SHREK: experimental challenges in He II turbulence

SHReK Collaboration[1−7]

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March 21^{th} 2016

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2. Two fluids model of He II
3. Inertially driven turbulence in He II
4. SHREK Experiment

Outline

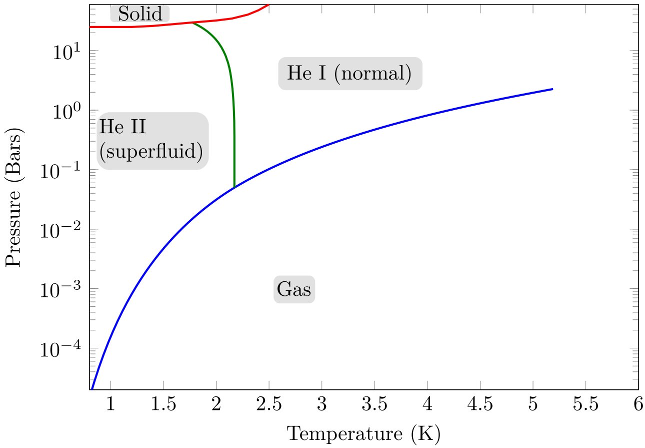
1 ^{4}He as working fluid

2 Two fluids model of He II

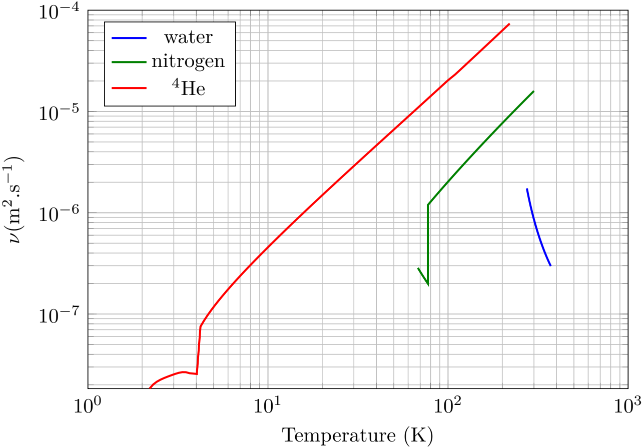
3 Inertially driven turbulence in He II

4 SHREK Experiment

Phase diagram



Viscosity - normal fluids



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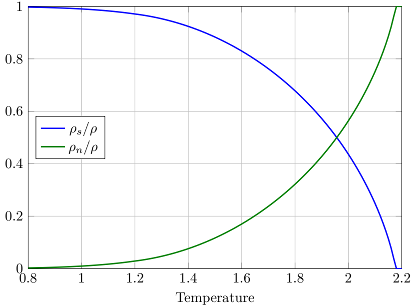
He below 2.17 K : a mixture of two fluids

The two fluid model :

- “normal component” : thermal excitations, interacting with the walls,
- “the superfluid component”

$$\rho = \rho_n + \rho_s$$



Two fluids model of He II

Equations of motion

- Normal component :

$$\rho_n\left(\partial_t \mathbf{v_n} + (\mathbf{v_n}.\nabla)\mathbf{v_n}\right) = -\frac{\rho_n}{\rho}\nabla \mathbf{p} + \mu\nabla^{\mathbf{2}}\mathbf{v_n}$$

- Superfluid component :

$$\rho_s\left(\partial_t \mathbf{v_s} + (\mathbf{v_s}.\nabla)\mathbf{v_n}\right) = -\frac{\rho_s}{\rho}\nabla \mathbf{p}$$

Two fluids model of He II

Equations of motion with thermal coupling term only

- Normal component :

$$\rho_n(\partial_t \mathbf{v_n} + (\mathbf{v_n}.\nabla)\mathbf{v_n}) = -\frac{\rho_n}{\rho}\nabla\mathbf{p} + \mu\nabla^2\mathbf{v_n} - \rho_s S\nabla\mathbf{T}$$

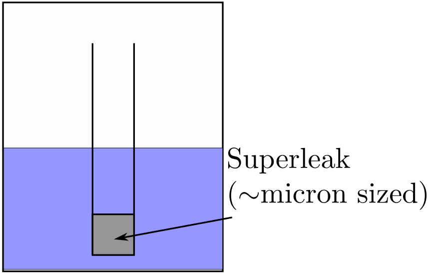
- Superfluid component :

$$\rho_s(\partial_t \mathbf{v_s} + (\mathbf{v_s}.\nabla)\mathbf{v_n}) = -\frac{\rho_s}{\rho}\nabla\mathbf{p} + \rho_s S\nabla\mathbf{T}$$

He below 2.17 K : a mixture of two fluids

The observation of some peculiar properties of ^{4}He below 2.17 K leads to the idea of a two fluid behavior :

- Fountain effect



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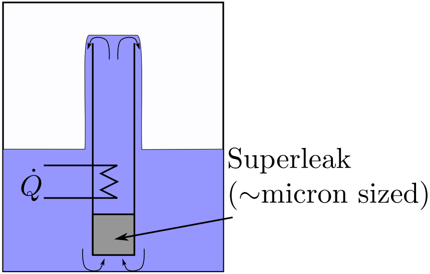

He below 2.17 K : a mixture of two fluids

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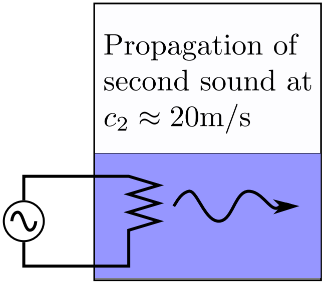
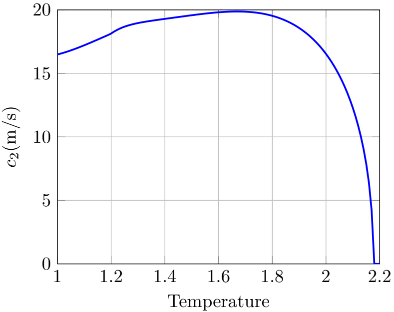
- Heat propagation through temperature waves

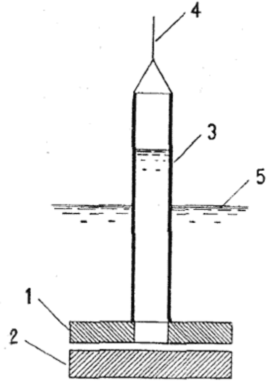




He below 2.17 K : a mixture of two fluids

The observation of some peculiar properties of ^{4}He below 2.17 K leads to the idea of a two fluid behavior :

- Motion through thin gaps



He below 2.17 K : a mixture of two fluids

The observation of some peculiar properties of ^{4}He below 2.17 K leads to the idea of a two fluid behavior :

- Motion through thin gaps
  "We are making experiments in the hope of still further reducing the upper limit to the viscosity of liquid helium II, but the present upper limit (namely, 10^{-9} *C.G.S.) is already very striking, since it is more than* 10^4 *times smaller than that of hydrogen gas (previously thought to be the fluid of least viscosity)"*
  P. Kapitza
  http ://www.nature.com/physics/looking-back/superfluid/index.html

He below 2.17 K : a mixture of two fluids

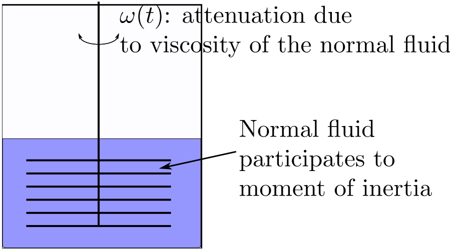
The observation of some peculiar properties of ^4He below 2.17 K leads to the idea of a two fluid behavior :

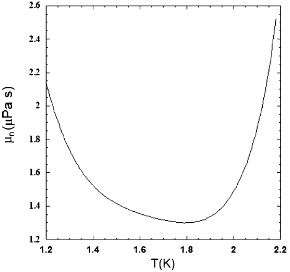
- Motion through thin capillaries
  “The observed type of flow, however, in which the velocity becomes almost independent of pressure, most certainly cannot be treated as laminar or even as ordinary turbulent flow. Consequently any known formula cannot, from our data, give a value of the ’viscosity’ which would have much meaning.”
  J.F. Allen and A.D. Misener
  http ://www.nature.com/physics/looking-back/superfluid/index.html

He below 2.17 K : a mixture of two fluids

The observation of some peculiar properties of ^{4}He below 2.17 K leads to the idea of a two fluid behavior :

- Damping of oscillatory objects

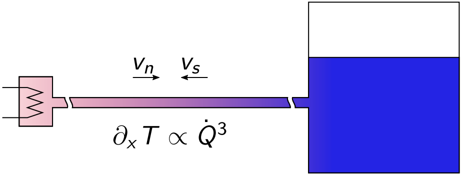




Superfluid (counterflow) turbulence

Counterflow : heat transport at null net mass flow,

$$\rho v = \rho_n v_n + \rho_s v_s = 0$$



Gorter and Mellink [1949] propose that a mutual friction force, proportional to the cube of the relative velocity can be added to the equations of motion :

$$f_{sn} = A\rho_s\rho_n(v_n - v_s)^3$$

with $\dot{Q} = \rho_s ST(v_n - v_s)$

Two fluids equations of motion

Equations of motion with the mutual friction term

- Normal component :

$$\rho_n(\partial_t \mathbf{v_n} + (\mathbf{v_n}.\nabla)\mathbf{v_n}) = -\frac{\rho_n}{\rho}\nabla \mathbf{p} + \mu\nabla^2\mathbf{v_n} - \rho_s S\nabla \mathbf{T} - f_{sn}$$

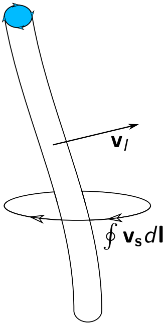
- Superfluid component :

$$\rho_s(\partial_t \mathbf{v_s} + (\mathbf{v_s}.\nabla)\mathbf{v_n}) = -\frac{\rho_s}{\rho}\nabla \mathbf{p} + \rho_s S\nabla \mathbf{T} + f_{sn}$$

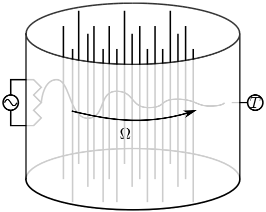
Quantized vorticity

The circulation of the velocity around a vortex in a superfluid is necessarily quantized :

$$\oint \mathbf{v_s} d\mathbf{l} = h/m_{^4He} = \kappa$$



Interaction between superfluid vortices and excitations



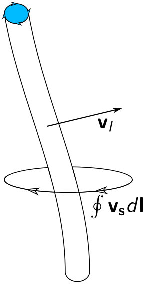
After Vinen [1957] seminal work on the attenuation of second sound in rotating He II, it becomes clear that the friction force is in fact proportional to $(v_n - v_s)$. It can be rewritten macroscopically

$$f_{sn} = A\rho_s\rho_n\Omega(v_n - v_s)$$

and in a steady state counterflow

$$f_{sn} = A\rho_s\rho_n(\underbrace{V_n - V_s}_{\text{Mean heat flux}})^2(v_n - v_s)$$

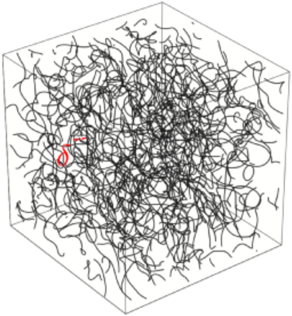
Interaction between superfluid vortices and excitations



After Vinen [1957] seminal work on the attenuation of second sound in rotating He II, it becomes clear that the friction force is in fact proportional to $(v_n - v_s)$. Along a single vortex line :

$$f'_{sn} = \frac{B\rho_s\rho_n\kappa}{2\rho}(v_n - v_s - v_l)$$

Interaction between superfluid vortices and excitations



http ://abag.wikidot.com/quantum-turbulence

After Vinen [1957] seminal work on the attenuation of second sound in rotating He II, it becomes clear that the friction force is in fact proportional to $(v_n - v_s)$. Average over $\mathcal{V} >> \delta^3$:

$$f_{sn} \approx \frac{B\rho_s\rho_n\kappa}{2\rho}\frac{2}{3}\mathcal{L}(v_n - v_s)$$

with $\mathcal{L} = 1/\delta^2$ the vortex line density

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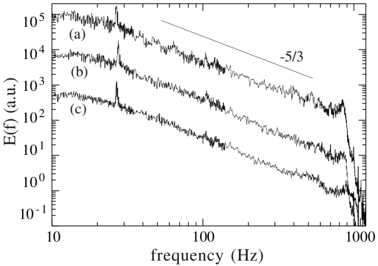
Inertially driven turbulence

First experiments with inertially driven turbulence led by Maurer and Tabeling [1998] in a V.K. flow :



Results

- Kolmogorov spectrum of kinetic energy
- Same intermittency corrections
- Later confirmed by Salort et al. [2010, 2012] in grid and pipe flows

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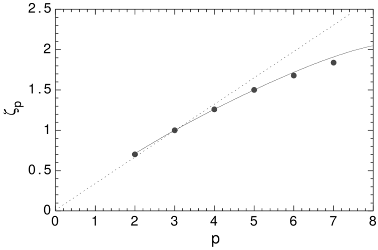

$$< \delta v^p > \propto r^{\xi_p}$$

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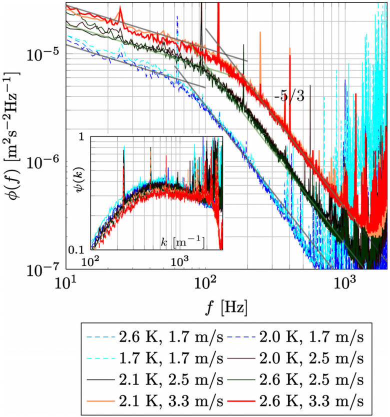

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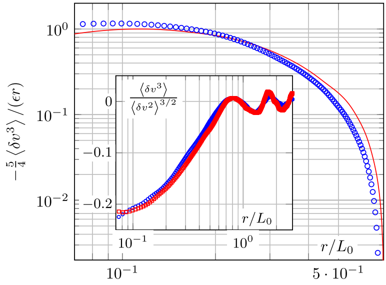

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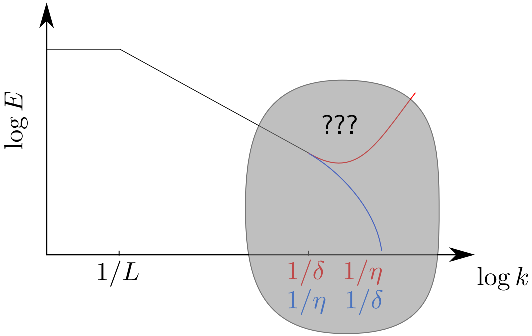
Inertially driven turbulence

Currently accepted picture of turbulence in He II at large scale :
Superfluid and normal components are locked by mutual friction at larger scale than δ.
At small scale/null temperature still debated question.



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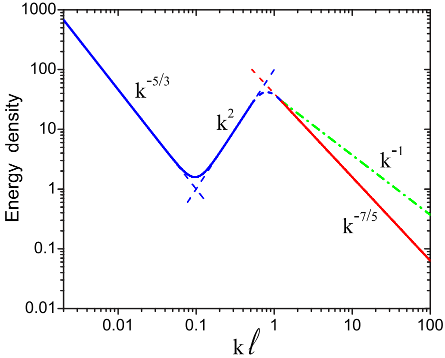

Example of proposed spectrum a zero temperature : L'vov et al. [2007]

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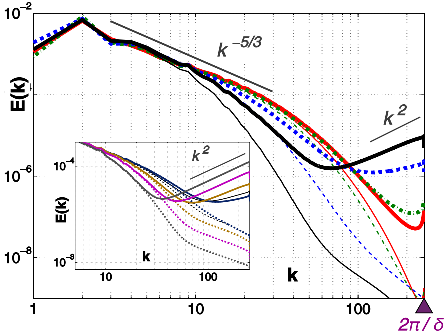

Two fluid DNS at $\rho_s/\rho = 0.1, 1, 10, 40$: Salort et al. [2011]

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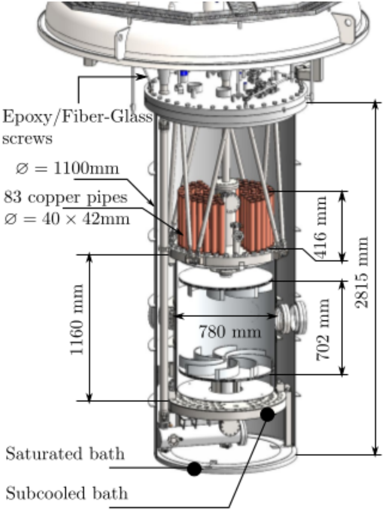
Experimental setup

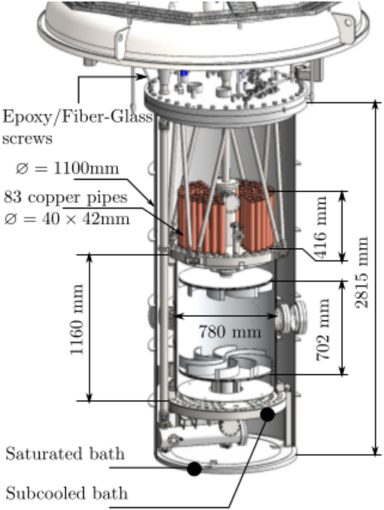


Rousset et al. [2014]

Features :

- Propellers : ⌀ 0.78 m disks fitted with 8 curved blades
- Motor : independent top and bottom driving at constant velocity or torque
- Temperature range : 1.6 K - 4 K (liquid He), any gas at room temperature
- Pressure : up to 4 bars

Experimental setup



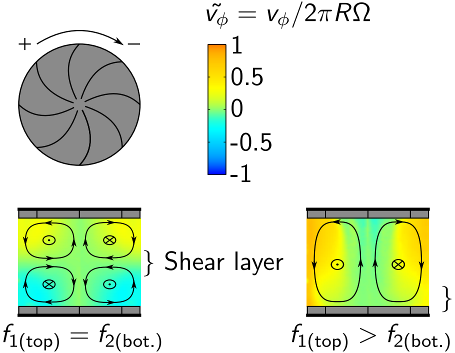
Rousset et al. [2014]

Features :

Normal (He I) or Superfluid (He II) flow in the same apparatus during the same run : **need for sensors operating in both He I and He II**

- Torque measurement : strain gauge based cold torque-meters

Multiple flow configurations



Control parameters

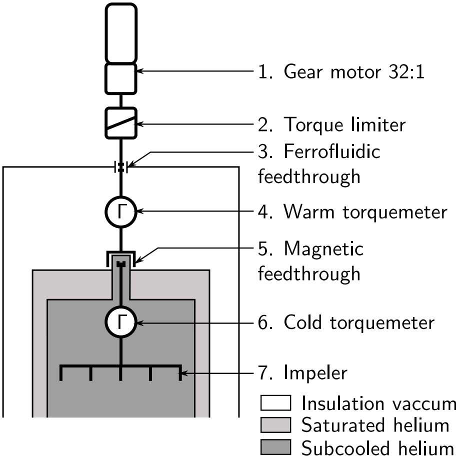
- Mean rotation pulsation

$$\Omega = \pi(f_1 + f_2)$$

- Reynolds number

$$Re = \Omega R^2 / \nu$$

Global mesurements : dissipation



Torque measurements

- Non-dimensional torque :

$$K_{pi} = \Gamma_i / \rho R^5 \Omega^2$$

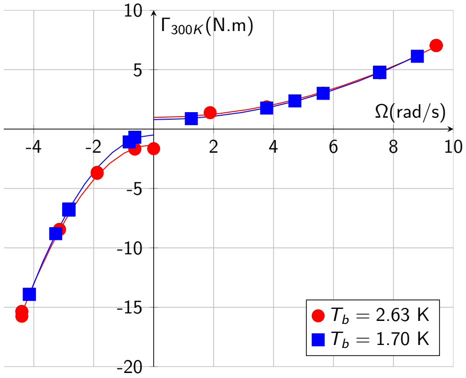
- Mean torque

$$K_p = (K_{p1} + K_{p2})/2$$

- Torque difference

$$\Delta K_p = (K_{p1} - K_{p2})$$

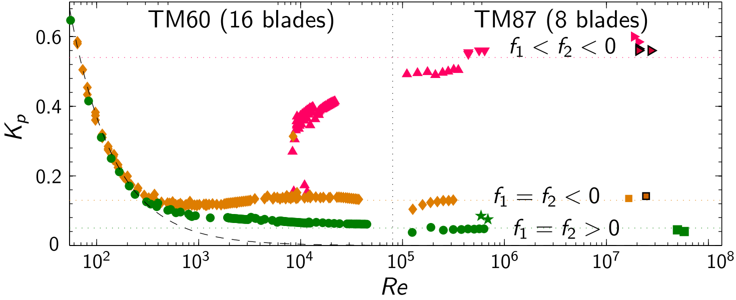
Global measurements : dissipation

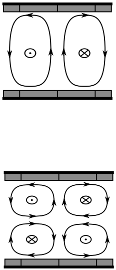


Torque measurements

- Static torque slightly different in He I and He II
- Quadratic evolution : developed turbulent flow
- Higher torque in (-) direction

Global measurements : dissipation

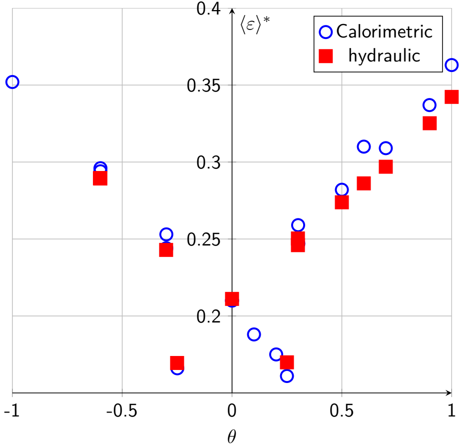




Results

- Confirmation of previous results for K_p at high enough Re
- Same dissipation in He I and He II : governed by large scales

Global measurements : dissipation



Two dissipation measurements

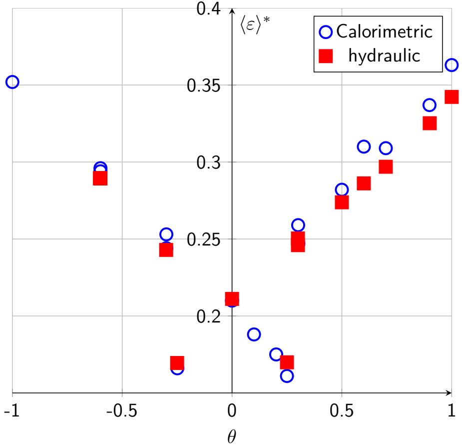
- Torque :

$$\langle\varepsilon\rangle^* = \frac{\Gamma_1\Omega_1 + \Gamma_2\Omega_2}{\rho\pi R^4 H\Omega^3}$$

- Calorimetric :

$$\langle\varepsilon\rangle^* = \frac{\dot{Q}_{\text{heat}}}{\rho\pi R^4 H\Omega^3}$$

Global measurements : dissipation



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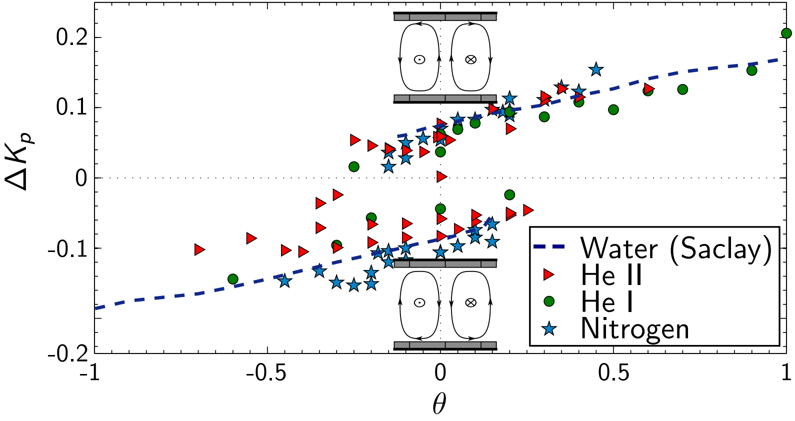
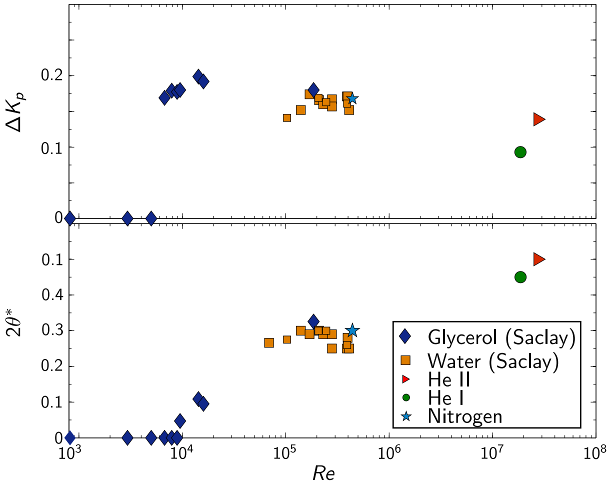
Bifurcation



- Rotation number $\theta = (f_1 - f_2)/(f_1 + f_2)$
- Confirmation of previous results for hysteresis ΔK_p

Bifurcation



Results

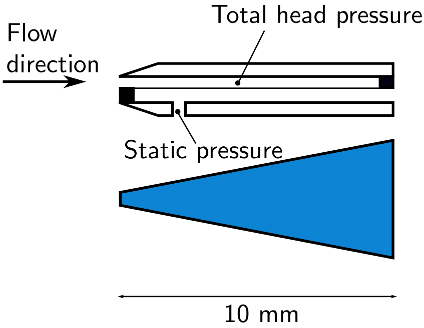
Towards local measurements

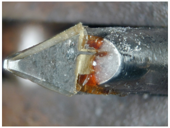
Local measurements in the equatorial plane :

- Pitot tubes
- Second sound attenuation
- Hot films (poster session)
- Hot wires
- Vorticity scattering of ultrasound
- Cantilevers

Towards local measurements : Pitot tubes

Novel design to increase Helmoltz resonance frequency :





Towards local measurements : Pitot tubes

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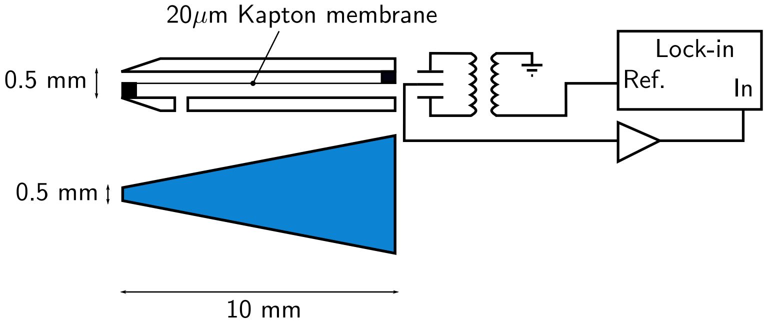
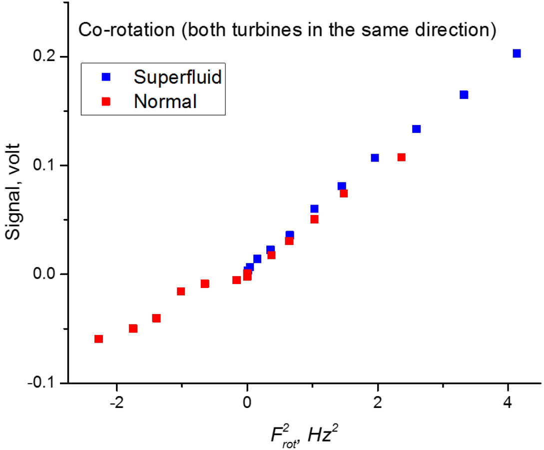


Towards local measurements : Pitot tubes

First calibration results :



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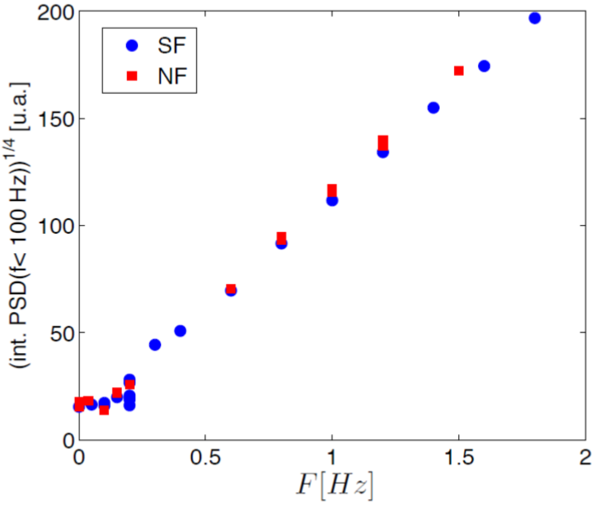
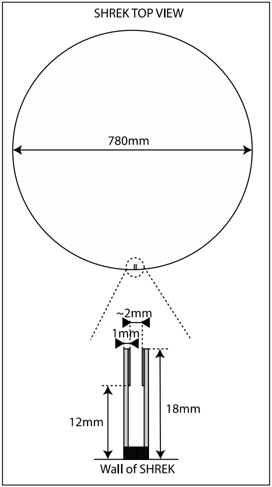
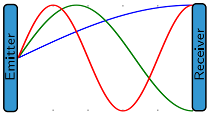
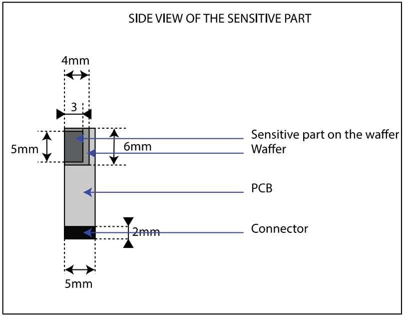


Towards local measurements : Second sound attenuation

Second sound resonator setup :

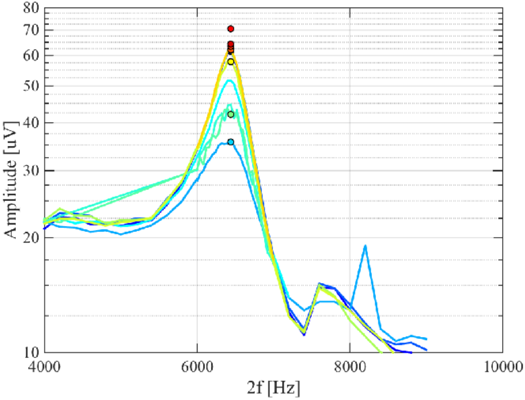






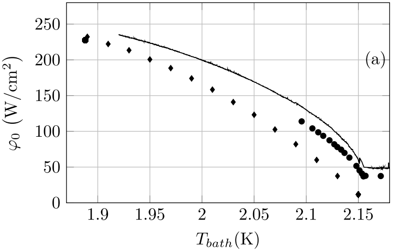
Towards local measurements : Second sound attenuation

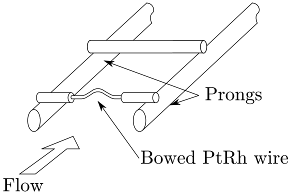
Typical resonance and attenuation :



Vortex line density : $\mathcal{L} = \frac{6\pi\Delta f_0}{B\kappa}\left(\frac{a_0}{a} - 1\right)$

Towards local measurements : hot-wires





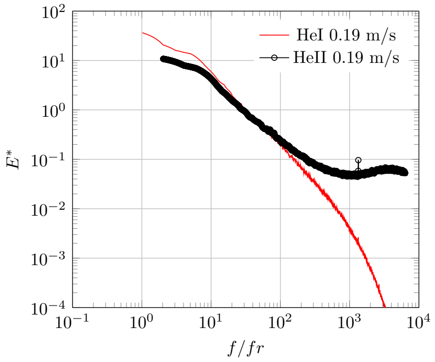
Durì et al. [2015]

Phenomenological model :

$$\varphi^m = f(T)\frac{\partial T}{\partial r},$$

where $m \approx 3$ and f is determined considering **the vortex lines tangle sustained by thermal counterflow itself.**

Heat transfer in He II

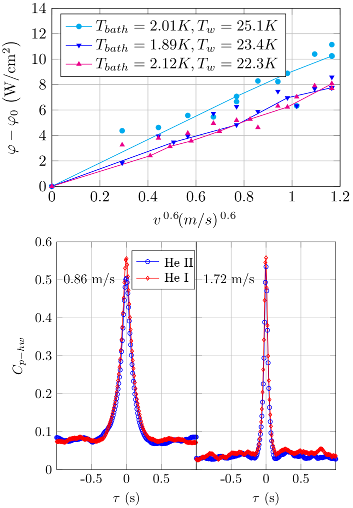


Spectra :

- Comparable $f^{-5/3}$ power laws and integral length scale
- Departure at length scale comparable to Kolmogorov length scale in He I.

At first glance it seams to work ... but what are we actually measuring ?

Velocity dependence in He II

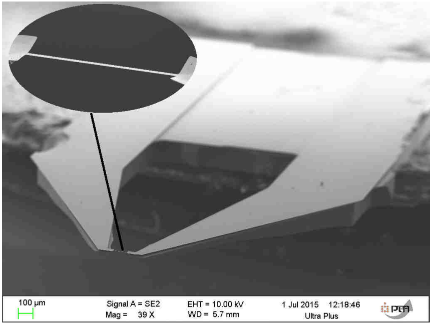


Durì et al. [2015]

Effect of velocity :

- $\varphi = \varphi_0 + Bv^{\alpha}$
- Weak temperature dependence for B
- Correlation coef. between hot-wire signal and Pitot tube similar in He I and He II

Towards miniaturization



After Bailey et al. [2010] design.

Benefits :

- Better spatial resolution, down to $\sim 50\,\mu m$
- Better control over sensing material at cryogenic temperature

Conclusion

- The challenge is now mostly experimental : designing sensors able to track small scales of the flow
- Dissipation identical in He I and He II
- Large scale, high temperatures : the two fluids are locked.
- Scales $\leq \delta$: ? ? ?

Come and propose experiments through the EUHIT program !

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