Новый тип «Tuning forks» с изгибными и вращательными колебаниями как генератор квантовой турбулентности в сверхтекучем гелии

V.B. Efimov,
Institute of Solid State Physics RAS,
Institute of Theoretical Physics RAS
Chernogolovka, 142432, Moscow distr., Russia

XXVI Научная сессия Совета РАН по нелинейной динамике

18 Dec 2017

Report outline

- Квантовая турбуленция в сверхтекучем гелии
- Генерация вихрей
- Tuning forks, электромеханический коэффициент
- Применение tuning forks
- Изгибные и вращательные моды нового типа tuning forks

Classical turbulence – measures of its intensity

Reynolds number

$$Re = \frac{UL}{\nu}$$

For isothermal flows

	T(P)	ν (cm^2/s)=10^{-2} St kinematic viscosity
air	20 C	0,15
water	20 C	1,004x10^{-2}
ethanol	20 C	0.022
mercury	20 C	1,2x10^{-3}
Helium I	2,25 K (VP)	1,96x10^{-4}
Helium II	1,8 K (VP)	9,01x10^{-5}
He-gas	5,5 K (2,8 bar)	3,21x10^{-4}

- **He II and 3He B – so far the only two media where quantum turbulence has been systematically studied under controlled laboratory conditions**

Classical turbulence

Oscillating grids as a source of nearly isotropic turbulence

I. P. D. De Silva and H. J. S. Fernando
Department of Mechanical and Aerospace Engineering, Arizona State University, Tempe, Arizona 85287-6106

(Received 4 May 1993; accepted 10 March 1994) Phys. Fluids **6** (7), July 1994

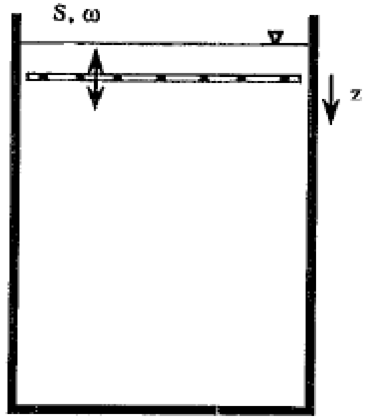
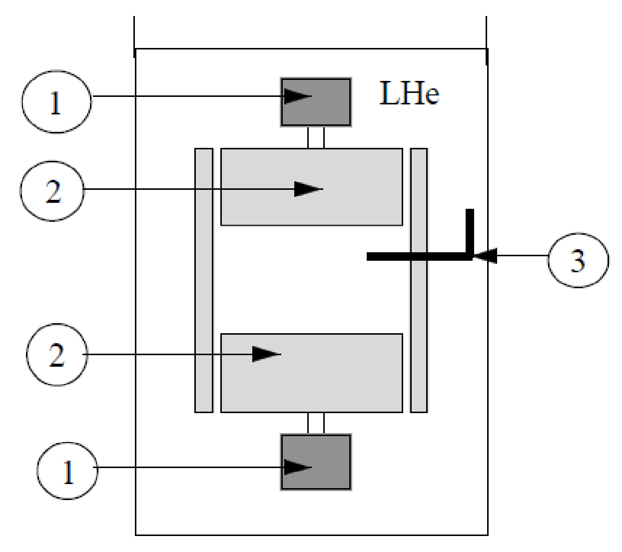
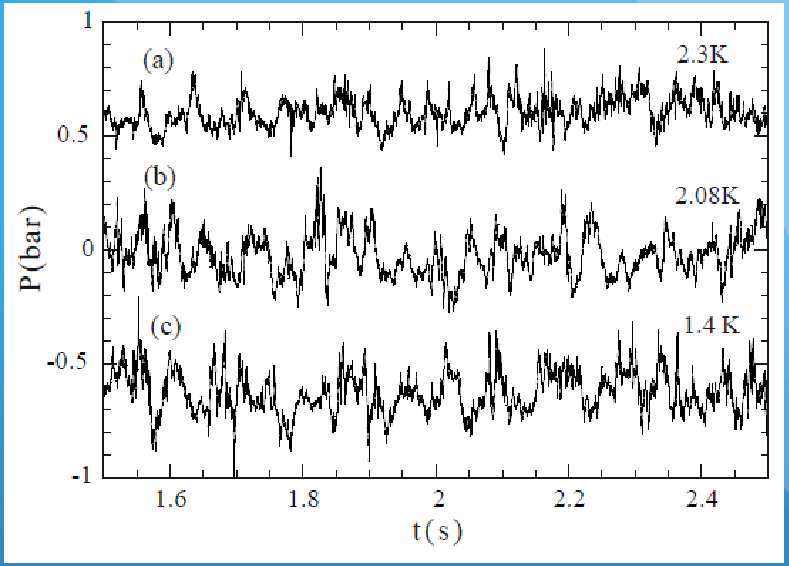


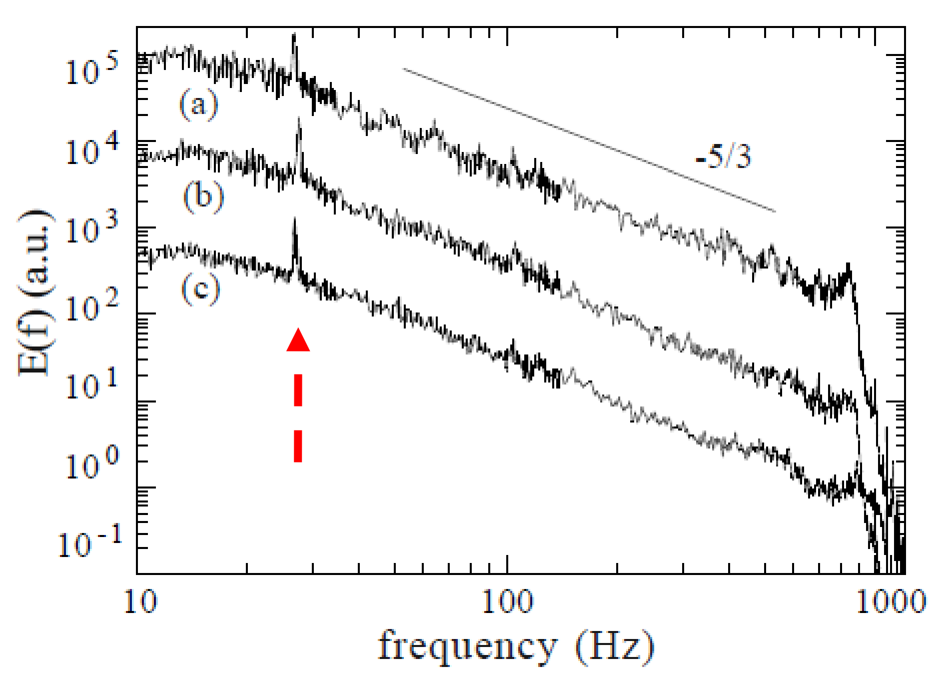
FIG. 1. A schematic of the experimental setup.

Maurer, Tabeling,
Europhysics Lett. 43 (1998) 29
Flow between counterrotating discs





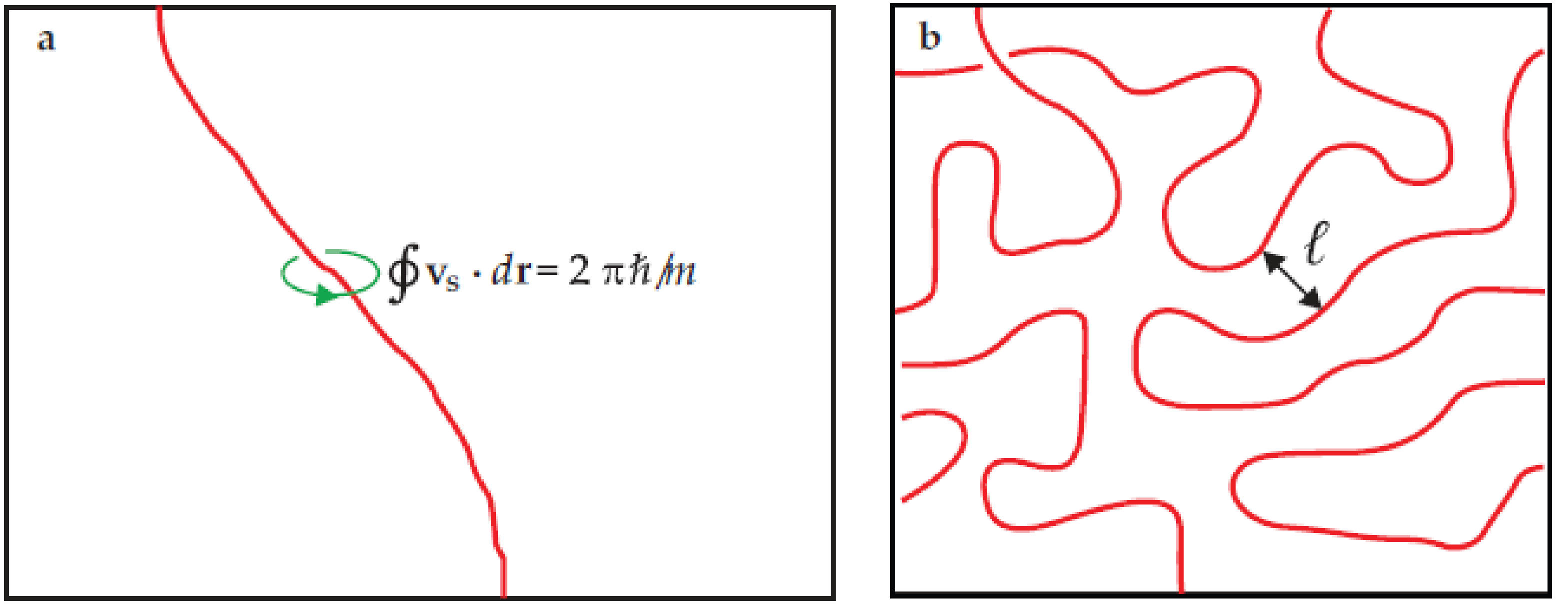
Energy spectra obtained in the same conditions:
U=80cm/s; Re=2x10^6 a-2.3K; b-2.08K; c-1.4 K
The spectra have bee shifted vertically so as to make their representation clear.



Quantization of vortex lines, core radius a_0 and intervortex distance ℓ

$$\oint \boldsymbol{v}_s \cdot d\boldsymbol{r} = n\,\kappa, \quad \text{where } \kappa = \frac{2\pi\hbar}{M} \quad \text{is the circulation quant.}$$

$M = 4$ for ^{4}He and $M = 6$ for a pair of ^{3}He atoms.



- ℓ is the mean intervortex distance,
- Vortex core radius $a_0 \simeq 1$ Å for ^{4}He & $a_0 \simeq 800$ Å at low p.

for ^{3}He

Systems (simplified) to understand turbulence in

^4He

T

normal liquid He I

2

Classical Navier-Stokes fluid of extremely low kinematic viscosity

Superfluid transition at Tc=2.17 K

He II – **a "mixture" of two fluids**

normal fluid of extremely low kinematic viscosity

+

Inviscid superfluid

3

Circulation is quantized

$$\kappa = \frac{2\pi\hbar}{m_4} \approx 10^{-3} [cm^2 / s]$$

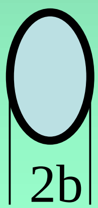
$T \rightarrow 0$ limit

1

0 **Pure superfluid**

Counterflow turbulence phenomenology (Vinen 1957)

Vortex ring



$$\mathbf{v}_t = \frac{\kappa}{4\pi b}\left(\ln\frac{8b}{a} - \frac{1}{4}\right) \cong \frac{\kappa}{b}$$

T → 0 $\quad \mathbf{v}_t$

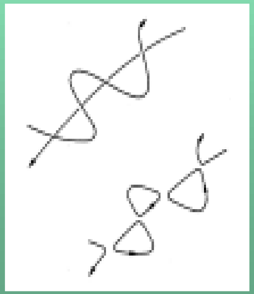
Finite T

In counterflow, though, if $|\mathbf{v}_t| < |\mathbf{v}_n - \mathbf{v}_s| = V_{CF}$ rings with $b > b_c$ expand

Dimensional analysis and analogy with classical fluid dynamics leads to the Vinen equation:

$$\frac{dL}{dt} = \chi_1 \frac{B}{2}\frac{\rho_n}{\rho} V_{CF} L^{3/2} - \chi_2 \frac{\hbar}{m_4} L^2 + (g(V_{CF}))$$

production $\qquad$ **decay**

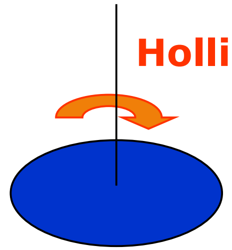


Reproduced by Schwarz (1988) – computer simulations
Local induction approximation
Importance of reconnections

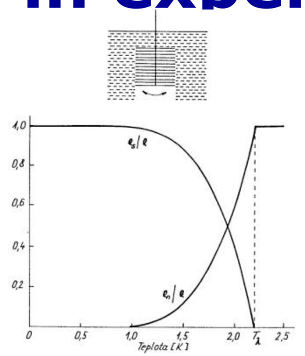
Oscillating objects used in experiments in He II and in ^{3}He

Discs and piles of discs

Hollis-Hallett



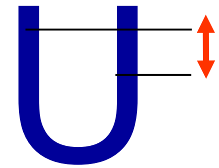
Andronikashvili



U-tubes

Donnelly

Penrose



Torsional oscillators

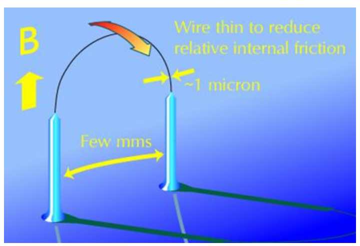
Many authors – vibrating wire viscometers

Vinen

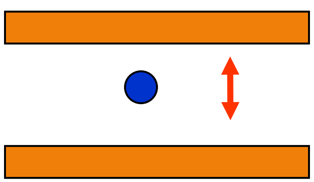
Morishita, Kuroda, Sawada, Satoh, JLTP 76, 387 (1989)

Lancaster – Pickett's group, Osaka – Yano et al., Kosice Skyba et al., Moscow Dmitriev et al., Helsinki- YKI group…, Grenoble Bunkov et al., …

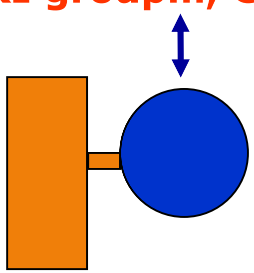
Wires
He II and
3He



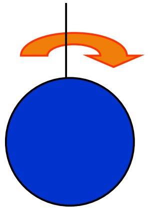
Spheres
He II
(3He?)



Schoepe et al



Luzuriaga

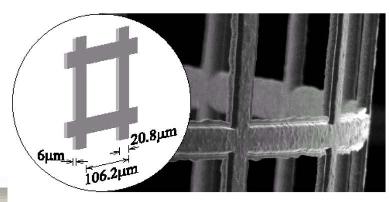


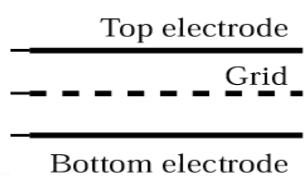
Hollis-Hallett

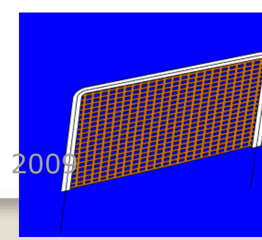
Lancaster – P. McClintock's group

Lancaster – G. Pickett's group

Grids
He II and
3He



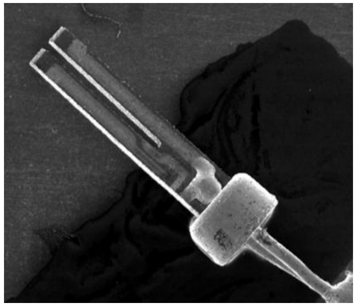




Typical characteristics of commercially available forks

Room temperature

closed fork — frequency 2^{15} Hz = 32764 Hz; linewidth around 0.5 Hz



Bare fork — frequency down by 7-10 Hz; linewidth around 5-6 Hz

Ground off can — linewidth around 3 Hz

Fork in vacuum:

LN2	32722 Hz	linewidth	0.2 Hz
LHe	32710 Hz	linewidth	0.06 Hz

Q about 500 000

Fork in cryofluids:

He I SVP 4.2 K 31600 - 31700 H

linewidth 12-13 Hz

He II SVP 1.3 K linewidth 1.2 Hz

Response to about 8 orders of magnitude of the ac drive (up to 130 V rms) fork rms velocity reaches up to 10 m/s

Thermal cycling is not a serious issue for most applications

Quartz Tuning Fork: Thermometer, Pressure- and Viscometer for Helium Liquids, R. Blaauwgeers, M. Blazkova, M. Clovecko et al, *JLTP, 146, 5/6, 537 (2007)*

- **Mechanical properties**

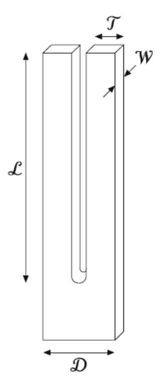
$$\frac{d^2x}{dt^2} + \gamma \frac{dx}{dt} + \frac{k}{m} x = \frac{F}{m}$$

- Resonance frequency

$$\omega_0 = \sqrt{\frac{k}{m}}$$

- Quality $Q = \frac{\omega_0}{\gamma}$, where width of resonance curve $\Delta\omega = \gamma$
- Effective mass of prong

$$m_{\mathrm{vac}} = 0.24267\, \rho_q\, \mathcal{L} \mathcal{W} \mathcal{T}$$



- **Electrical properties**
- Fork response $U = U_0 \cos(\omega t)$

$$I(t) = a \frac{dx(t)}{dt}$$

- The mechanical oscillator with the equivalent electrical RLC series resonance circuit. The corresponding differential equation for the current is

$$\frac{d^2I}{dt^2} + \frac{R}{L}\frac{dI}{dt} + \frac{I}{LC} = \frac{1}{L}\frac{dU}{dt}$$ =>

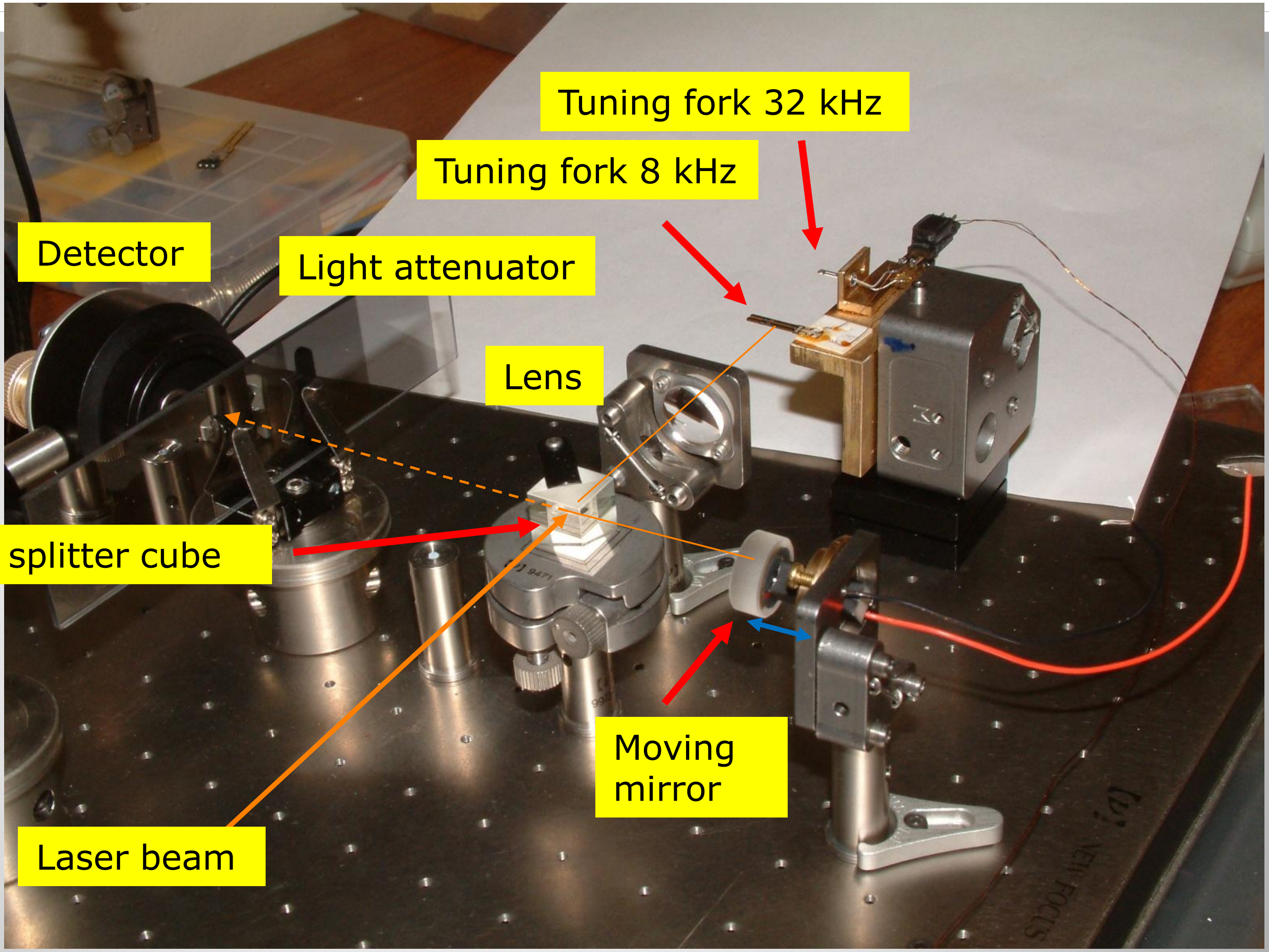
$\omega_0^2 = 1/(LC),\ \ \gamma = R/L,$ and

$$1/L = (F_0/U_0)\, a/m$$

$$F_0 = (a/2)\, U_0,$$
$$R = 2m\gamma/a^2,$$
$$L = 2m/a^2,$$
$$C = a^2/(2k).$$

$$a = \sqrt{\frac{2m\,\Delta\omega}{R}}$$

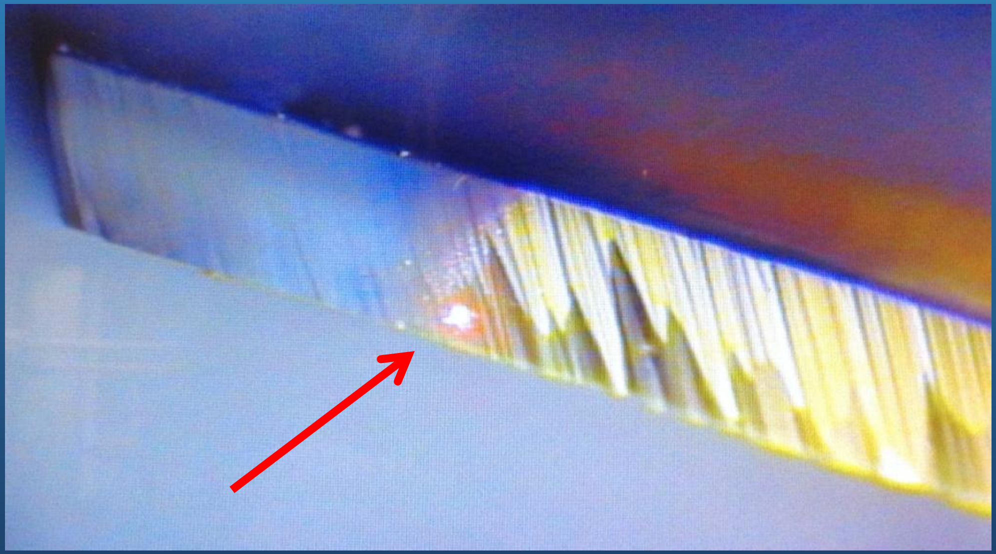
Electro-mechanical calibration



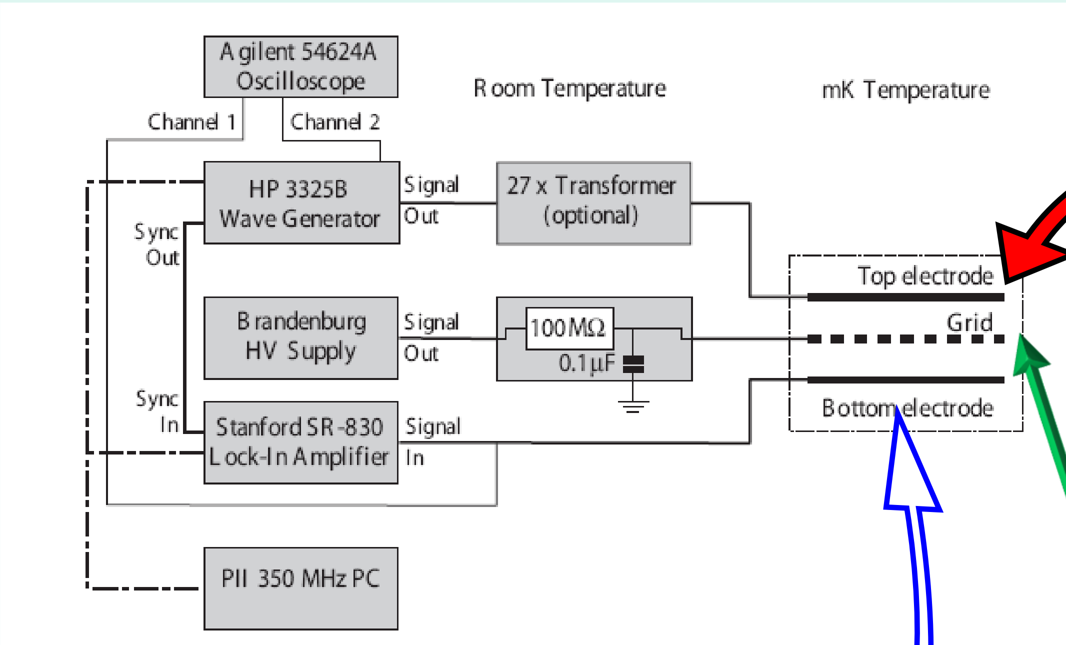
Michelson interferometer scheme for measurement of amplitude of fork vibration

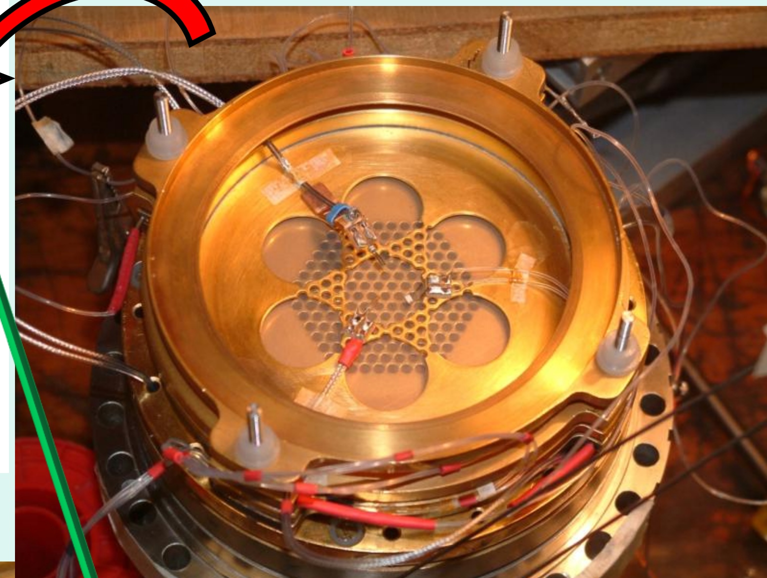
Absolute prong's velocity (T_{room}, air)

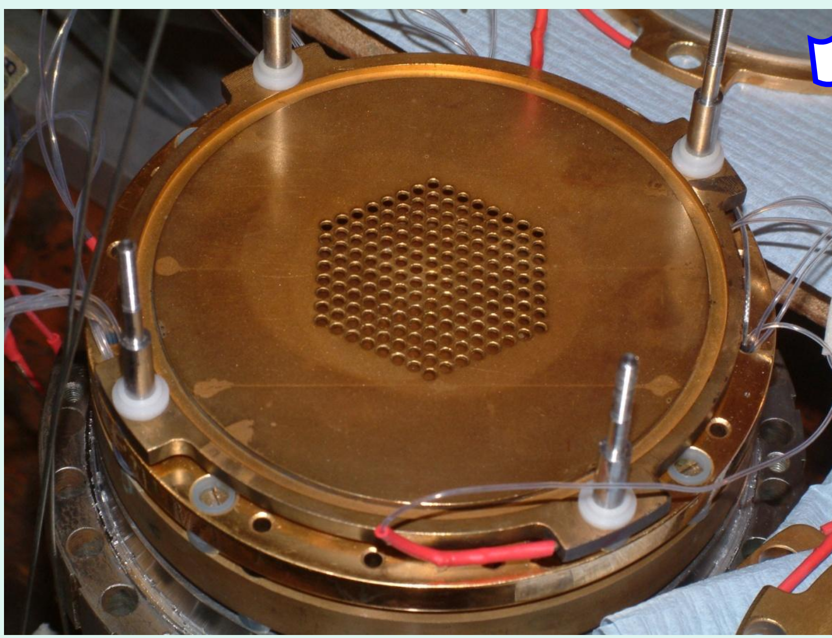
Bending vibration f_C=75,64 kHz
V_{drive}=800 mV_{PP}; f = 76,228 kHz, Δf=17 Hz;
sensitivity of Doppler analyzer (DA) 100 mm/s/V
signal of DA = 4.8 V, velocity of vibration v_P=48 cm/s
No changing in DA signal at scanning perpendicular to prong width. Laser point was near the end of the fork's prong (v_{max} ~1.2* v_P)

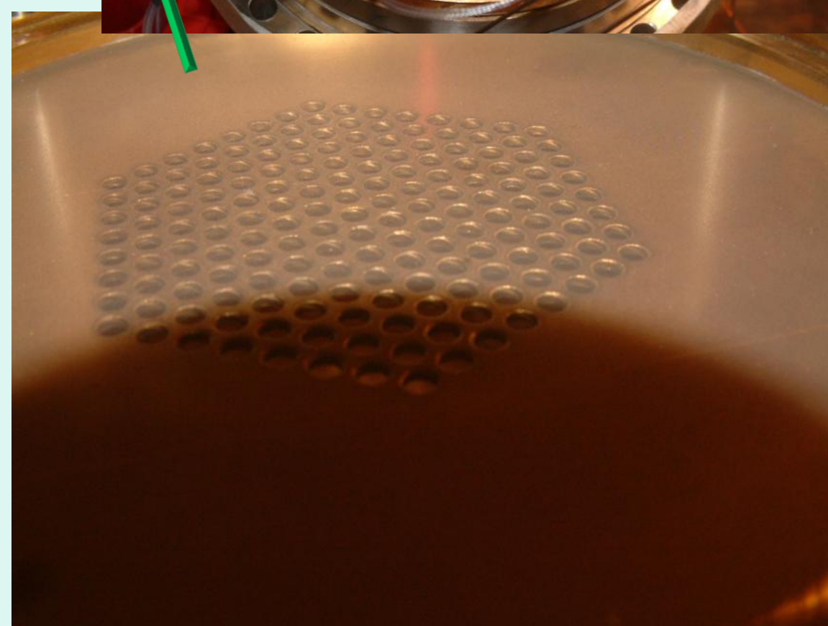


Scheme of experiments

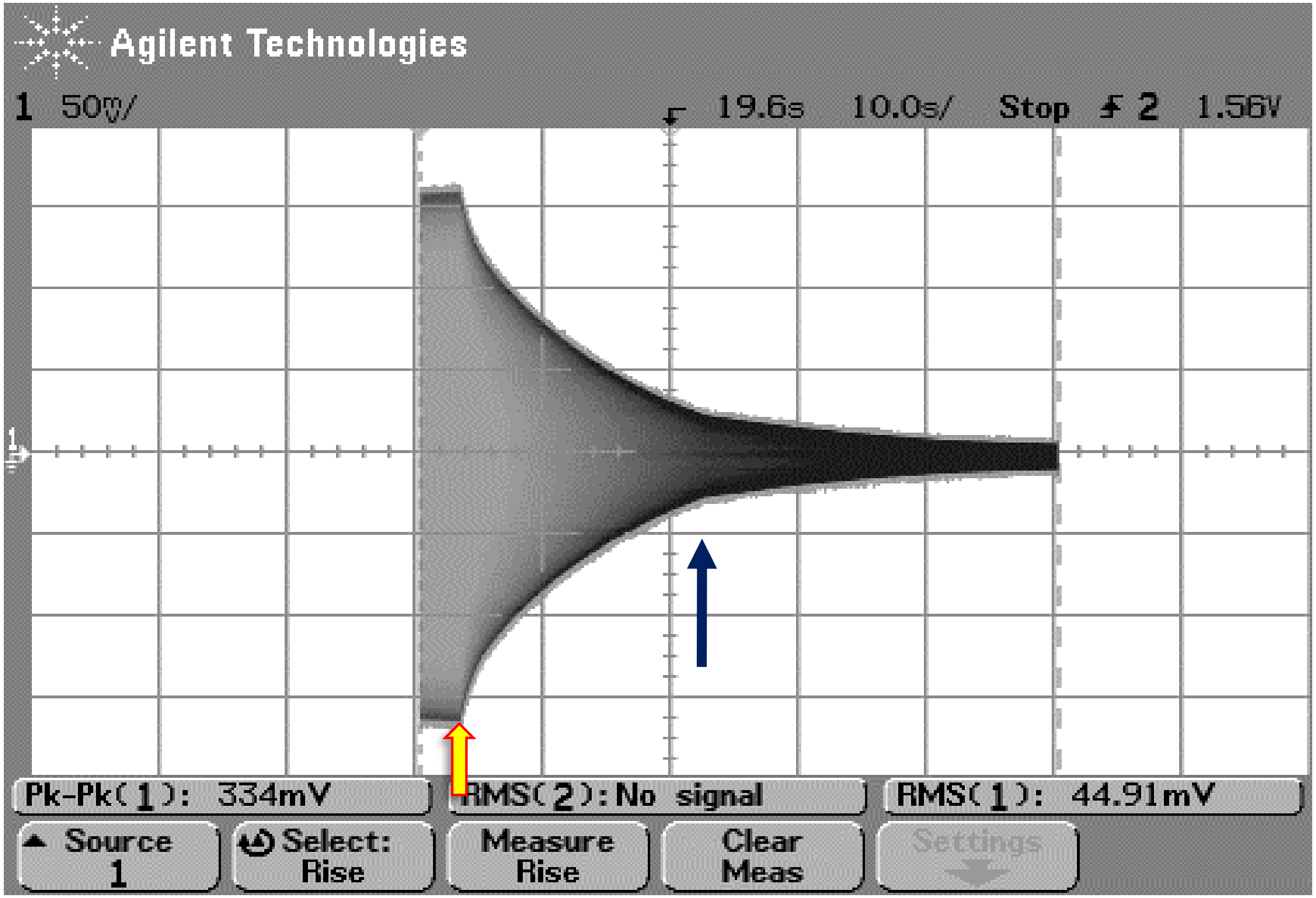


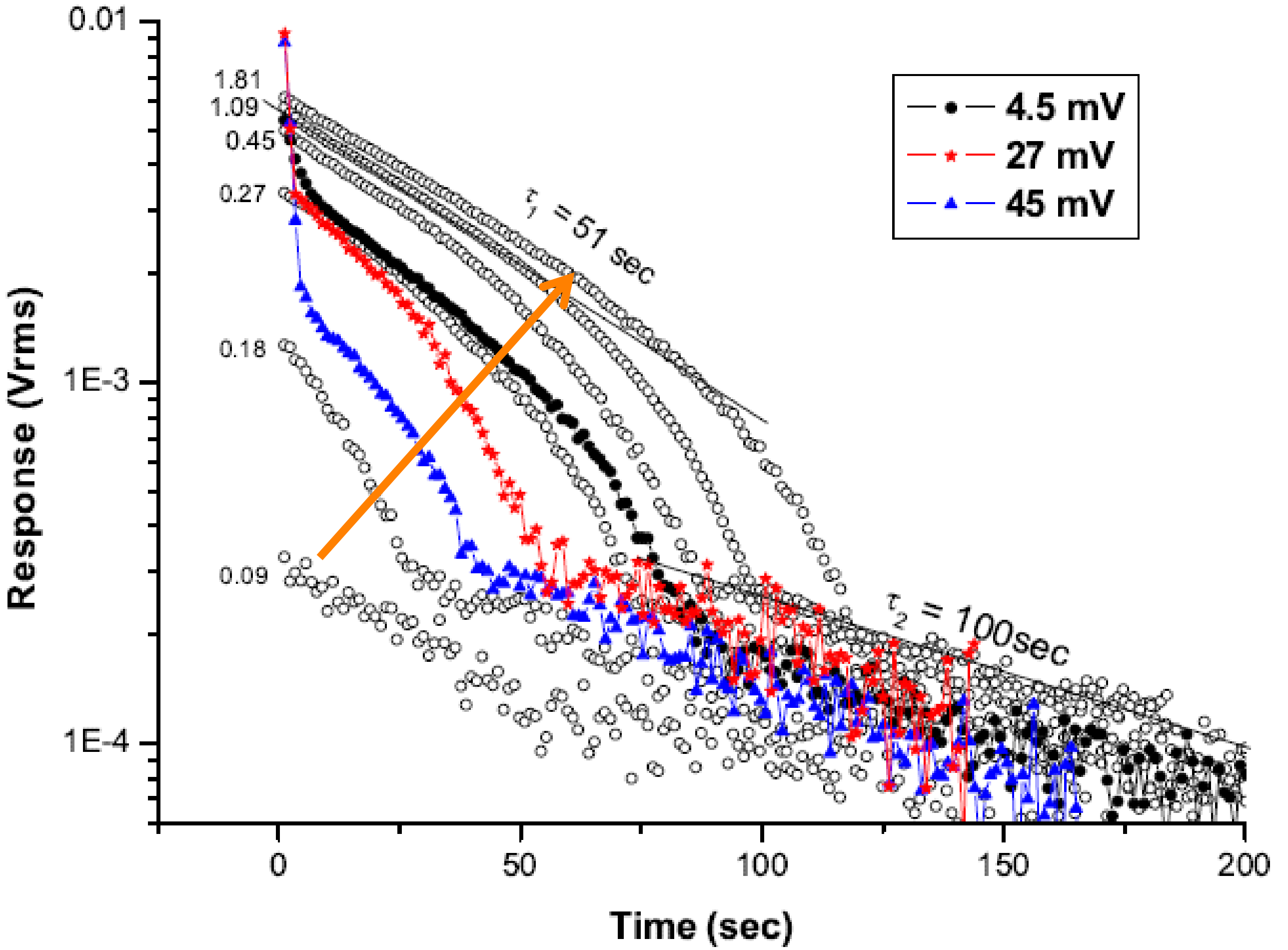






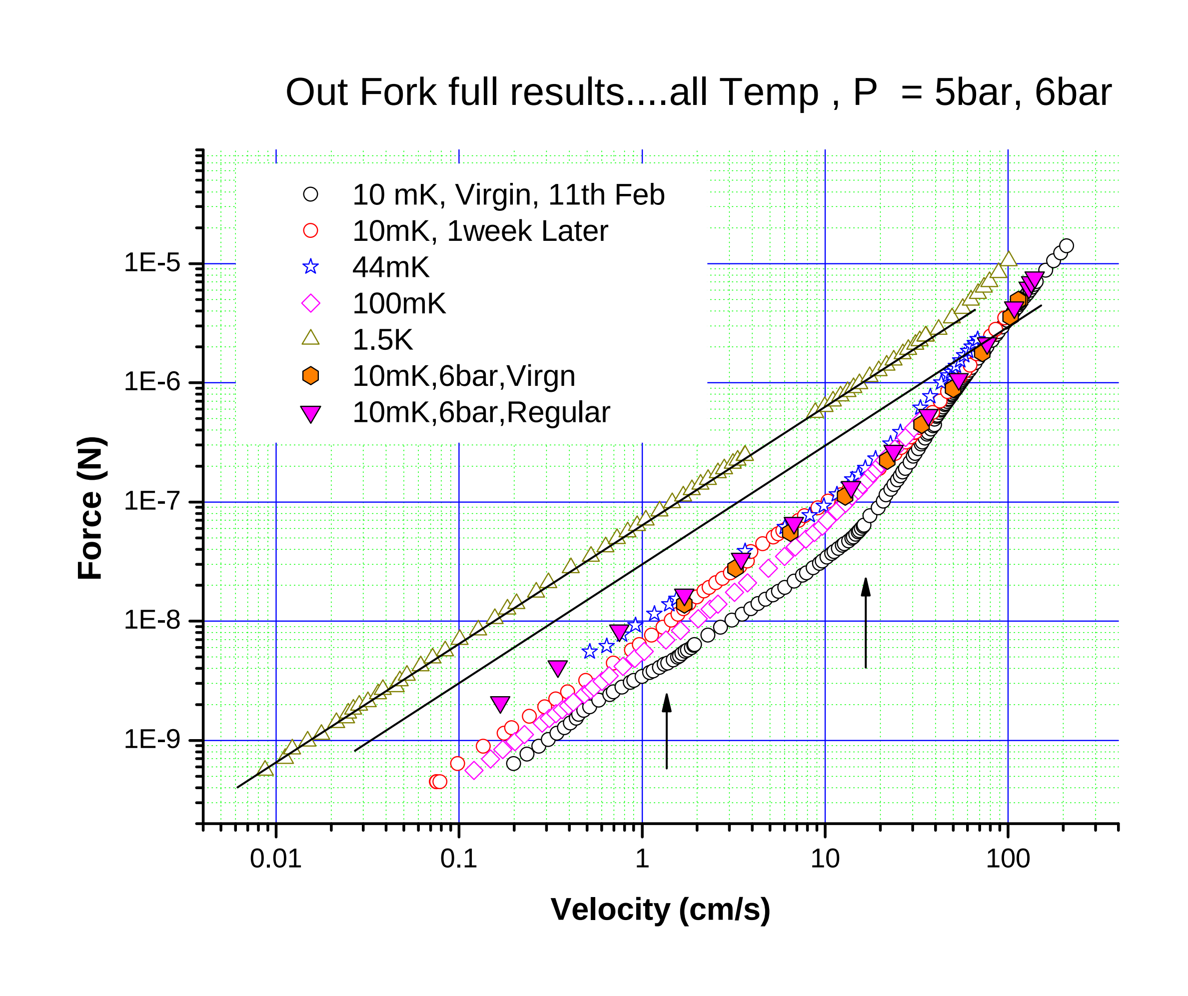
Free decay of grid oscillation





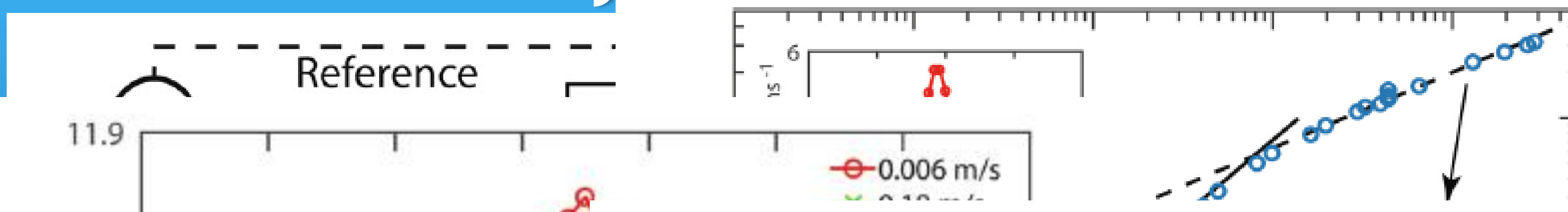
T~44 mK

Free decay of grid vibration



Temperature behaviour of fork response

Generation of the quantum turbulence by tuning fork



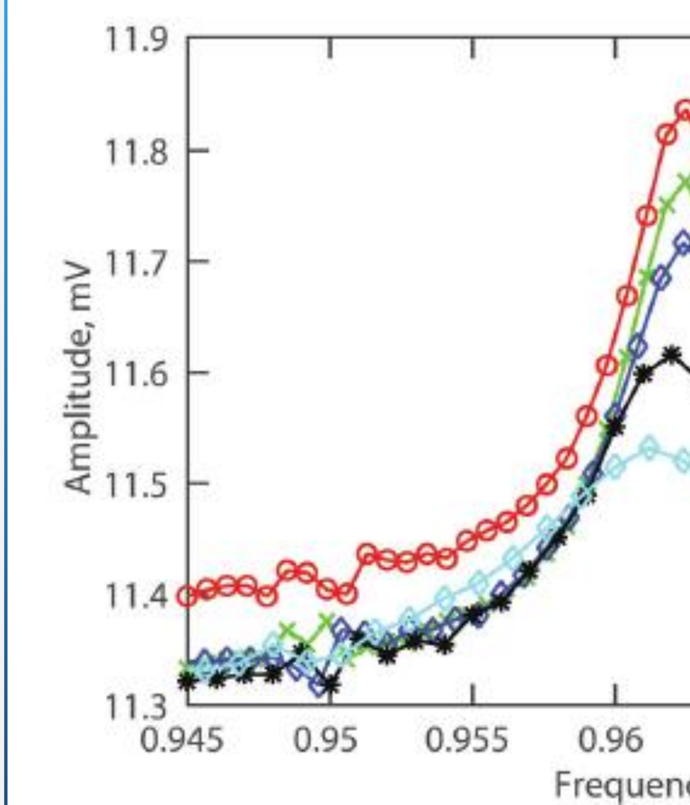


Fig. 3 Second sound frequency sweeps of the 5th secon
Note that the change in the resonance frequency is caused
to the temperature drift of a few millikelvin and is not due

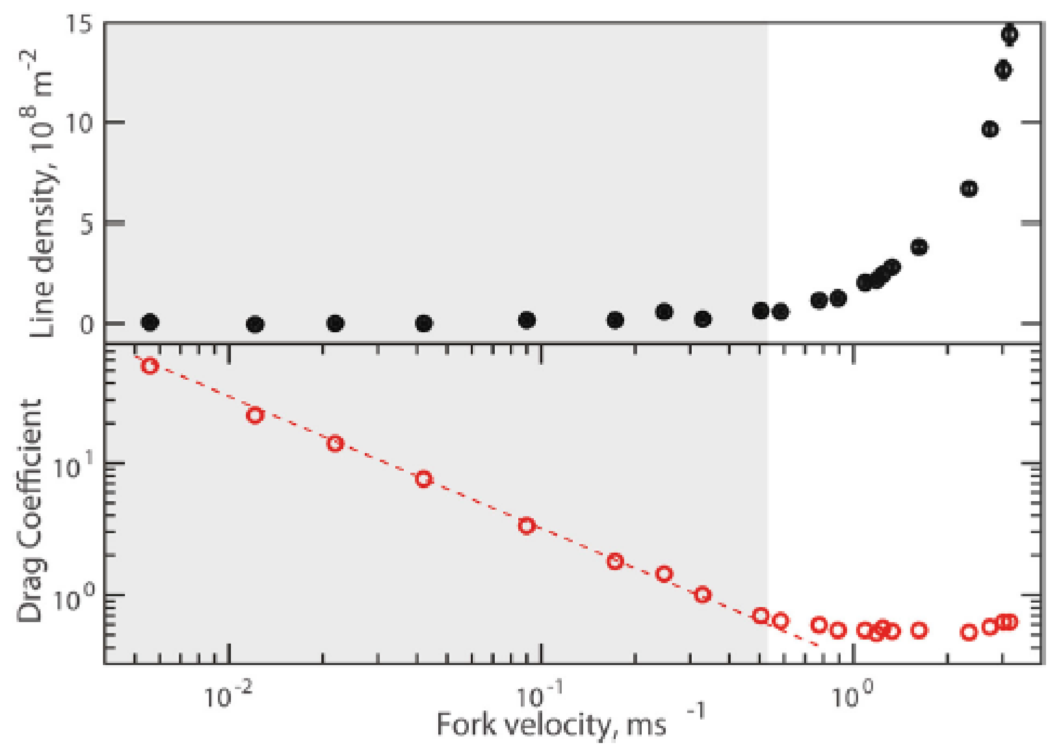
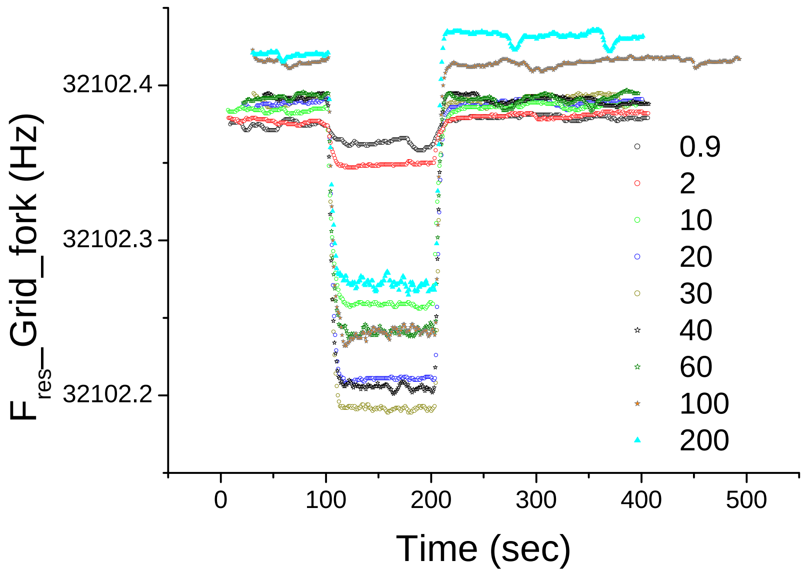
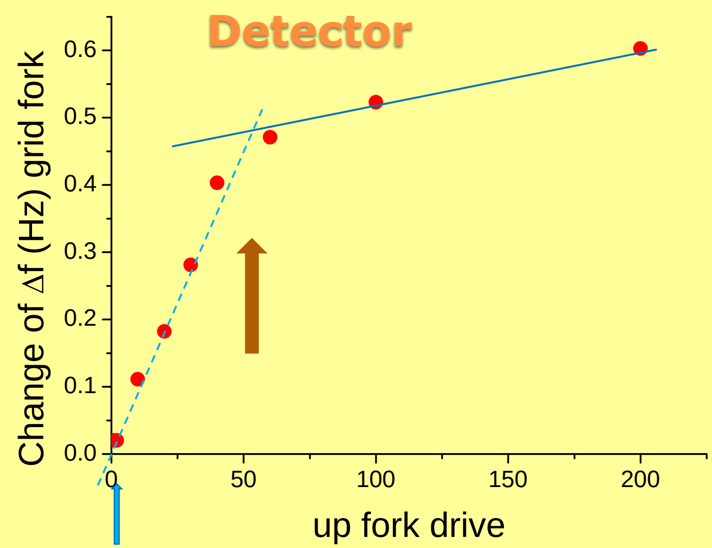


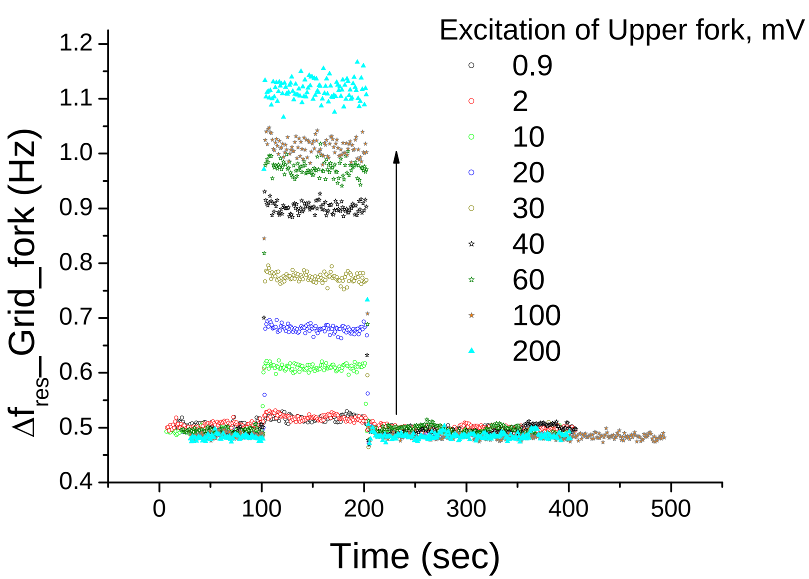
Fig. 4 *Top Vortex line* density inferred from the second sound attenuation as a function of tuning fork velocity. *Bottom* drag coefficient experienced by the tuning fork versus tuning fork velocity. The *dashed line* is a guide for the eye and the *shaded area* highlights the laminar regime. For details, see text (Color figure online)

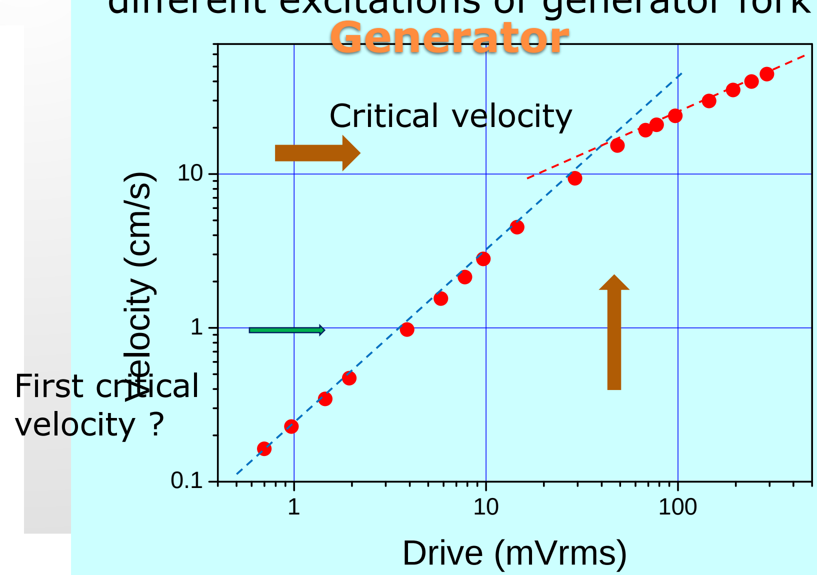
M.J.Jackson et al, JLTP, 183, 208 (2016)



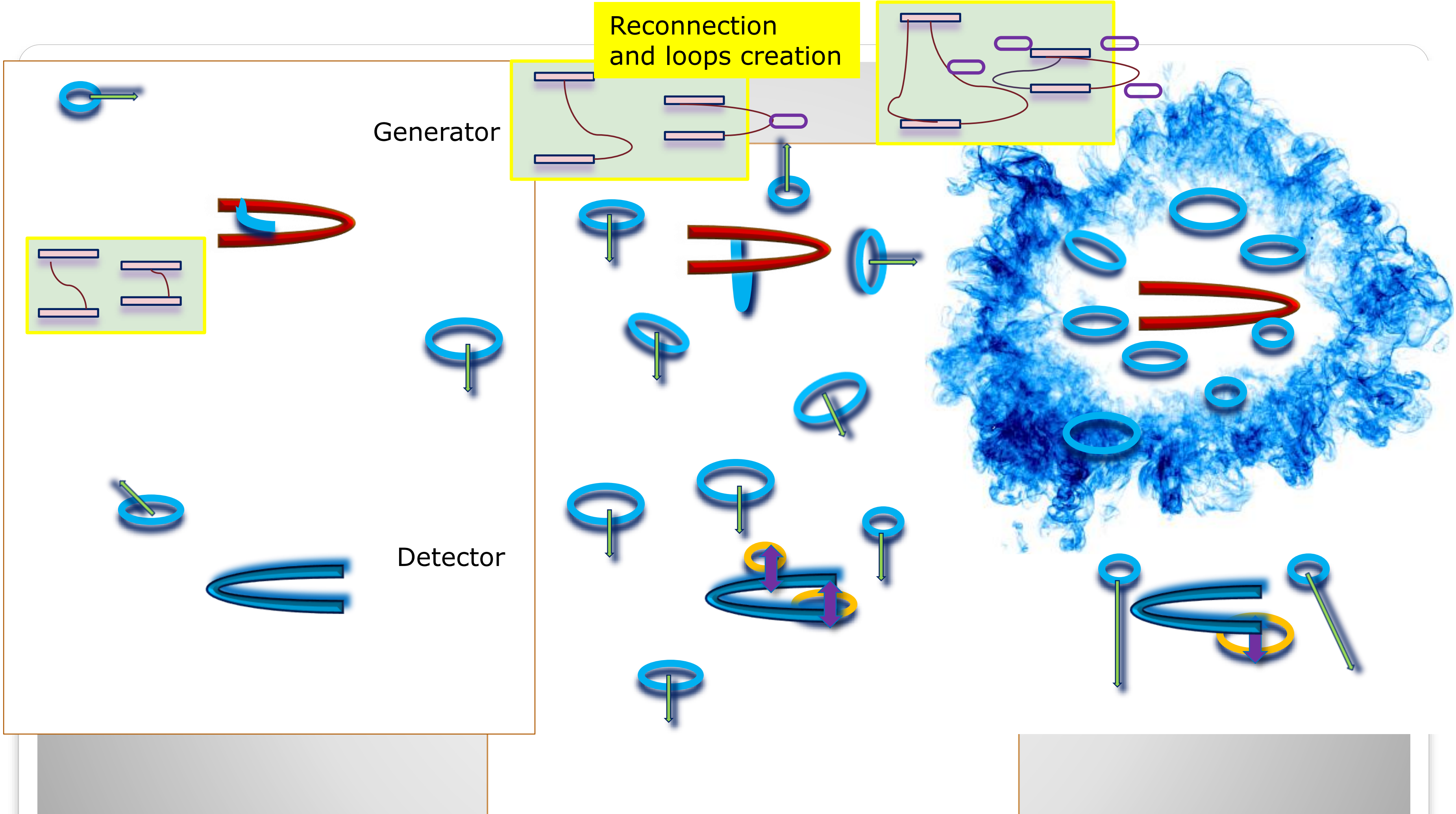


Change of detector fork response at different excitations of generator fork





Response (velocity of fork prongs) at different excitations for generator fork.



Laminar – vortex loops - turbulence
flow formation regime

0 Vc1 Vc ∞

ration bodies

PHYSICAL REVIEW B **85**, 014501 (2012)

Crossover from hydrodynamic to acoustic drag on quartz tuning forks in normal and superfluid ^{4}He

D. I. Bradley, M. Človečko, S. N. Fisher, D. Garg, E. Guise, R. P. Haley, O. Kolosov, G. R. Pickett, and V. Tsepelin*
Physics Department, Lancaster University, Lancaster, LA1 4YB, United Kingdom

D. Schmoranzer and L. Skrbek
Faculty of Mathematics and Physics, Charles University, Ke Karlovu 3, 121 16 Praha, Czech Republic

(Received 14 September 2011; revised manuscript received 5 December 2011; published 6 January 2012)

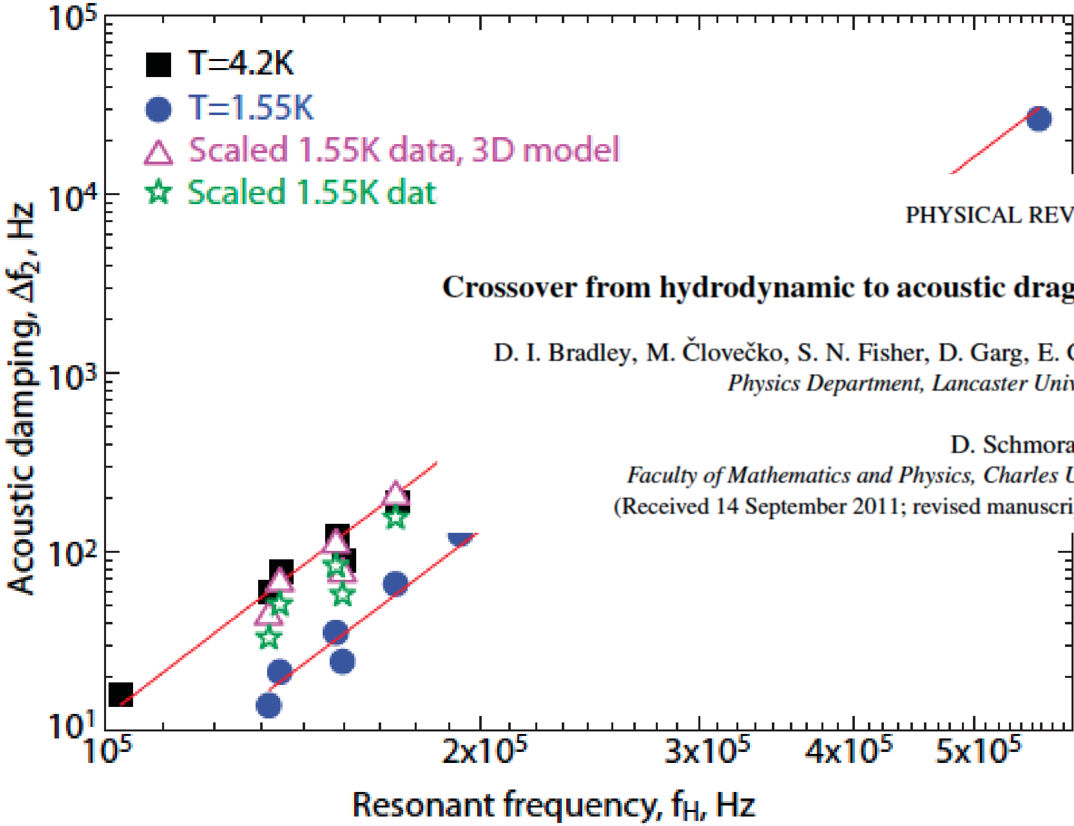
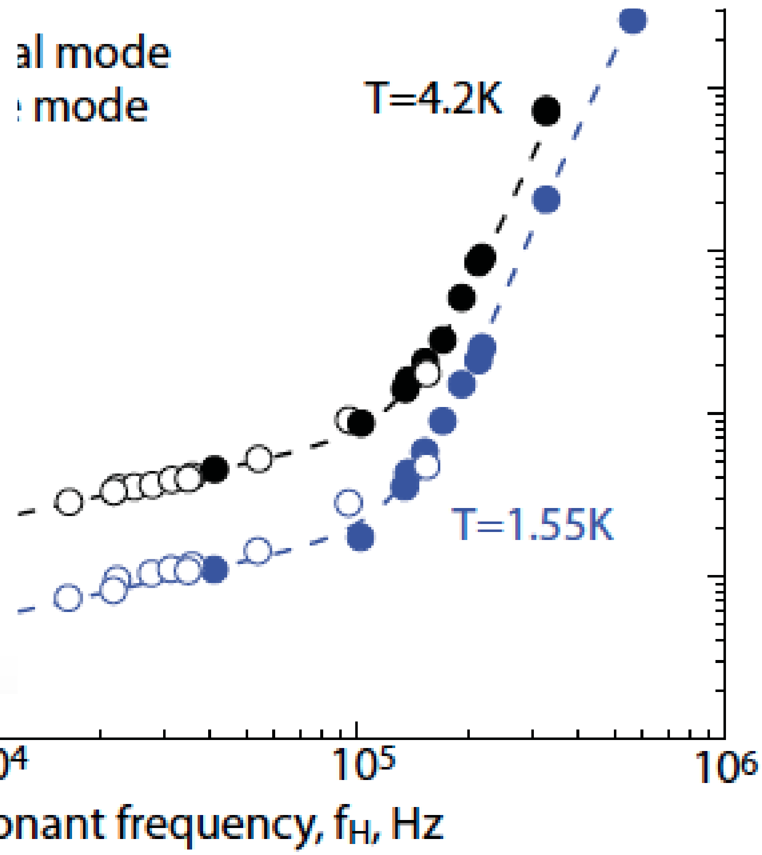


FIG. 6. (Color online) The acoustic damping of tuning forks as a function of frequency. The squares and circles correspond to the inferred acoustic contribution to the damping at 4.2 and 1.55 K, respectively. Red lines are least-squares fits given by $\Delta f_2^{4.2\,\mathrm{K}} = 2.7 \times 10^{-26} f^{5.33}$ and $\Delta f_2^{1.55\,\mathrm{K}} = 1.6 \times 10^{-26} f^{5.26}$. Open triangles and stars show the 1.55 K data scaled using the full expressions for the 3D and 2D models, respectively (see text).

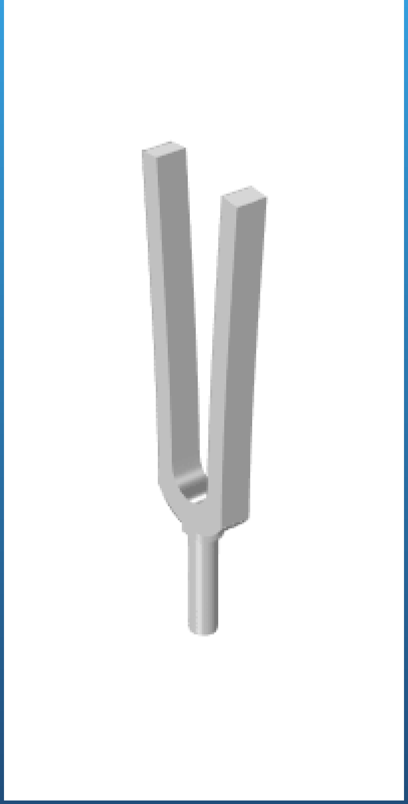
Stycast-impregnated graph paper
(not shown).

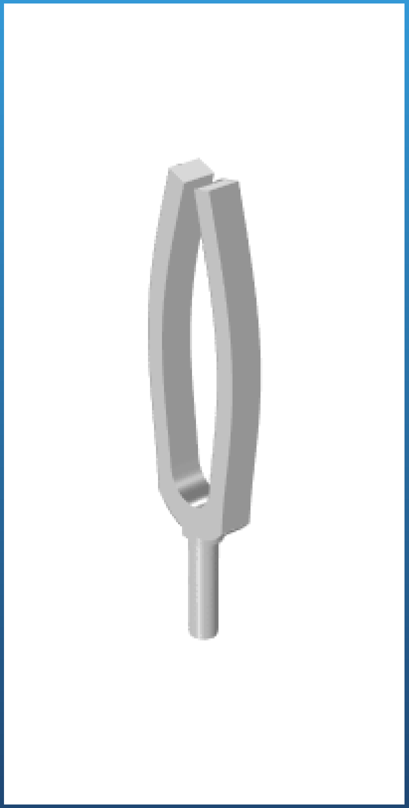


Torsion tuning forks

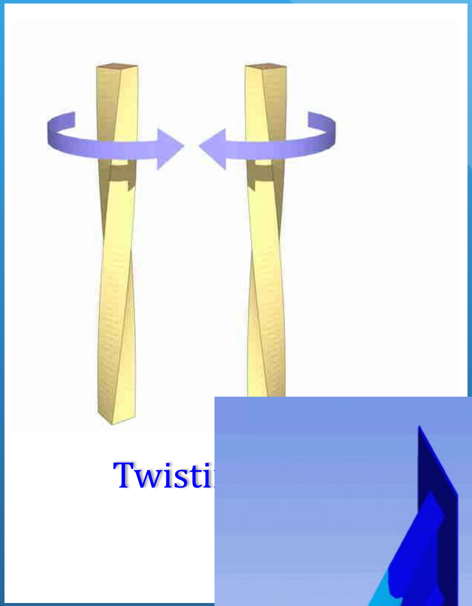
New tuning fork vibration modes

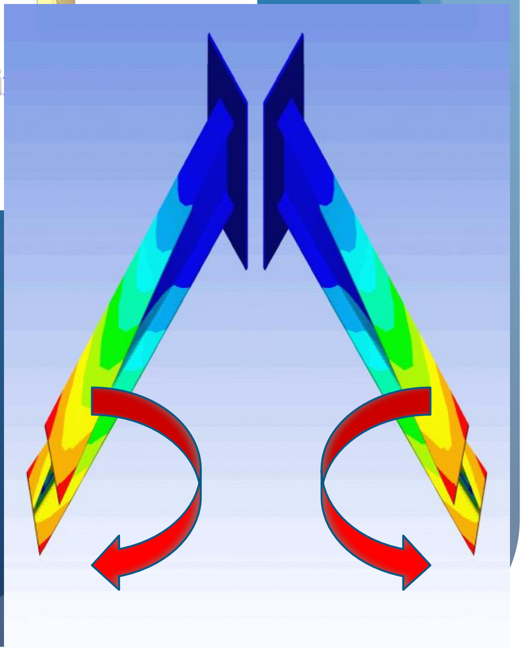
Flexible modes



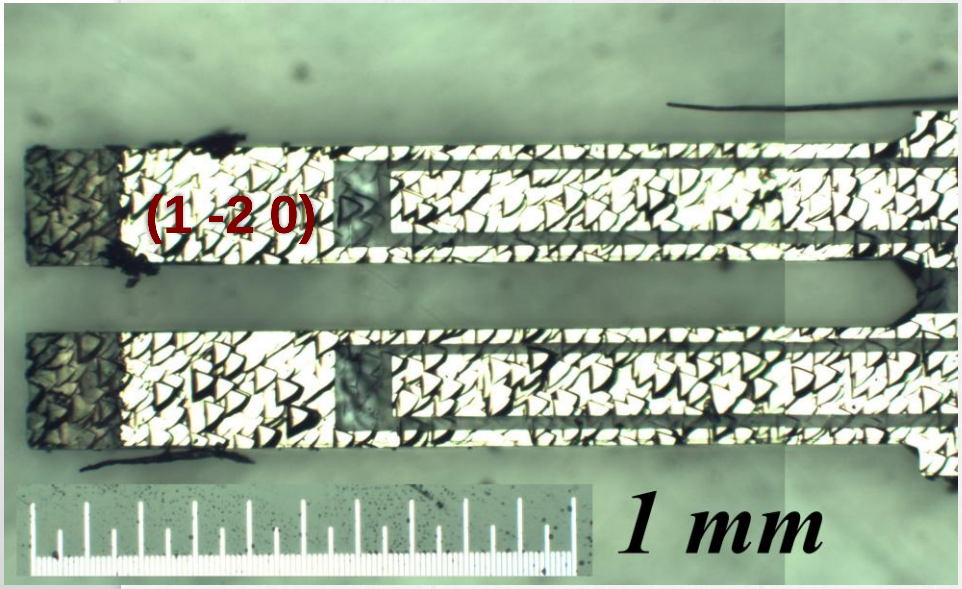


Twisting modes





Size and vibration modes



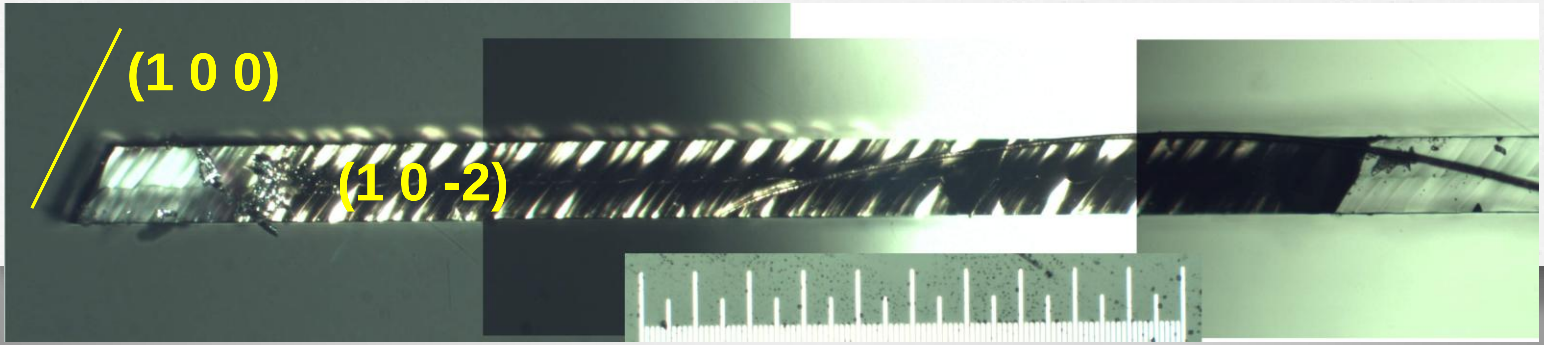
L=1.61 mm - length
T=0.223 mm - thickness
W=0.143 mm – width

Mode of vibration: bending

$$\omega_n = 2\pi f_n = \sqrt{\frac{EI}{\mu}}\frac{\beta_n^2}{L^2}$$

f_1=77.2 kHz, f_2= 482 kHz
f_3=1.35 MHz

Measured vacuum T_{room}
f_1=76,228 kHz; f_3=1.112 MHz



Size and vibration modes

Mode of vibration: twisting

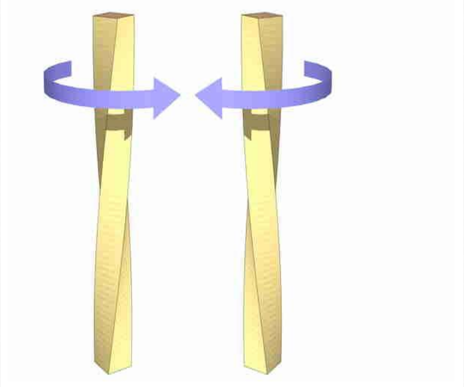
$$G = (\frac{2L\omega_n}{n})^2 \rho_q K$$

$$K = \frac{\left(\frac{W}{T}\right) + (\frac{T}{W})}{4\left(\frac{W}{T}\right) - 2.52\left(\frac{W}{T}\right)^2 + 0.21(\frac{W}{T})^6}$$

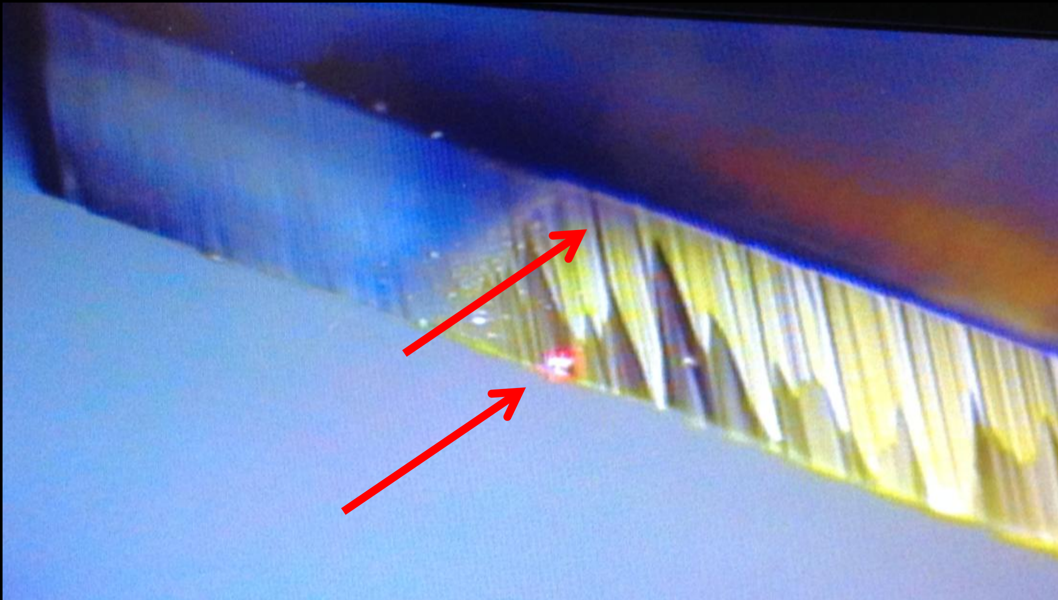
f_1=424 kHz, f_2= 848 kHz
f_3=1272 kHz

Measured vacuum T_{room}
f_1=393 020 Hz

$f_B \sim f_1 * (2n-1)$
$f_T \sim f_1 * n$

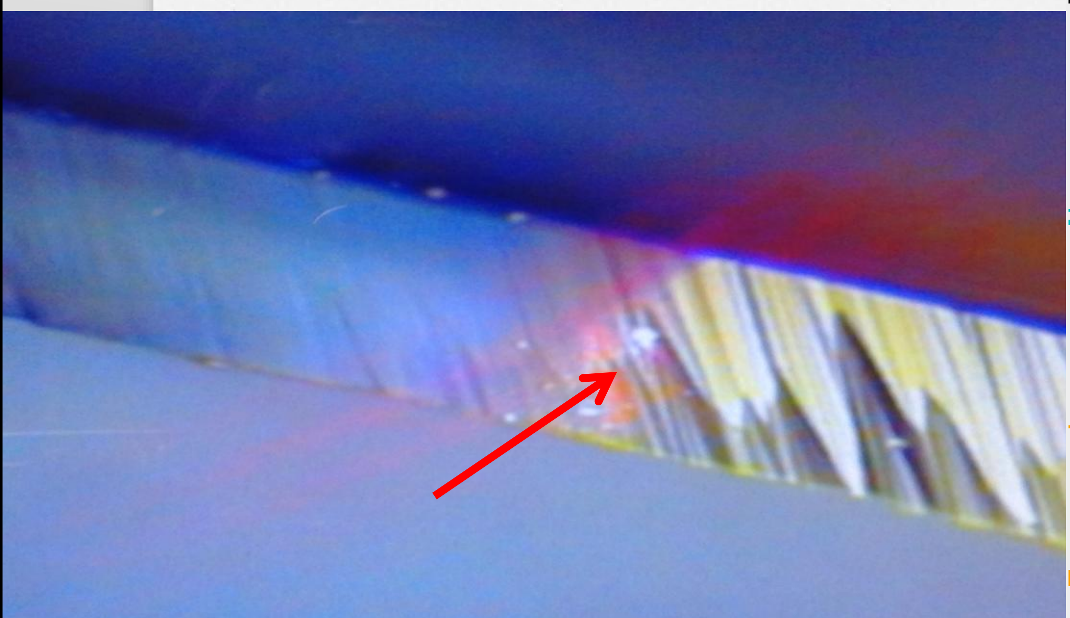


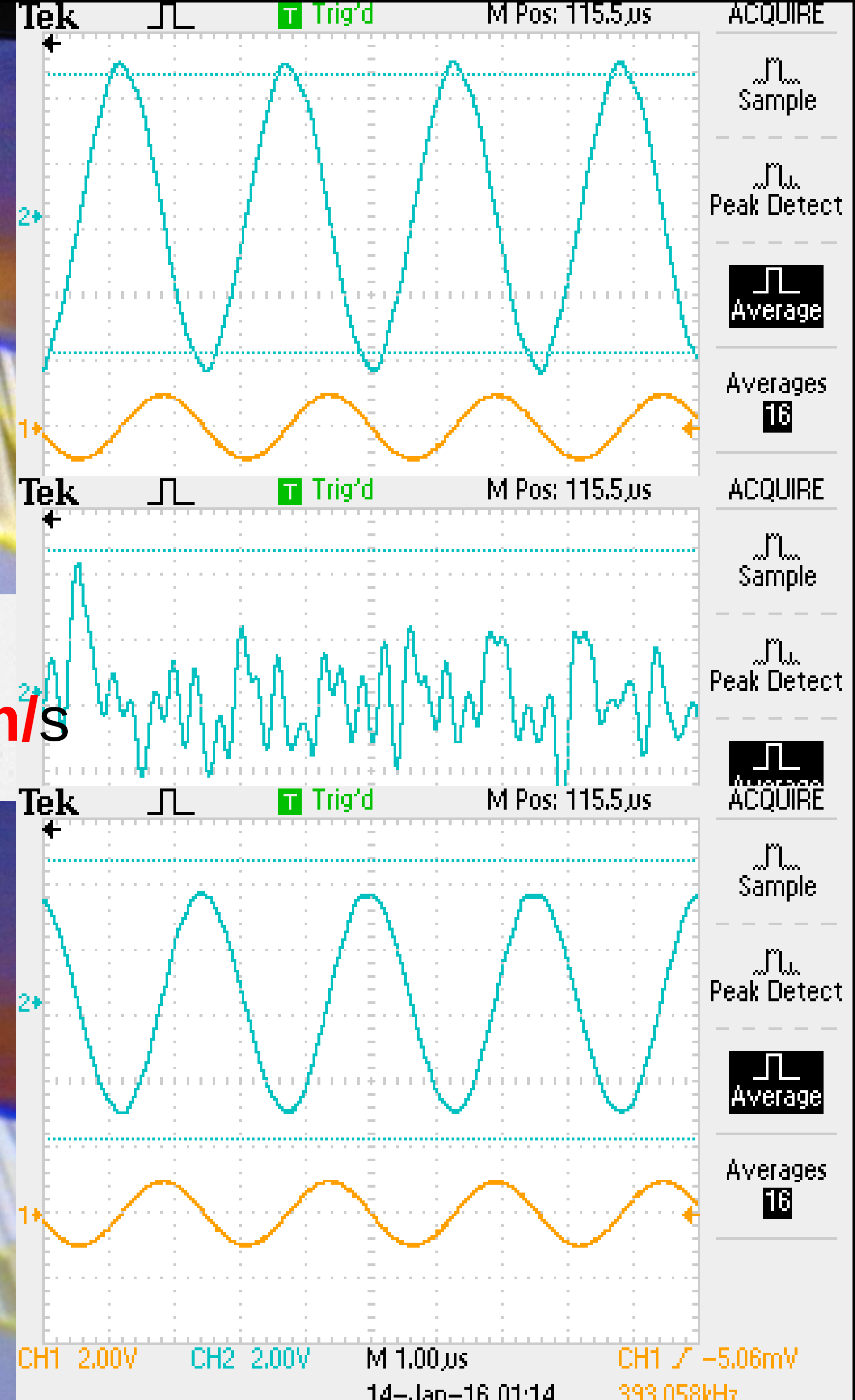
Twisting turning fork



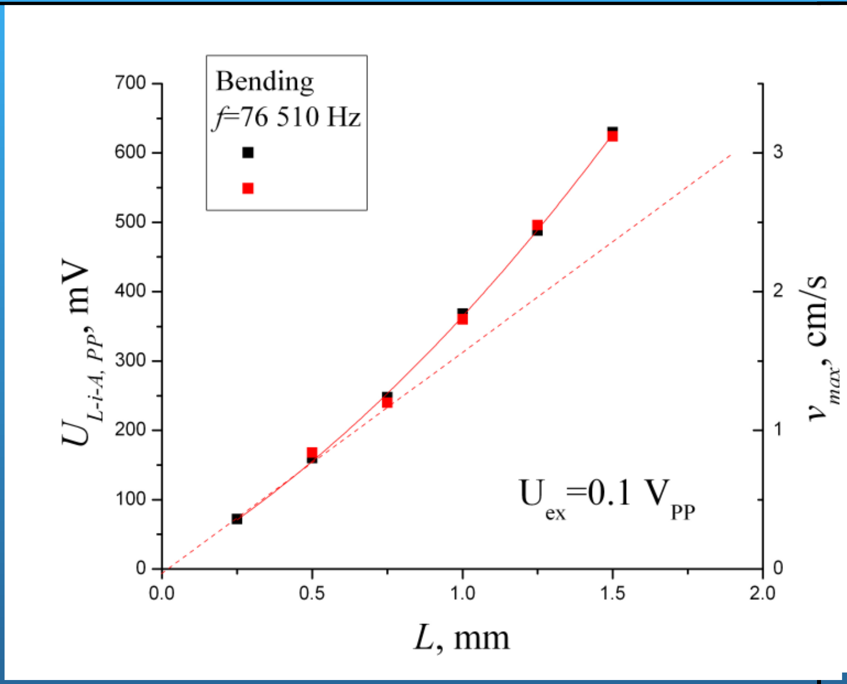
f = 393 093 Hz, Δf=60 Hz;

velocity of vibration v_P=10.4 cm/s





Torsion fork motion at different modes



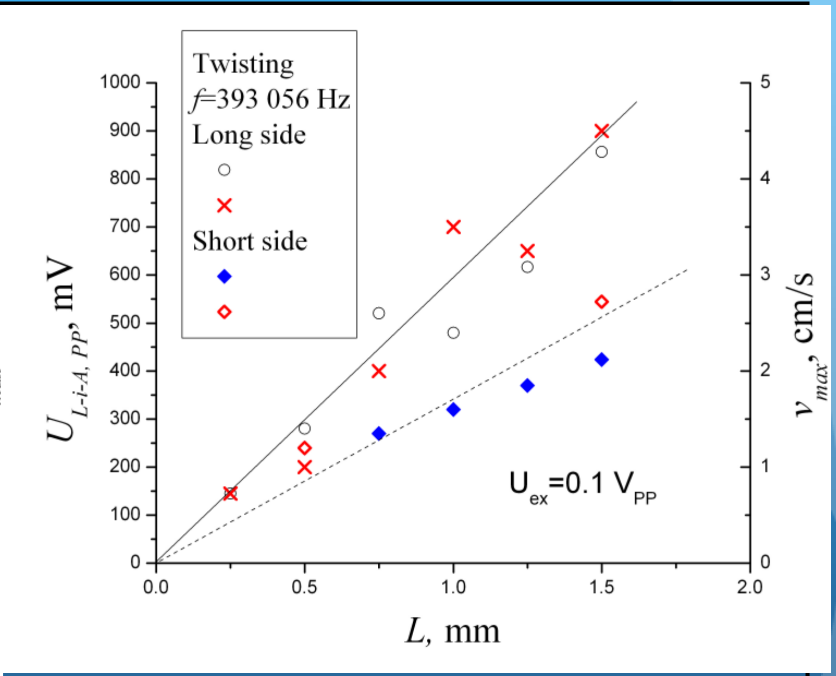


Fig.3 Scanning of the DA signal along the prong for different mode of vibration, a) bending mode and b) twisting mode from different sides of the prong. The right scale indicates a prong velocity (results 2017, air, T_{room}).

Different media of fork vibrations

Calibration of I-V convertor.

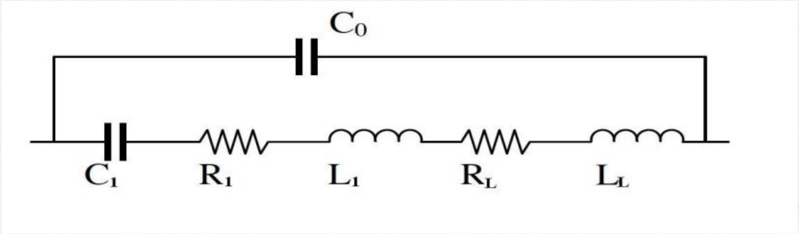
393 kHz	0.571 V on R=33 kOm	Uex=0 dB
76 kHz	0.629 V on R=33 kOm	Uex=0 dB

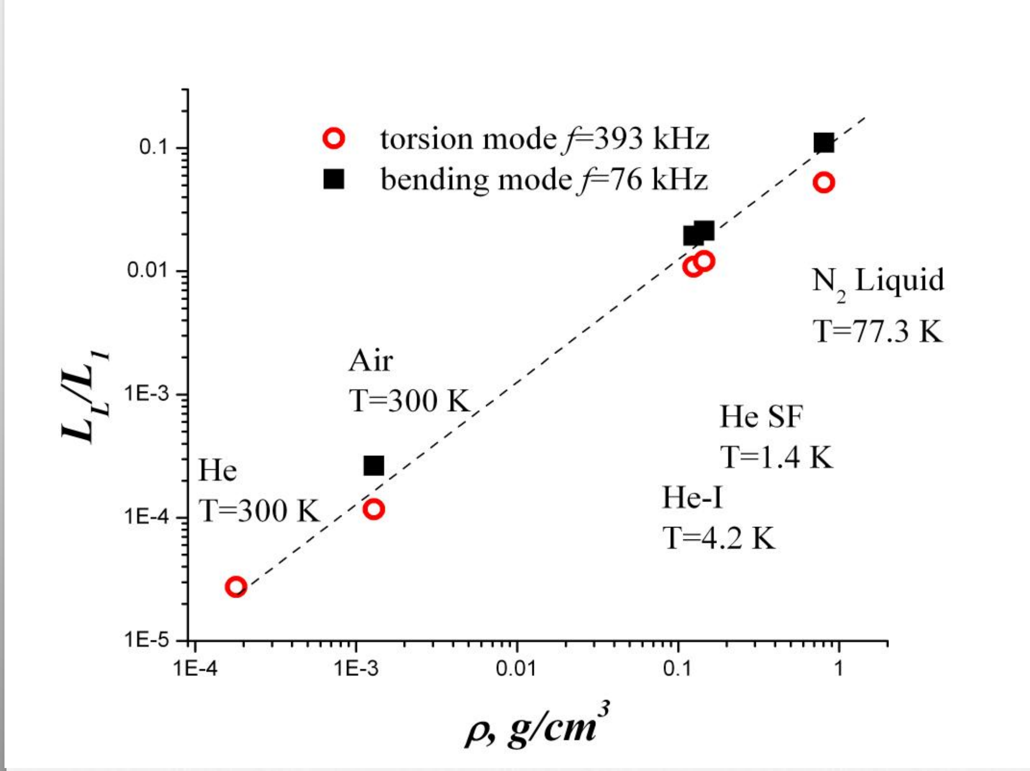
Frequency of resonance U_{ex}=0dB (1V):

Gases	Vacuum Room	He Room	Air Room	N2 Low T
393kHz	393 020,1	393 014,75	392 973,5	392 653.5
76 kHz	75 663,24	75 688,8	75 643,75	75 927,6

Liquids	SF He T=1.4 K	He T=4.2 K	Liquid N_2	N2 Low T
393kHz	387 892,5	388 372,5	371 997,5	392 653.5
76 kHz	74 308,9	74 458	67 567,5	75 927,6

Different media of fork vibrations





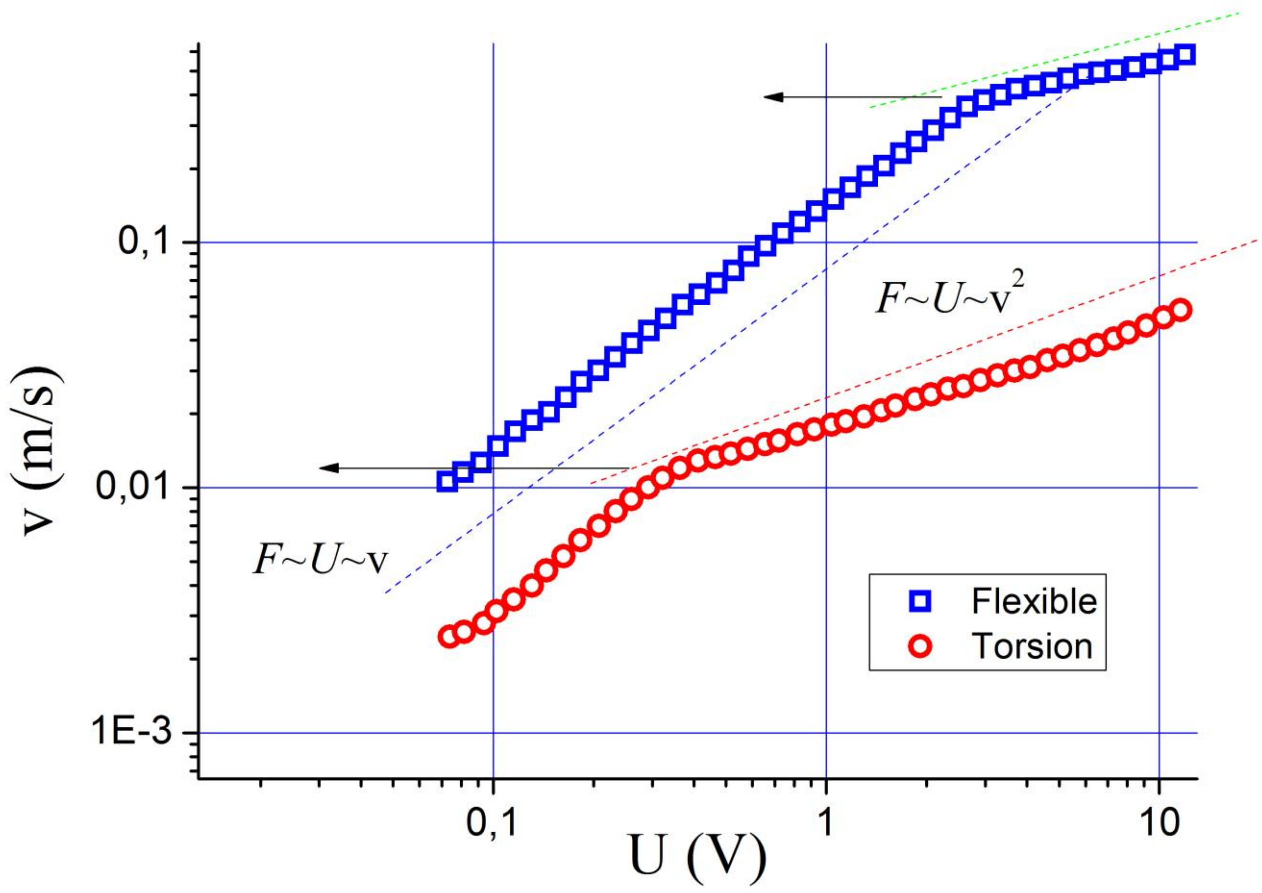
The resonant frequency of the circuit is given by

$$f = \frac{1}{2\pi\sqrt{(L_1 + L_L) * C_1}}$$

The resonant frequencies were measured in different media, so for these measurements changed only L_L

$$\Delta f \cong -\frac{1}{2} f_1 \frac{L_L}{L_{1:}}$$

Fork vibration in superfluid helium



- Tuning forks are cheap, robust, reproducible, easy to install and very sensitive;
- Vibrating forks in superfluid helium use as a generator and a detector of turbulence;
- Influence of one fork on another at distance more bigger the size of fork – the vertexes move through cm's distance at T~0 K;
- Virgin and disturb states exist in superfluid helium. The disturb state maintains hundreds hours at base temperatures (T~10 mK);
- The energy loss of vibrating grid at free decay and tuning forks comes through three stages:

 - very quick energy loss – energy pumping into turbulent state (inject of vortex loop flux or classical turbulence?),

 - quick linear loos of energy (create of vortexes?),

 - slow free vibration (laminar motion, quality of grid);
- The torsion tuning fork has two modes: flexible and twisting. The transition into turbulent state has drastically different critical velocities for bending and twisting motion.

Conclusions