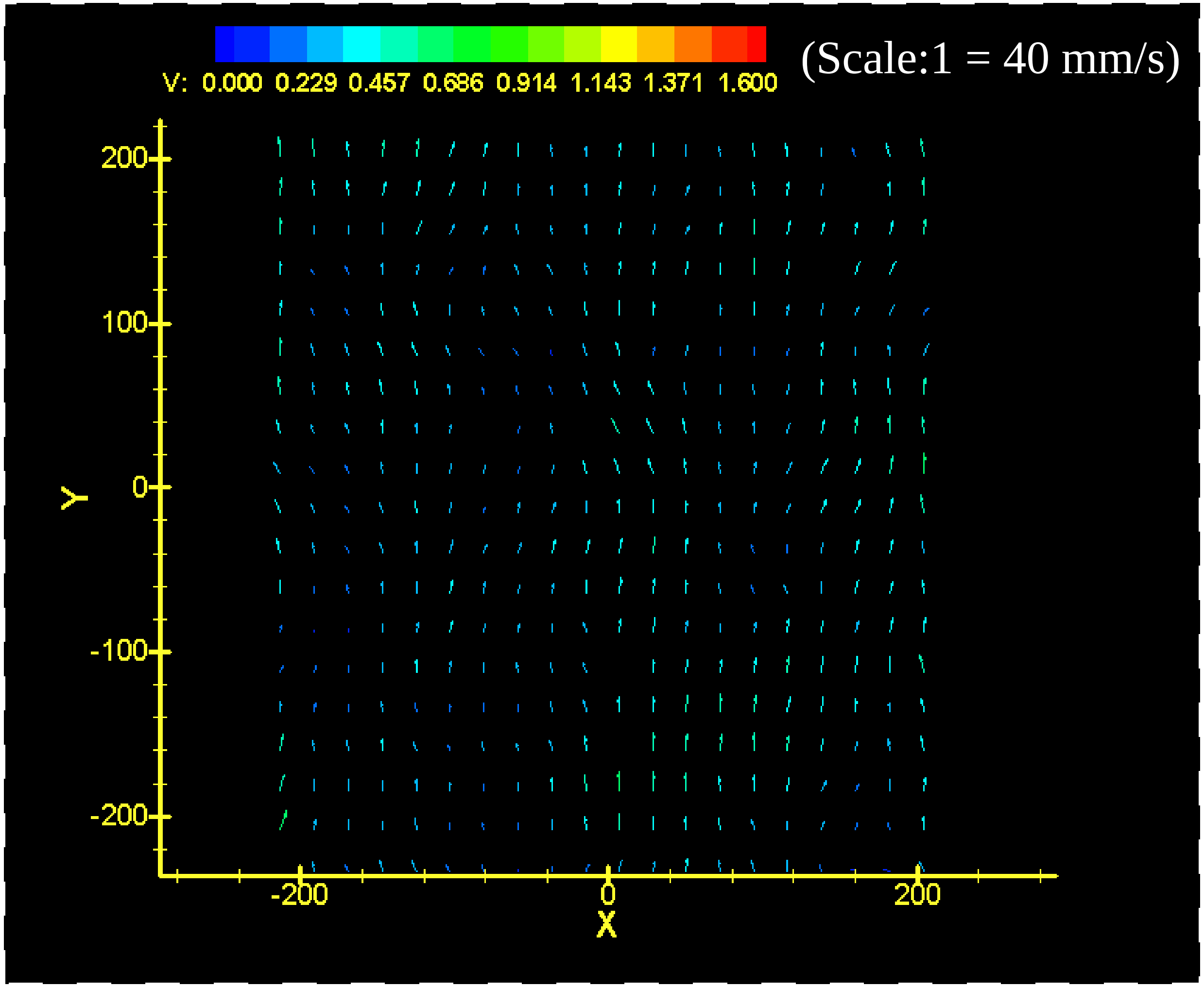
Detection of second sound with PIV



Time under analysis: from 0 to 30 ms after heater was on.

Time interval between frames: 1.67 ms

He II heat diffusion detection with PIV

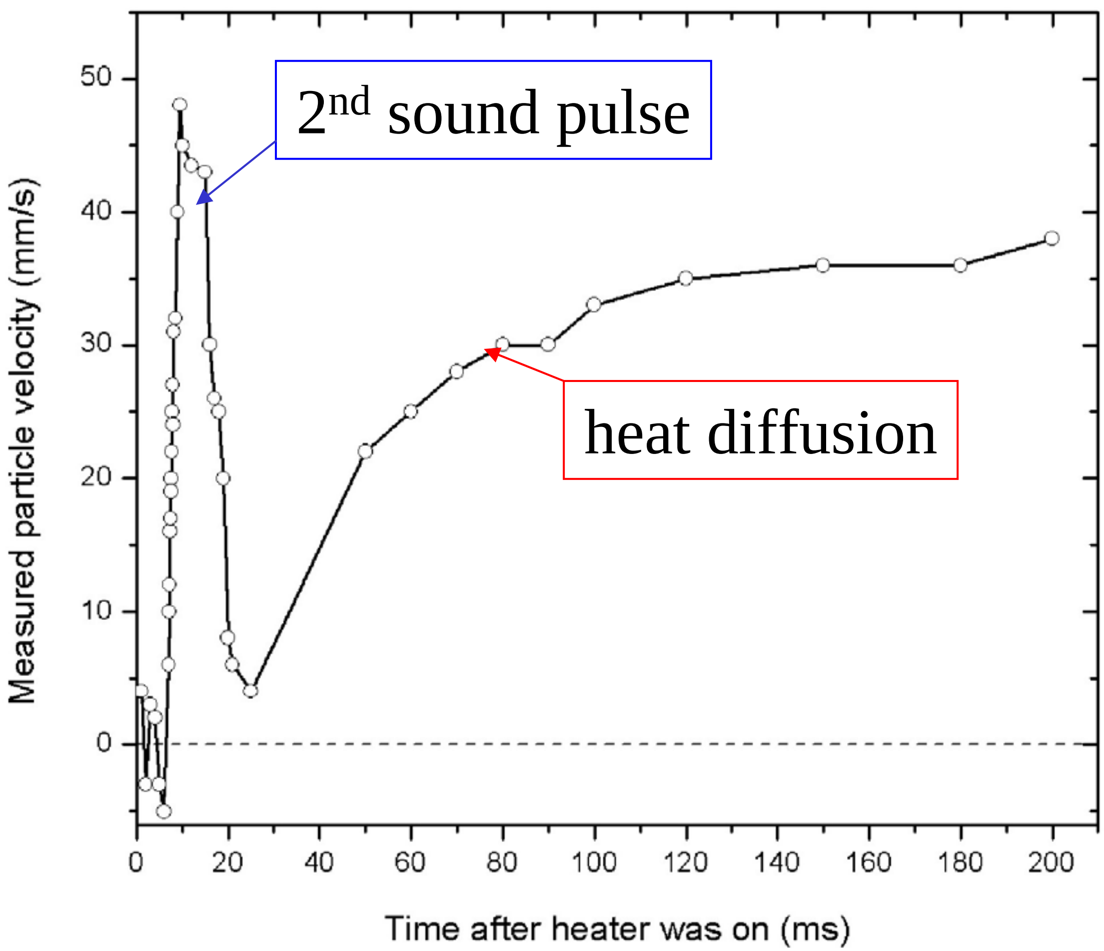


Time under analysis: from 30 to 830 ms after heater was on.

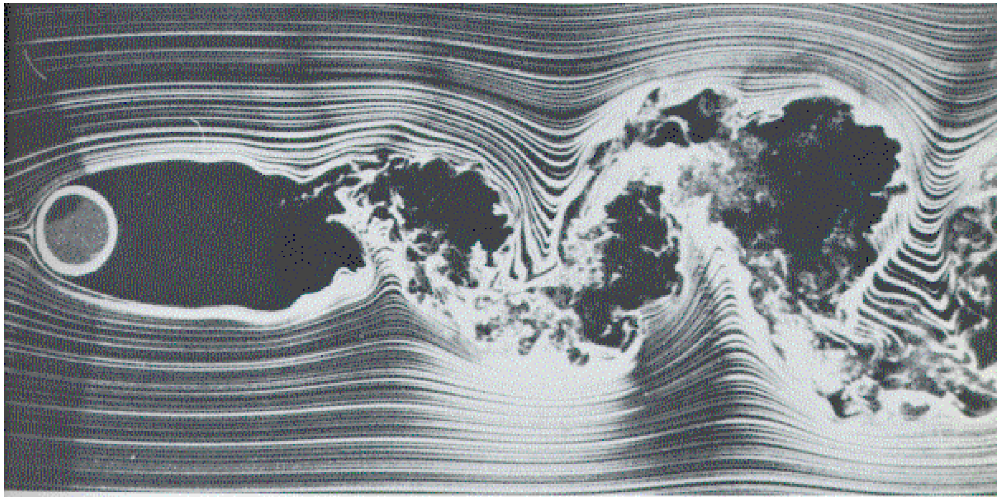
Time interval between frames: 10 ms.

PIV - Transient Heat Transport

- Arrival of 2nd sound pulse and heat diffusion tale are clearly visible using PIV.
- Characteristic particle velocities are less than v_n (similar result to steady state experiments)
- For details see: T. Zhang and S. Van Sciver, Phys. Fluids Vol. 16, L99 (2004)



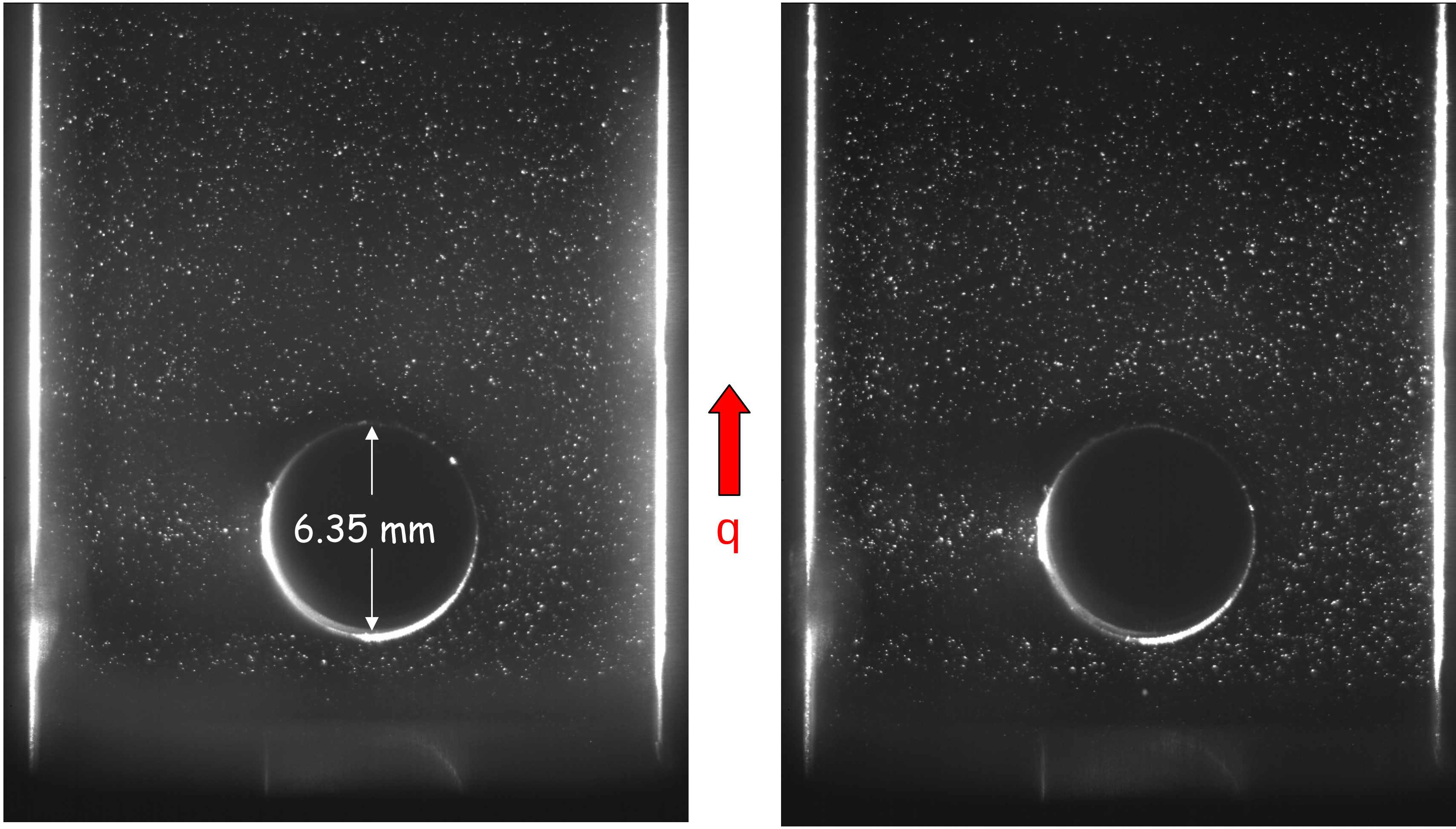
Counterflow around a cylinder



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

- This is a classic problem of fluid mechanics.
  - Large scale vortex shedding occurs behind the cylinder
  - Details scale with Re_d
- Question: What if the flow over cylinder were counterflow He II?

Particle motion - counterflow over cylinders

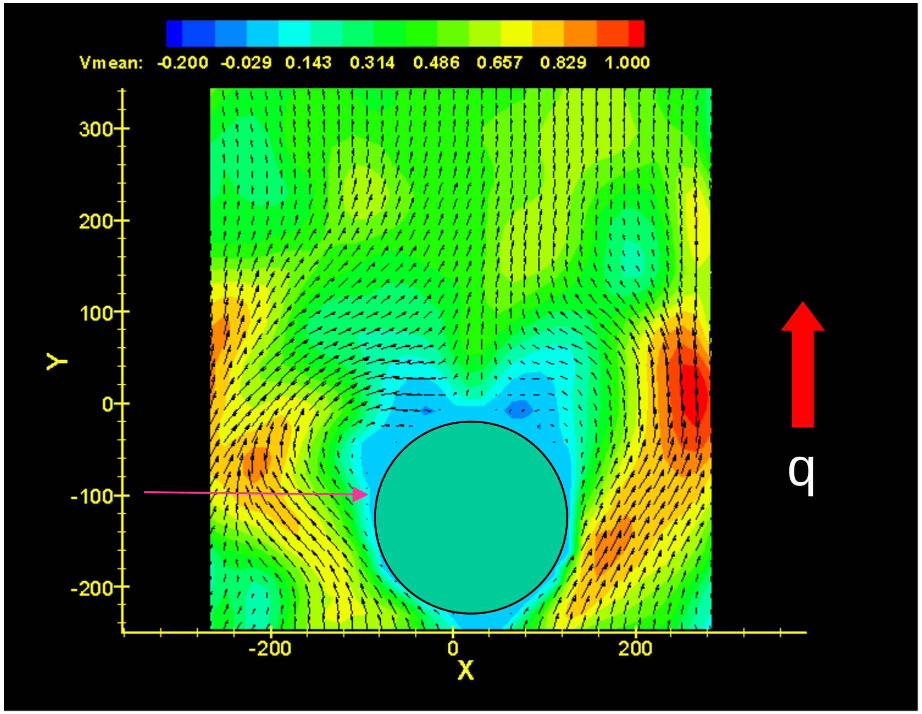


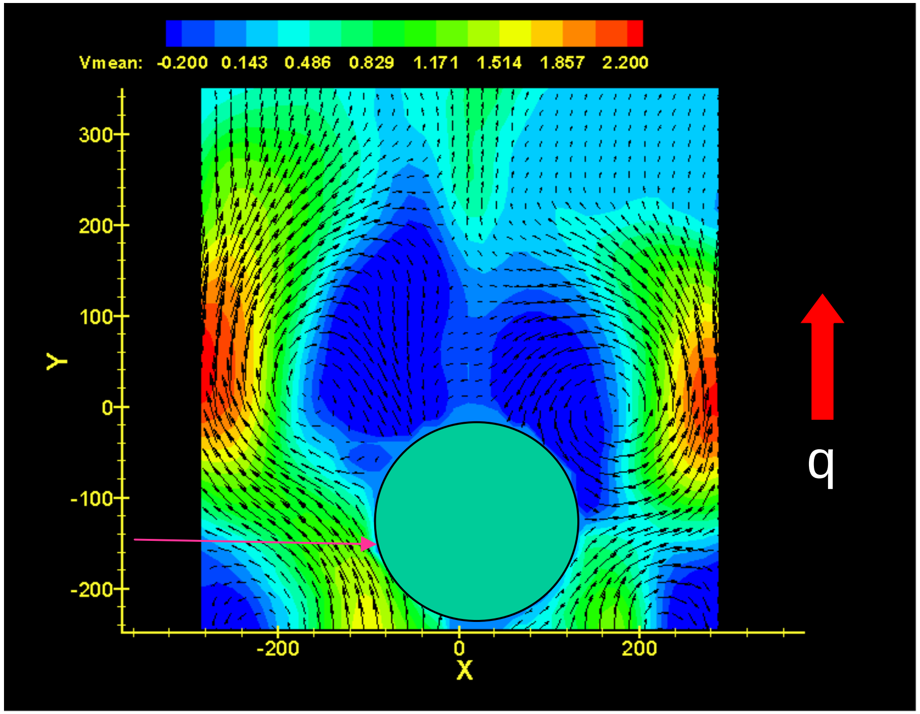
T = 1.60 K, q = 8.7 kW/m², Re=88040 T = 2.03 K, q = 14.1 kW/m², Re = 26044

Frame rate = 5 Hz, movie is real time = 20 s

Temperature dependence (Matching Re)

$$\mathrm{Re}_n = \frac{\rho v_n d}{\mu_n}$$



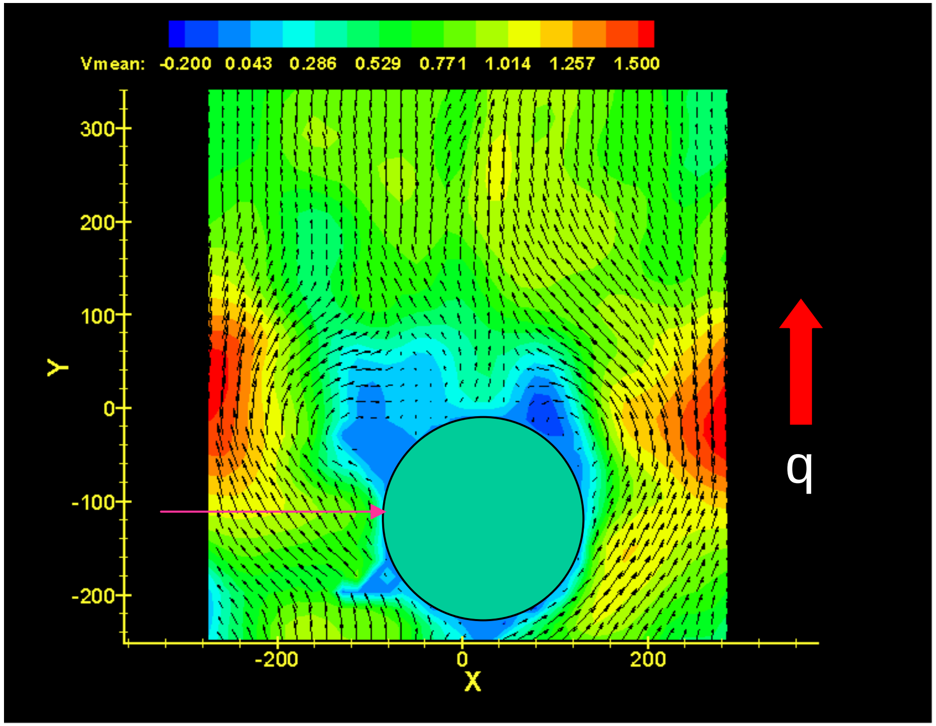


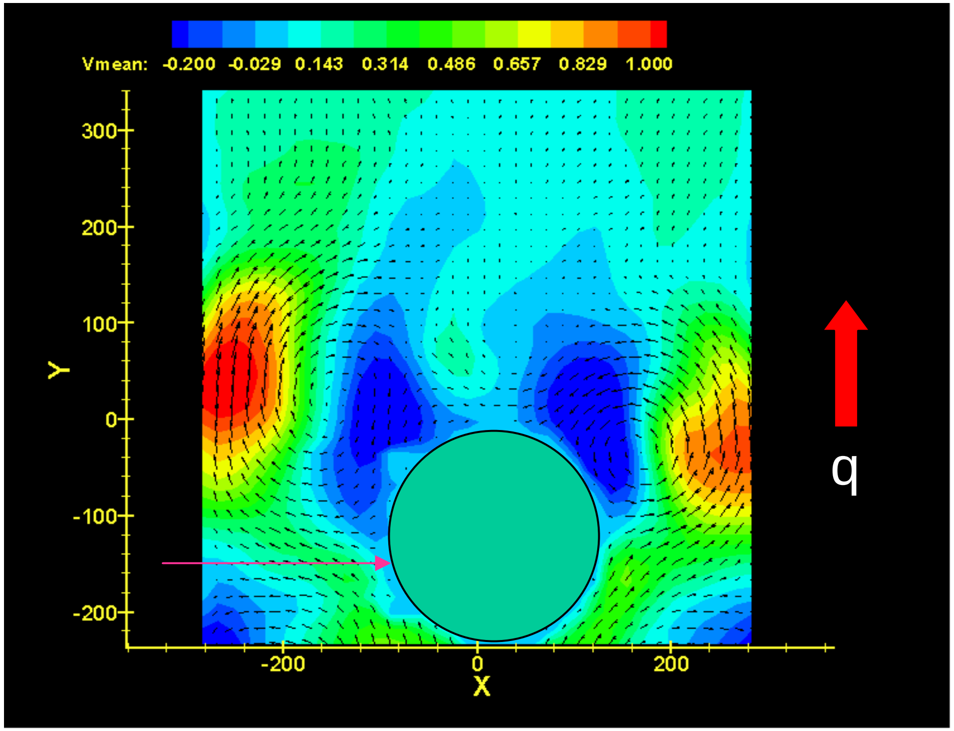
T = 1.60 K, I = 120 mA, q = 2.59 kW/m^2
Re = 26194 v_n = 39.4 mm/s
Re_n = 4828 v_s = 8.9 mm/s

T = 2.03 K, I = 280 mA, q = 14.1 kW/m^2
Re = 26044 v_n = 45.7 mm/s
Re_n = 17775 v_s = 98.2 mm/s

Temperature dependence (Matching Re_n)

$$Re_n = \frac{\rho_n v_n d}{\mu_n}$$



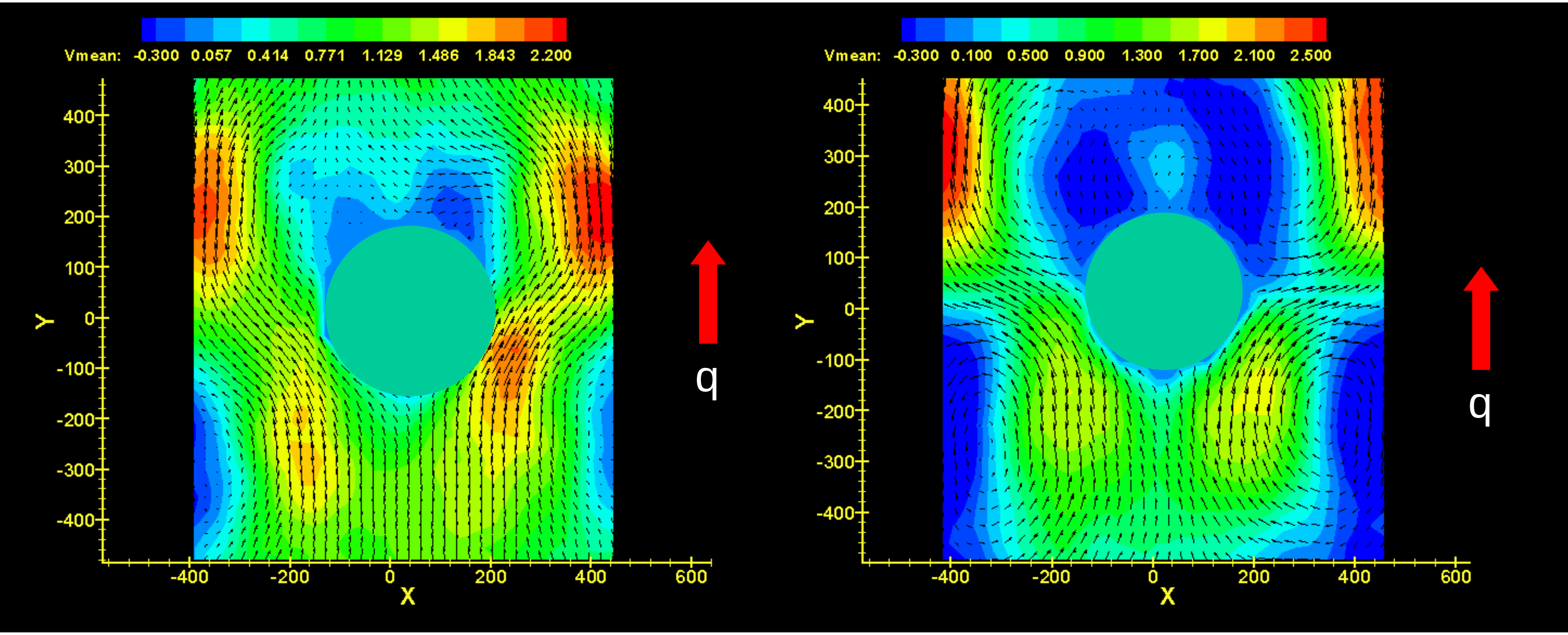


T = 1.60 K, I = 150 mA, q = 4.04 kW/m^2
Re = 40928 v_n = 61.5 mm/s
Re_n = 7543 v_s = 13.9 mm/s

T = 2.03K, I = 180 mA, q = 5.82 kW/m^2
Re = 10763 v_n =18.9 mm/s
Re_n = 7346 v_s = 40.6 mm/s

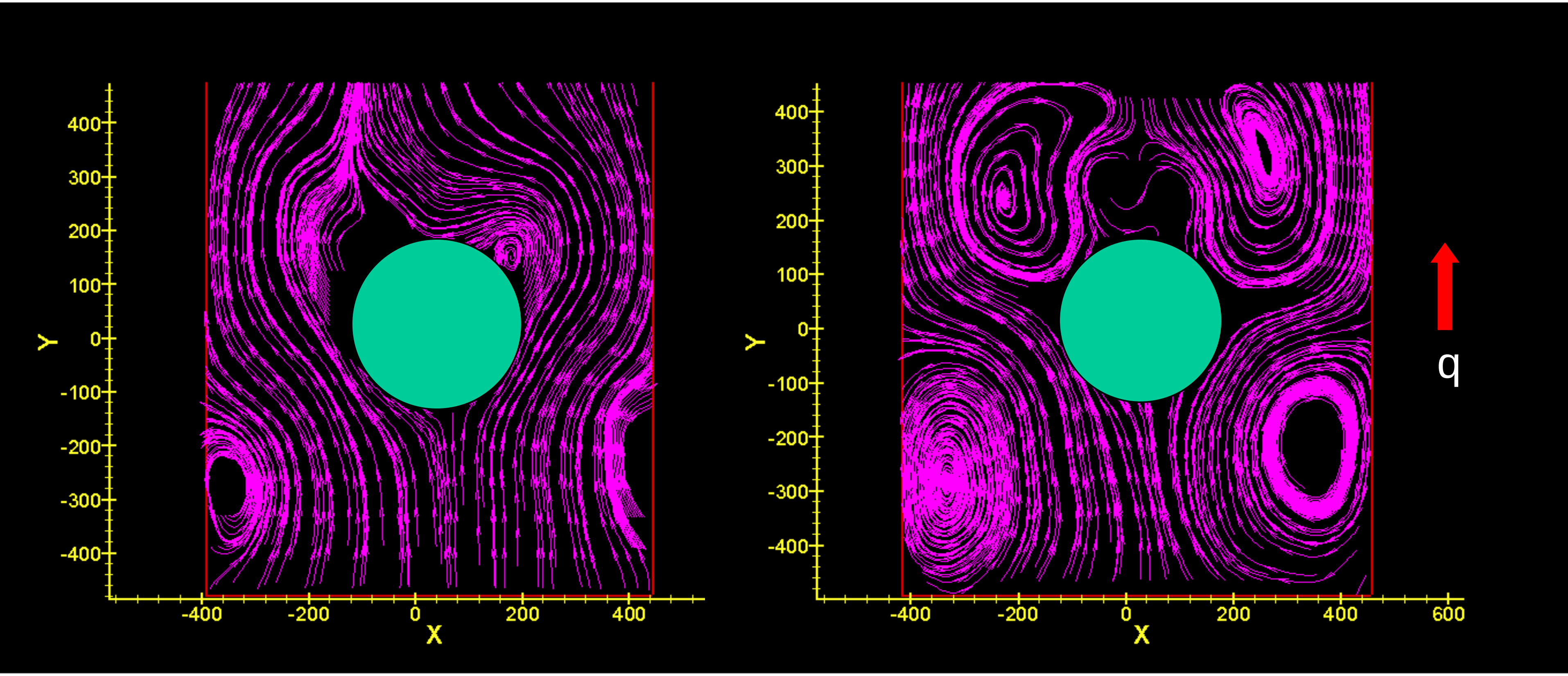
Convection in front of cylinder

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

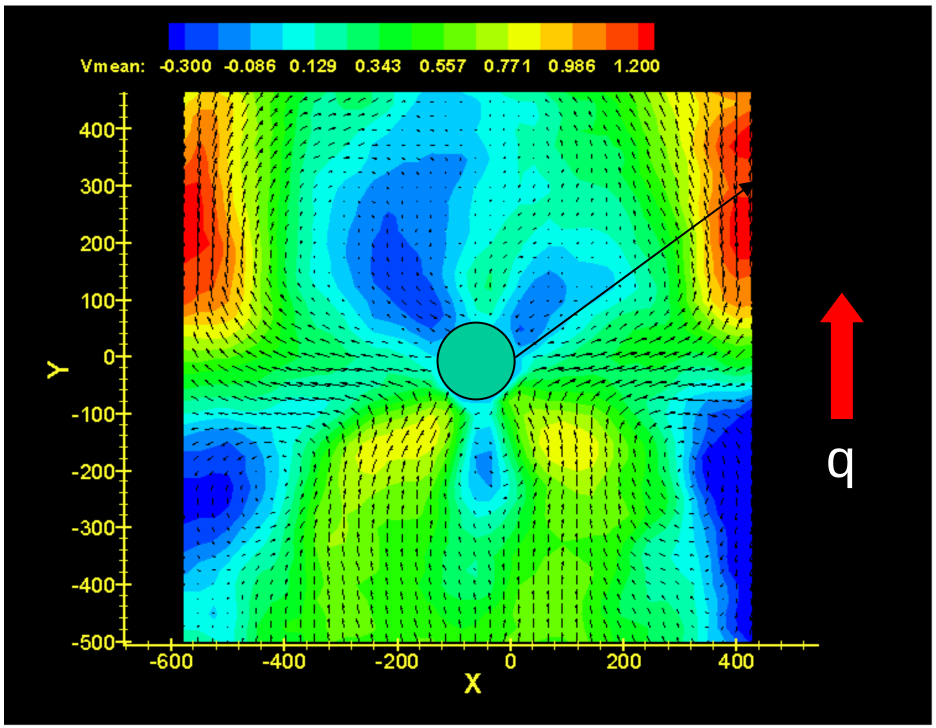


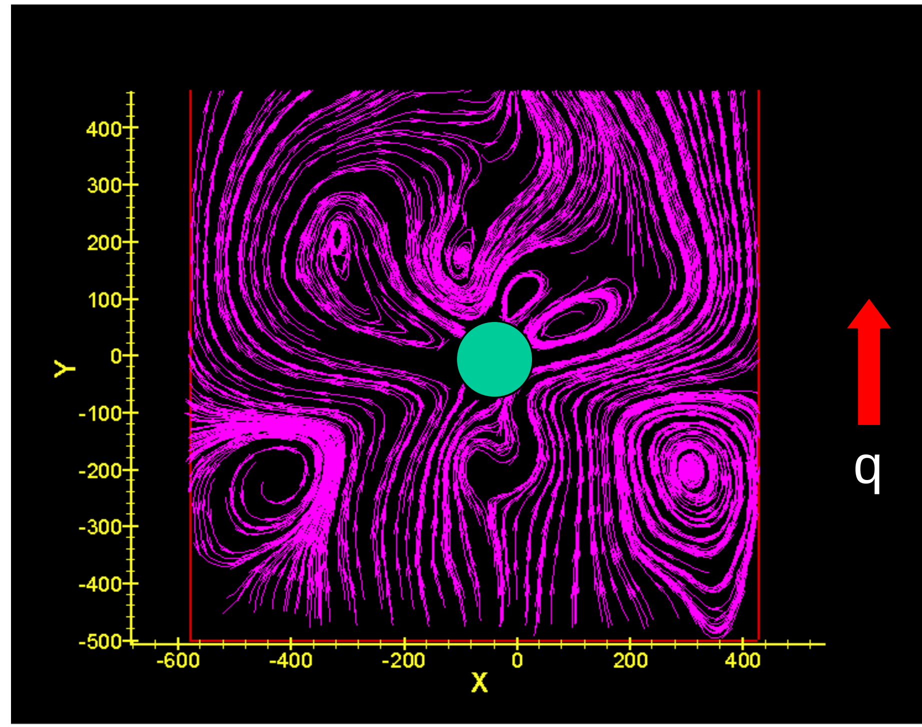
T = 1.60 K, q = 4.04 kW/m^2, Re = 40928 T = 2.03 K, q = 11.2 kW/m^2, Re = 20762

Smaller cylinder (2 mm) to reduce wall interference

Parameters:
q = 9.1 kW/m^2
T = 2.0 K
v_n = 32 mm/s
v_s = 55 mm/s
Re = 6150
Re_n = 3870
Movie run time = 30 s
Actual run time = 0.48 s

Smaller cylinder (2 mm) to reduce wall interference





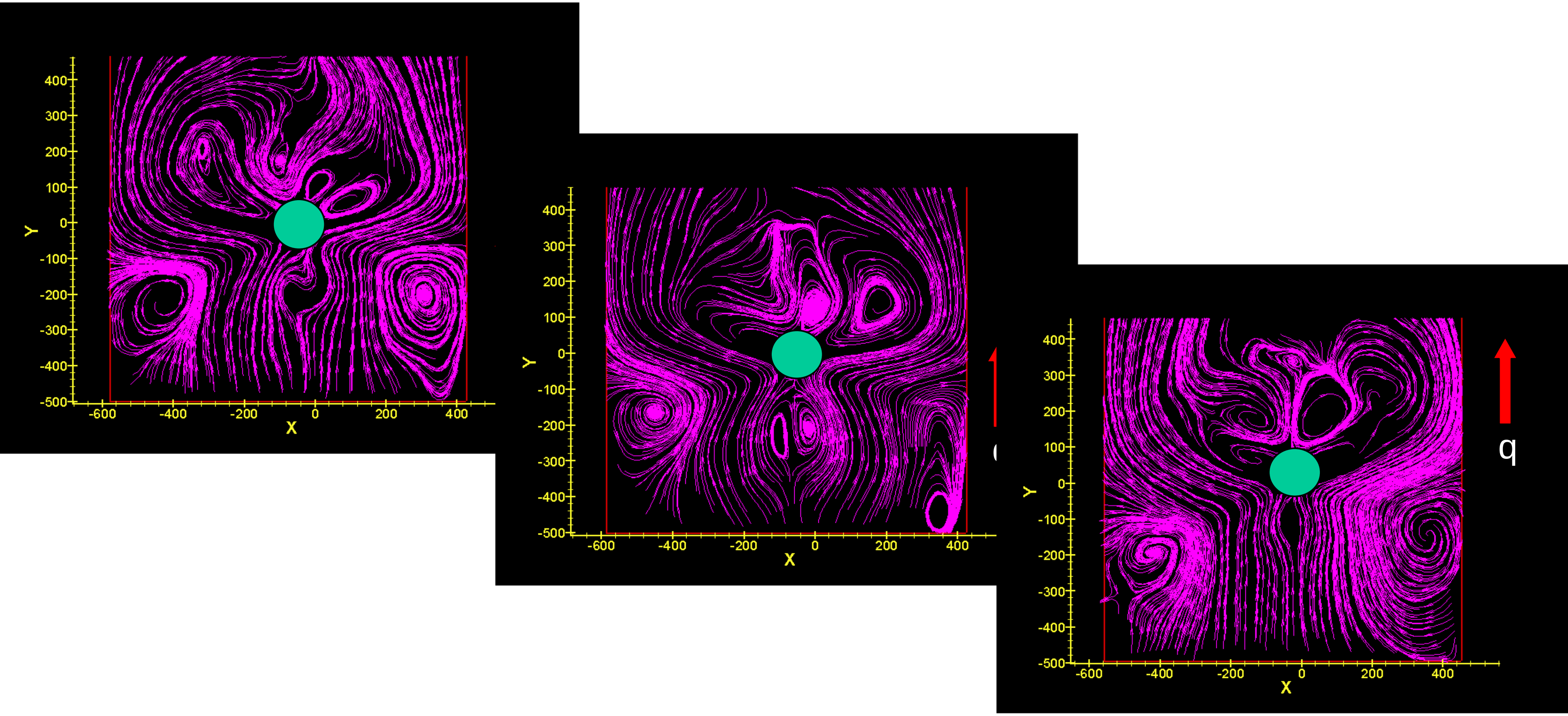
average velocity field

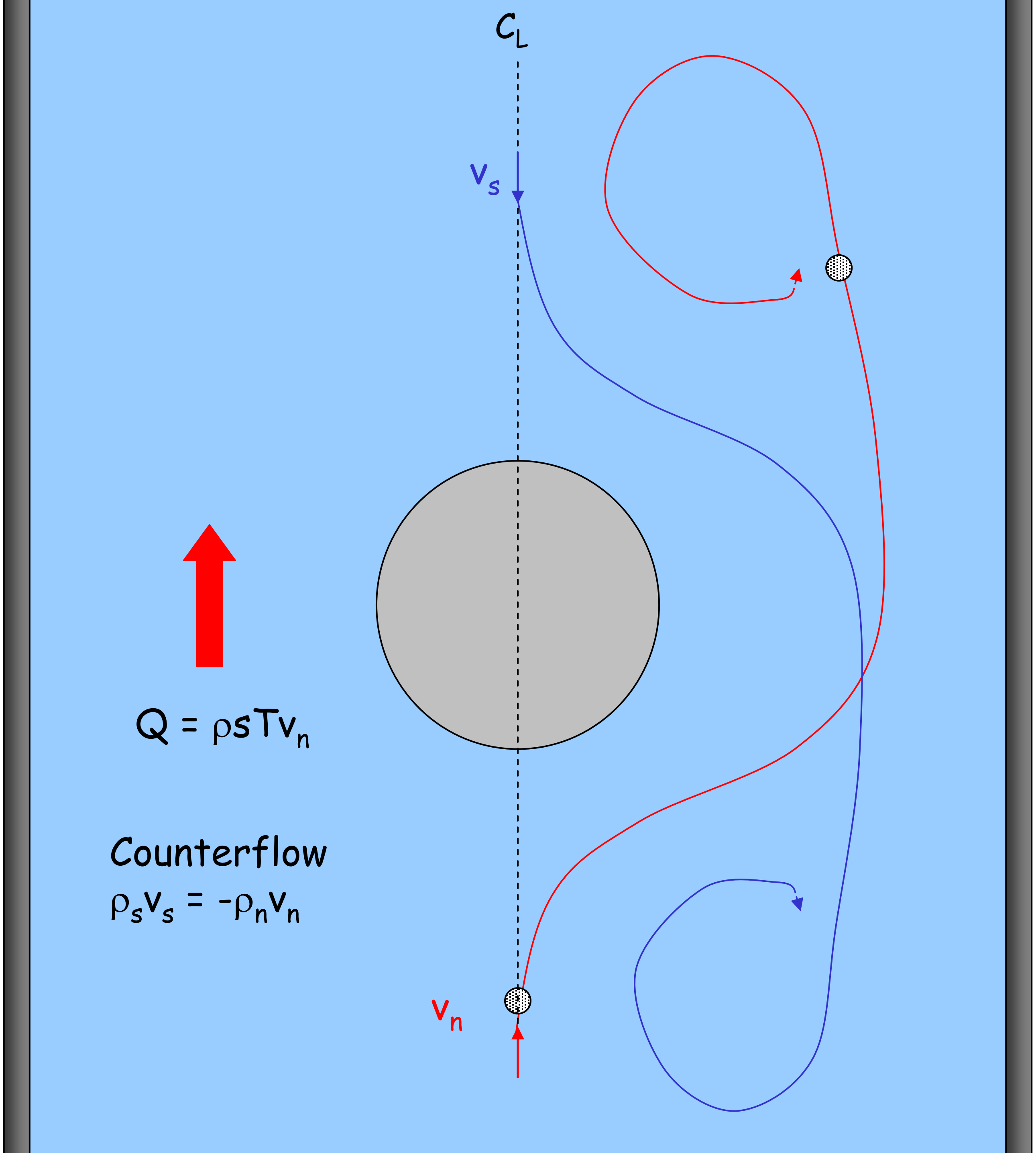
streamline profile

T = 2.03 K, q = 7.2 kW/m^2, Re = 4185

Are these results repeatable?

Example: T = 2.03 K, q = 7.2 kW/m², Re = 13697




C_L
v_s
$Q = \rho s T v_n$
Counterflow
$\rho_s v_s = -\rho_n v_n$
v_n

Discussion/Summary

- First successful PIV experiments with He II counterflow including 2nd sound and heat diffusion
- $v_p < v_n$ for all measurements suggesting interactions in addition to the normal fluid viscous drag
- Flow over cylinder shows large scale vorticity behind and in front of cylinder
- Future work will focus on:
  - Quantitative analysis of particle velocity
  - What does the vorticity suggest about thermal fluctuations?
  - Flow over other configurations (plates, orifice, etc.)
  - Fundamental understanding in terms of two fluid model