Contents

1. Experimental Approach

Experiments presented in this Thesis were conducted in Prague, with members of department of low-temperature physics, under Charles University.

Many experimental methods were conducted in order to launch the production of quantum turbulence: by an oscillating objects (wires, the tuning forks, oscillating discs, etc.) or by *coflow* and *counterflow* techniques (in other words, using indirect flow sources).

In our investigation, we used the tuning fork oscillator, driven by alternating source Agilent A33220 and measured by SR830 amplifying lock-in, using an I/V converter with an conversion ratio 1000 V/A [**?**]. We measured both the in-phase and anti-phase componentes of signals. Measurements with other oscillators are included and analysed in this Thesis, but the experimental work was not performed by the Thesis' author.

1.1 Apparatus

All the measurements were performed in a helium cryostat, cooled down to the desired temperatures using a rotary and Roots pump, and stabilized (with errors of a few mK) either manually or using a Lake Shore temperature controller Model 340. The most of used technologies are captured in a photograph **Figure 1.1**.

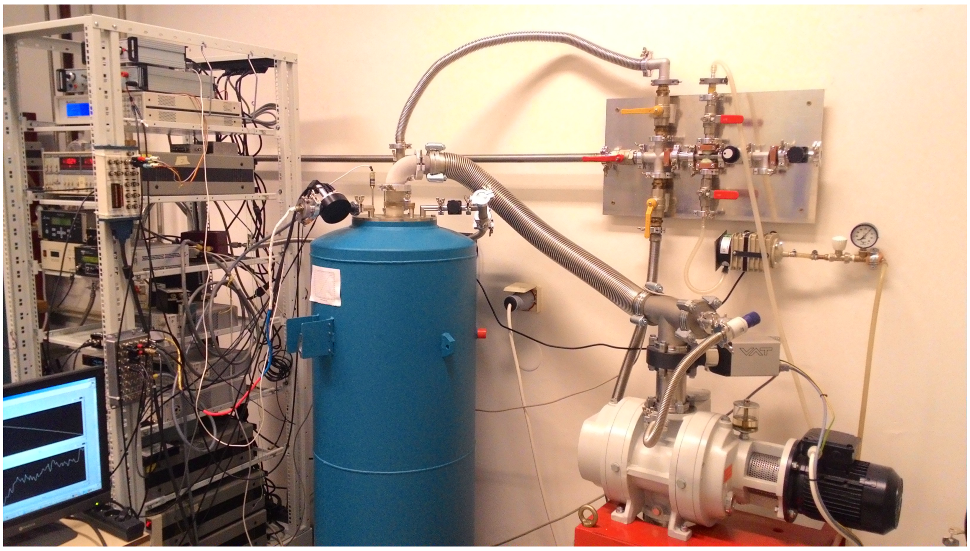

Figure 1.1: A photograph of the experimental setup. From left: source generators, lock-in, cryostat, gas handling system for emerging gas, Roots pump. Source: [**?**]

The working temperatures are from a wide range from a little above T_λ to the lowest (experimentally) possible one $T_{\text{min}} \approx 1.3\,\text{K}$. We also added series of measuremens from area far above T_λ, when $T = 3\,\text{K}$ to compare our results with a fully classical fluid in hydrodynamic regime.
The range $(1.3\,\text{K} - 2.17\,\text{K})$ allows access to the most ratios of the two-fluid regime ($\rho_s/\rho_n \ll 1$ at $T \sim 2.17\,\text{K}$ and $\rho_s/\rho_n \approx 20$ at $T \sim 1.30\,\text{K}$).

Measurements at temperatures $T < 0.6\,\text{K}$ in the ballistic regime were performed on a Leiden Cryogenics MNK126-400 dilution refrigerator with a base temperature below 10 mK. The description of sub-Kelvin measurements is not included in this Thesis, but are discussed in sufficient detail in the attached manuscript [**?**]. However, refrigerator results are analysed in **Results** part to test the *uniform scaling* theory, introduced in **Theoretical part**.

A *second-sound resonator* housing the tuning fork oscillator was attached at the bottom (**Figure 1.2**) of the *insert* - a large metallic construction holding all measuring micro-devices.

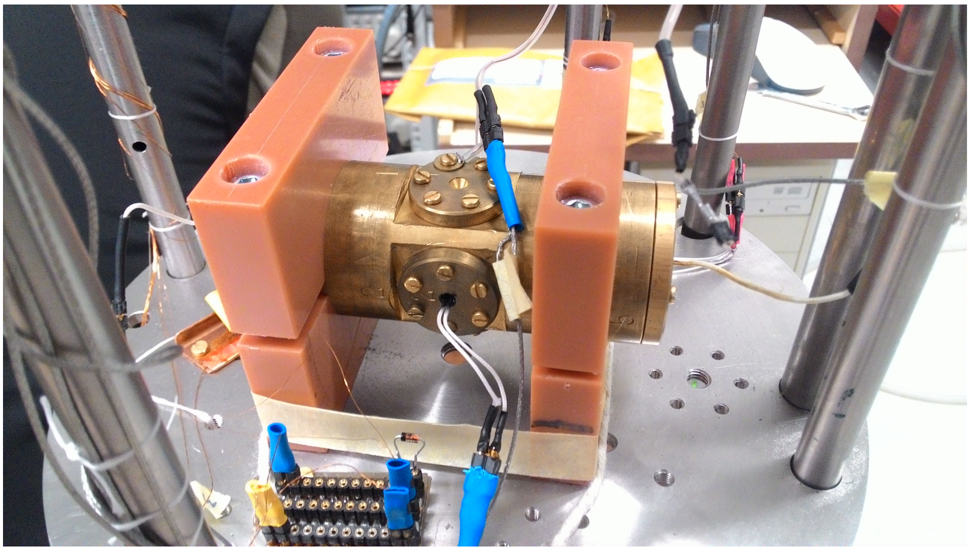

Figure 1.2: A photograph of the second-sound resonator attached at the bottom of metallic insert. Source: [**?**]

To obtain the best results at low temperatures in superfluid helium, the cryostat containing oscillators was repeatedly flushed with pure liquid ^{4}He from Dewar transport container. After this pre-cooling step, the liquid ^{4}He was transferred using a siphon.

The inner space of resonator was separated from the outer part (cryostat body) by a sinterred copper, forming a solid mass of material by pressure. This ensures that no parasitic helium ices microparticles or other inpurities will interfere with the oscillators inside of resonator.

1.2 Resonators

In this section we briefly describe the principles of micro-scale oscillators used in experiments with Helium-II.

Vibrating Wire

Vibrating wire resonator consists of a semi-circular loop of wire inserted to a vertical magnetic field $\mathbf{B}$, as shown in **Figure 1.3**. As we turn on the alternating current flux $\mathbf{j} \propto e^{i\omega t}$ inside the wire, these currents forces the wire to oscillate due to Lorentz force $\mathbf{F}_L \propto \mathbf{j} \times \mathbf{B}$. As the wire moves through the field, the Faraday voltage is induced of magnitude [?]:

$$V = -\frac{\mathrm{d}(\mathbf{B}\cdot\mathbf{S})}{\mathrm{d}t} \sim \frac{\pi}{4} BDU \,, \tag{1.1}$$

where $\mathbf{S}$ is the area vector, enclosed by the wire loop and D is the distance between wire's legs. Experimentally used magnetic field was about $\approx 170\,\mathrm{mT}$ with an uncertainty of $\pm 10\,\mathrm{mT}$.

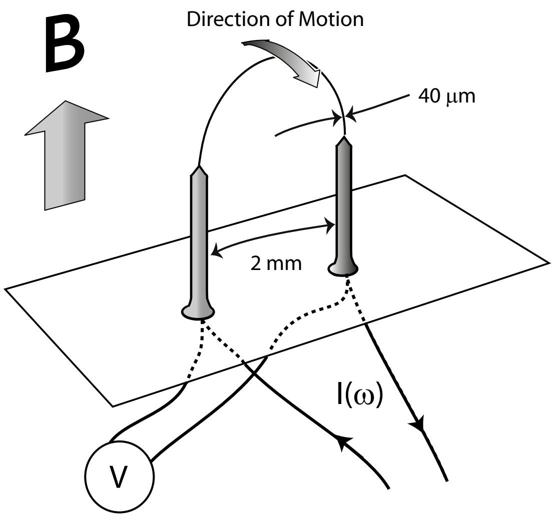

Figure 1.3: Schematic diagram of the vibrating wire resonator. Source: [?]

Tuning Fork

Quartz tuning forks (TF) are commercial piezoelectric oscillators with a well-calibrated resonant frequency. They are usually used as frequency standards in watches or as force sensors in microscopes. Also, TFs have started to be widely used in cryogenic Helium II experiments [?].

In our experimental setup, we used the fork of following dimensions: prongs length $\mathcal{L} = 3.50\,\text{mm}$, prongs width (perpendicular to the fork plane) $\mathcal{W} = 75\mu\,\text{m}$, thickness $\mathcal{T} = 90\mu\text{m}$ prongs interdistance $\mathcal{D} = 90\mu\text{m}$. The same type of fork was also used and discussed in [?] [?] A sketch of the fork architecture is depicted in **Figure 1.4**:

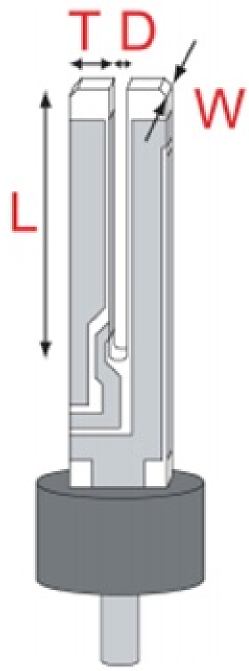

Figure 1.4: Schematic diagram of the quartz tuning fork. Source: [?]

There are several achievable resonant modes at which the fork can oscillate. We chose to work with the *fundamental* one at $f_0 = 6.7\,\text{kHz}$ and with the first *overtone* one at $f_1 = 41\,\text{kHz}$.
The fork is driven by applying an alternating voltage $V(t) \propto e^{i\omega t}$ from a generator to the metalic plates (deposited on fork surface). The piezoelectric effect causes a tension resulting in a force, which is proportional to the applied voltage. In fundamental mode, the fork exhibits an anti-phase oscillating motion of its prongs with a single node. In case of overtone, there would be just two nodes. The fork's flexion induces a piezoelectric current $I(t)$ which is proportional to the velocity $U(t)$.

The conversion relations between applied $V(t)$, measured $I(t)$ and mechanical properties $F(t)$, $U(t)$ are given [**?**] as:

$$F(t) = \frac{1}{2} a_f V(t)\,, \qquad U(t) = \frac{I(t)}{a_f}\,, \tag{1.2}$$

where a_f is the so-called *fork constant*. This constant can be derived from a fork's geometry, material and an oscillation mode. Usually the formula for this constant is given by a deflection measurement:

$$a_f = \sqrt{4\pi m_{eff} \Delta f \frac{I}{V}}\,, \tag{1.3}$$

where $m_{eff} = TWL\rho_q/4$ (ρ_q as the quartz density) is the fork's effective mass and Δf is the measured peak width from the fequency-sweep deflection measurement. In our case we used fork with the effective mass and fork constants for fundamental and overtone mode of following values:

$$m_{eff} = 1.52 \times 10^{-8}\,\mathrm{kg}\,, \qquad a_{f0} = 0.30 \times 10^{-8}\,\mathrm{Cm}^{-1}\,, \qquad a_{f1} = 1.41 \times 10^{-8}\,\mathrm{Cm}^{-1} \tag{1.4}$$

The measurement scheme of the experiment with tuning fork is shown in **Figure 1.5**. The arrangement of experiments using dilution refrigerator were slightly more complex and are described in [**?**] .

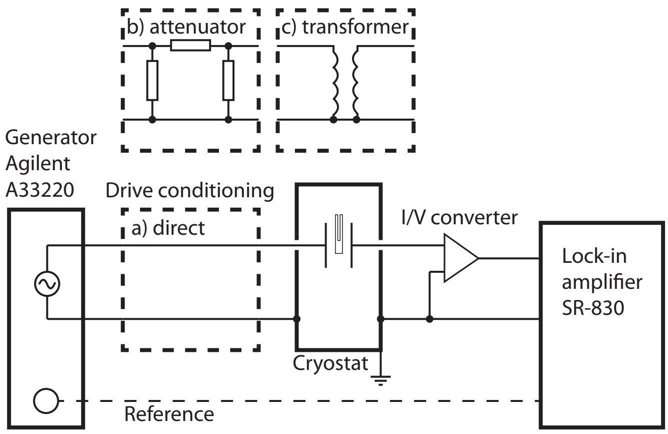

Figure 1.5: Diagram of the measurement scheme used in Prague. To achieve the full range of velocities, the applied voltage was either (a) directly fed to the tuning fork, (b) attenuated by one or more inline attenuators, or (c) amplified by a transformer. The transformer's output was constantly monitored by a Keithley digital multimeter Model 2100. Source: [**?**]

Oscillating Disc

The torsional oscillator consists of a 50μm wire with a glass disc fixed to the wire at its midpoint. The disc is 1 mm thick with a diameter of 40 mm. A schematic picture is showed in **Figure 1.6**.
Sixteen black marks around the circumference of the disc are used to determine the deflection and angular velocity of the disc from recorded video sequences.

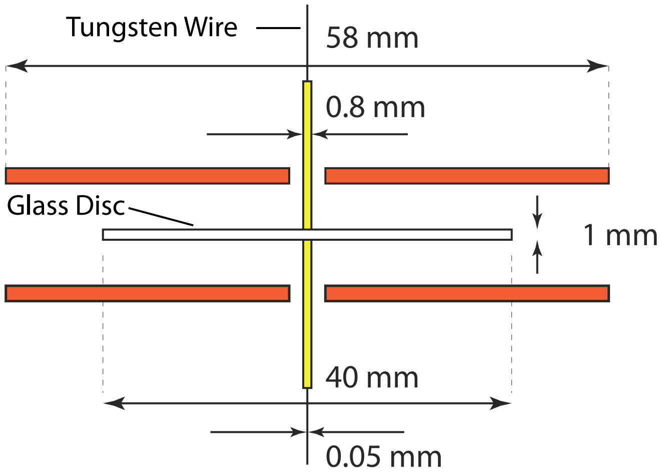

Figure 1.6: Schematic diagram of the torsionally oscilating disc. Source: [**?**]

The raw data is in the form of video recordings of the disc motion and fairly complex post-processing method was required to extract quantities. The optical distortion from the lenses and the curved walls of the cryostat are negligible.