Probing Vortex Density Fluctuations in Superfluid Turbulence

P.-E. Roche¹, B. Chabaud¹, O. Français², L. Rousseau², and H. Willaime³

¹ Institut Néel - CNRS, BP166, 38042 Grenoble Cedex 9, France

² Groupe ESIEE, BP99 - 93162 Noisy le Grand Cedex, France

³ ESPCI, 10 rue Vauquelin, 75231 Paris Cedex 05, France

1 Introduction

The flow dynamics of a superfluid can be described by a viscousless tangle of quantized vortex lines [1, 2, 3, 4]. In spite of these unusual mechanical properties, strong similarities have been reported between superfluid (or “quantum”) turbulence and its Navier-Stokes counterpart. Most of them were detected by macroscopic sensors probing the largest scales (integral length) of the flow. At smaller scales, the zero-viscosity and quantization is expected to ruin this similarity between the two turbulences but probing the inertial range is already an experimental challenge [5]. In a keystone experiment, Maurer and Tabeling measured local fluctuations in a bulk flow of helium with and without superfluid[6]. In both case, they found a Kolmogorov-like spectrum for velocity in the inertial range, which has been confirmed since by numerical simulations [7, 8, 9].

Recently, we micro-machined and operated a local probe of the vortex line density fluctuations (projected on a plane). It provides a second direct experimental characterization of the inertial range of superfluid turbulence. The flow, the operation of this probe and the first physical results are presented in another paper[10]. On figure 1 (left), we illustrate these results with power spectra of the vortex line density. In the present paper, we present further details on micro-machining of the probe. To our knowledge, this is the first fully micro-machined sensor used in a cryogenic turbulence experiment.

2 Flow and Probe

The flow

The flow is confined in a cryostat and continuously powered by a centrifugal pump (see figure 1). Turbulence is probed in a 23 mm-diameter pipe, located upstream from the pump. Velocity can span the range $0.25 - 1.3\text{ m/s}$. The

Fig. 1. (Left) Power spectrum of the projected vortex line density for a mean velocities from 0.25 (bottom curve) up to 0.78 m/s (top curve). Saturations at high frequencies result from the noise floor and filtering. Solid lines are $-5/3$ power laws. (Center and Right) The closed loop of He.

measurements are performed in ^4He near 1.6 K. In such conditions, 84% of helium is superfluid, the rest being a normal (viscous) fluid superimposed to the superfluid. More details are presented in [10].

The probe's micro-machining

The principle of operation of the sensor is presented in [10]. In short, it consists in an open second-sound resonator inserted across the flow. Second sound (thermal waves) is known to be attenuated by the vortex lines which are polarized in the plane of propagation[1]. Thus, a time-resolved measurement of the standing wave amplitude provides a direct measurement of the total length of the (projected) vortices within the fluid element advected through the resonator. This signal is somehow analog to an enstrophy defined using a projected vorticity.

Both mirrors of the cavity are $15\,\mu\text{m}$ thick silicon beams separated by a $250\,\mu\text{m}$ gap. The length and width of both beams is $1.5\,\text{mm} \times 1\,\text{mm}$ and they are facing each other with a lateral positioning within a few tenths of mm typically. A granular Al film is deposited over a $0.8\,\text{mm}$ square area at the tip of one beam. This film is used as transition edge superconducting thermometer. Facing this thermometer, a chromium heating film is deposited on the tip of the other beam. Between both beams, a third silicon spacer sets the gap of the cavity. On both sides of it, contact pads provide electrical connections of both beams to the electronic circuit.

The micro-machining process is given in figure 2. SOI wafers (4 inches diameter) have been used with the following typical thicknesses of the 3 layers : $15\,\mu\text{m}$, $0.5\,\mu\text{m}$ and $500\,\mu\text{m}$. Figure 3 (left and center) shows the wafer with

Fig. 2. Steps of the micro-machining process of one beam (the other beam is machined following a similar procedure). 1-Electrical isolation (thermal oxidation, 400 nm), 2-contact pads (Cr 150 nm, Au 500 nm), 3-Heater (Cr, 500 nm), 4-DRIE front side (15 μm), 5-DRIE back side (500 μm), 6-oxide, cleaning...

beams of various sizes. The picture on figure 3 shows the resonator after assembly.

Fig. 3. (Left) Schematics of a region of the wafer, at the end of the micro-machining process. (Right) Picture of the tip of the probe after assembly.

acknowledgments

We thanks P. Tabeling, C. Lemonias, E. André, T. Fournier, B. Hébral and B. Castaing for their inputs. We acknowledge financial support from the IPMC, the Région Rhône-Alpes and of the ANR (TSF project).

References

1. R. J. Donnelly: *Quantized Vortices in Helium-II* (Cambridge Studies in Low Temperature Physics, Cambridge University Press, Cambridge 1991)
2. S. K. Nemirovskii and W. Fiszdon: *Rev. Modern Phys.* **67**, 37 (1995)
3. C.F. Barenghi et al. (Ed.): *Quantized Vortex Dynamics and Superfluid Turbulence* (Springer, Lecture Notes in Physics 571, 2001)
4. W. F Vinen and J. J Niemela: *J. Low Temp. Phys.* **128**, 167 (2002)
5. W. F Vinen: *J. Low Temp. Phys.* **124**, 101 (2001)
6. J. Maurer and P. Tabeling: *Europhys. Lett.* **1**, 29 (1998)
7. C. Nore et al.: *Phys. Fluids* **9**, 2644 (1997)
8. D. Kivotides et al.: *Europhys. Lett.* **57**, 845 (2002)
9. M. Kobayashi and M. Tsubota: *Phys. Rev. Lett.* **94**, 065302 (2005)
10. to appear in *Europhys. Lett* (2007)