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Vibrating grids in 4He at very low temperatures (plus some comments on quartz tuning forks)

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Vibrating grids in ^{4}He at very low temperatures

(plus some comments on quartz tuning forks)

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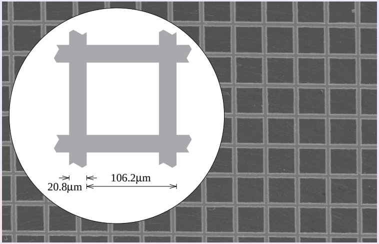
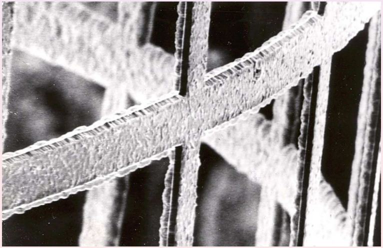
Outline

1. Introduction
   - Beginnings
2. Experiments
   - The oscillating grid
   - Grid resonance results
   - Free decay results
3. Comments on quartz forks
   - Forks for QT creation/detection
4. Discussion
   - The emerging picture?
   - Conclusion

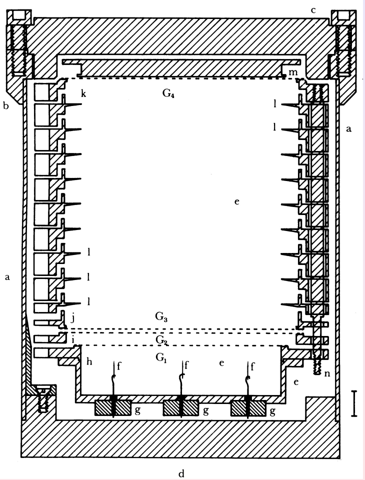
Creation of QT by moving grid, detection by quartz forks?





Inference of QT creation and decay

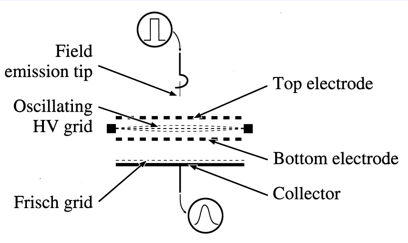
- In experiments ($\sim 30\,\mathrm{mK}$) to measure Landau velocity, noticed:
  - (a) There was no build-up of charged vorticity – though ions from field emitters produce charged vortex rings & tangles.
  - (b) If the tip voltage was made momentarily "too high", signal disappeared, and then took many minutes/hours to return.
- So QT does decay!
- But the decay rate can be slow.

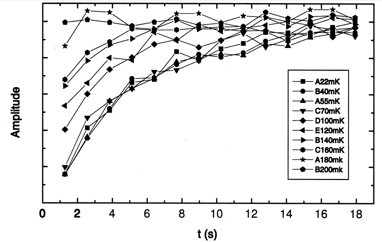


Ellis & McC, *Phil Trans R Soc A* **315**, 259 (1985).

Observation of decaying QT

Davis et al, Physica B **280**, 43 (2000).





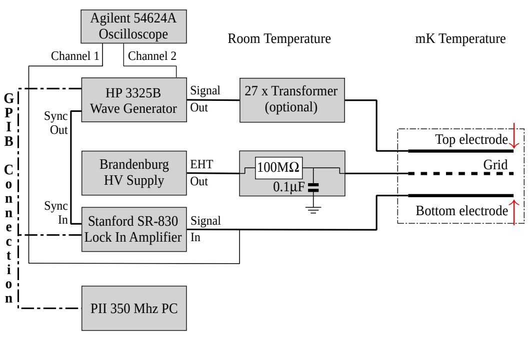
- Create QT by oscillating the grid for a few seconds.
- Probe the QT region with pulses of negative ions.
- Trapping of ions on vortices attenuates the signal.
- So expect signal to return gradually to its vortex-free level.
- Some caveats –
  - More qualitative than quantitative – “Circumstantial”!
  - Distribution of QT was unknown.
  - Vortex/ion trapping cross-section was unknown.

Experiments on grid dynamics

Our recent experiments do not use ions for QT detection. Instead –

- Try to infer QT creation processes from the dynamical response of the grid to driving force.
- Or, more recently, monitor free decay of grid oscillations after the driving force has been removed.
- Can we detect QT produced by the grid via its effect on a quartz fork?

Experimental arrangement



$V_1 = V_{10} \cos \omega t$

$\leftarrow V_0 \simeq 500$ V DC

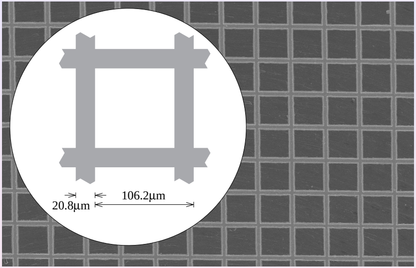
Signal pick-up, V_2

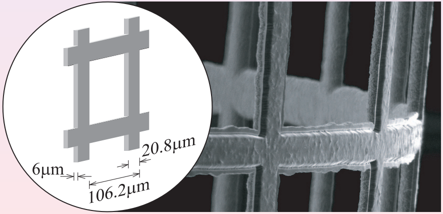
Force on grid, $f_d = \epsilon_0 \epsilon_r \pi R^2 V_0 V_1 / d^2$, produces oscillations of amplitude ΔD, and a signal of amplitude

$$V_2 = V_0 \Delta D / d.$$

Signal reduced by factor $(1 + C_c/C)^{-1}$

Electron micrographs show that grid is quite regular $\longrightarrow$



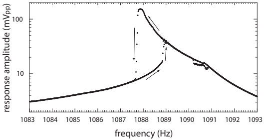


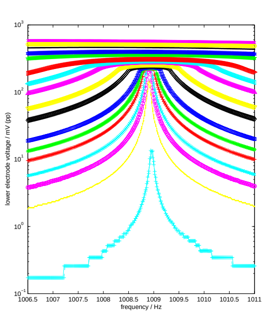
$\longleftarrow$ but that the surface is rather rough

Results from different grids

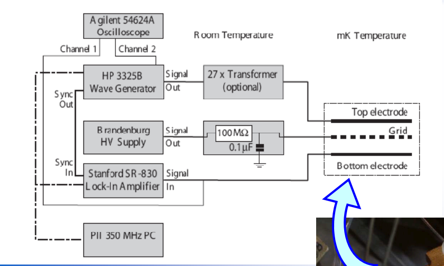
Three major series of experiments, using three different grids, all in isotopically pure ^{4}He at $\sim$20 mK –

1. First grid
   - Gold-plated nickel grid
   - $\nu \sim 10^3$ Hz, $Q \sim 5000$
   - Highly nonlinear, very hysteretic
2. Second grid
   - Different gold-plated nickel grid
   - $\nu \sim 10^3$ Hz, $Q \sim 5000$
   - After “cleaning”, minimal nonlinearity
3. Present grid
   - Gold-plated copper grid
   - $\nu \sim 10^3$ Hz, $Q \sim 10^5$
   - Slight hysteresis, and jumps

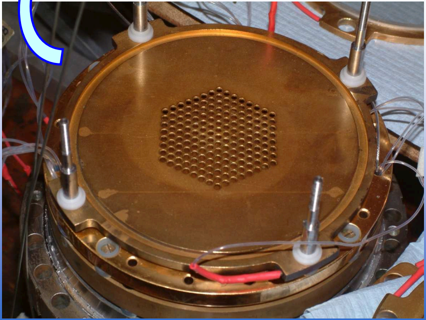




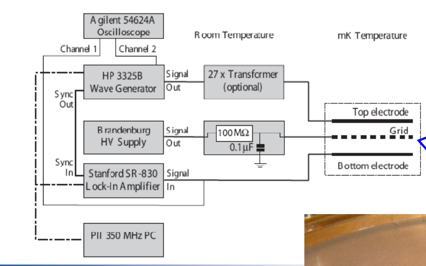
Scheme of experiments



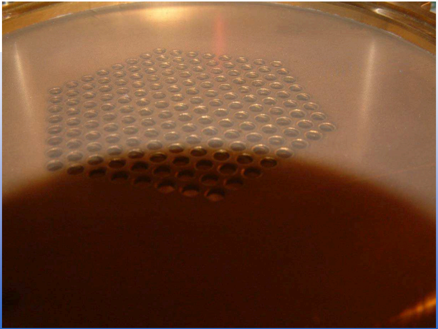
Bottom electrode



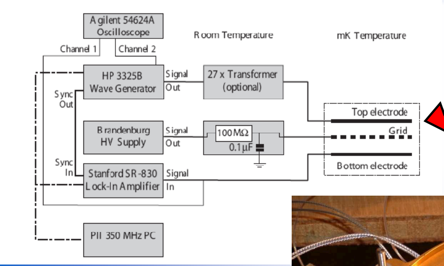
Scheme of experiments



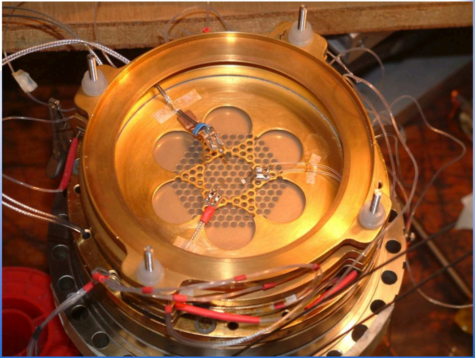
Vibrating grid



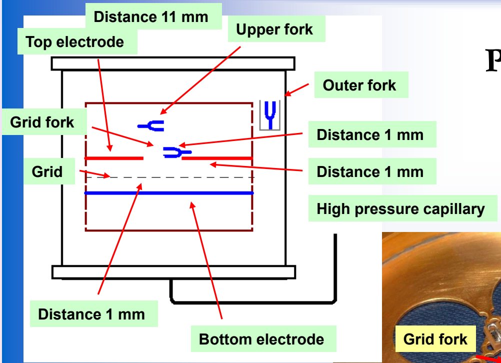
Scheme of experiments

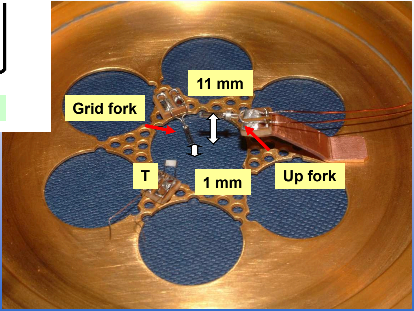


Top electrode

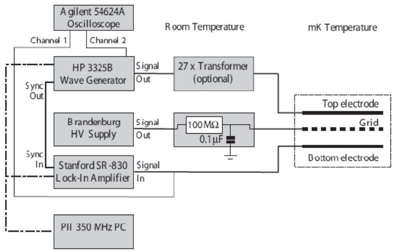


Positions of forks in the cell

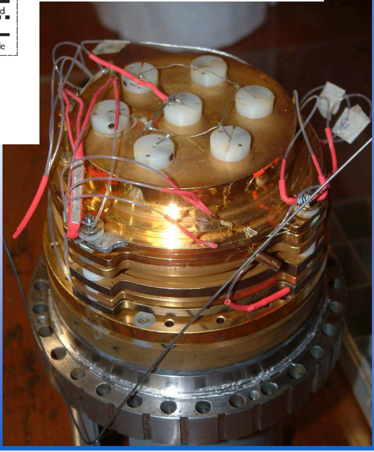




Scheme of experiments



Assembled electrodes



To be borne in mind...

- Relatively large dimensions – 13 cm. diameter grid in 1.5 ℓ of liquid.
- Isotopically pure ^{4}He.
- Gold-plated copper grid (cf. nickel in earlier work).
- History dependences, long timescales –

  "Virgin" $\Rightarrow$ cooled from He I
- All new data, not yet properly digested or understood – but immediately interesting and general picture is becoming clear.

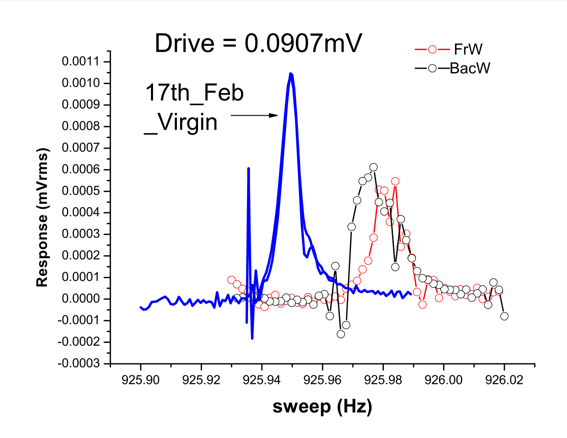
Resonances at lowest drive

Virgin response (blue) is –

- Reproducible
- Roughly Lorentzian.
- $Q \sim 250,000$.

After excitation to 63 mV (points) get –

- Hysteresis
- Jumps
- Irreproducibility



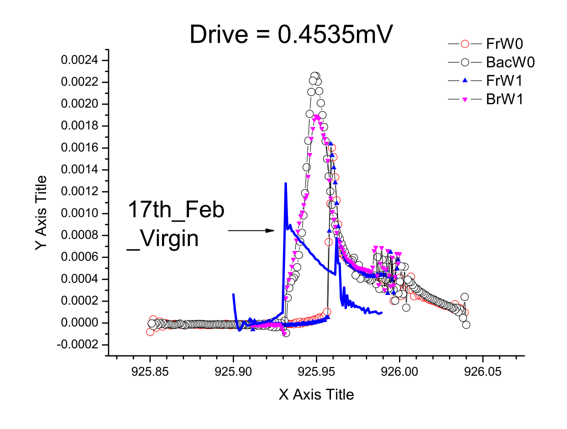
Resonances at very low drive

Virgin response (blue) –

- Exhibits jumps
- Not Lorentzian
- Q is still huge

After excitation to 63 mV (points), get –

- Hysteresis
- Jumps
- But good reproducibility
- And larger Q



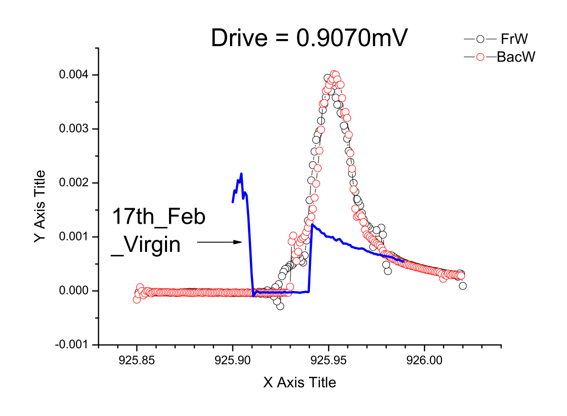
Resonances at low drive

Virgin response (blue) –

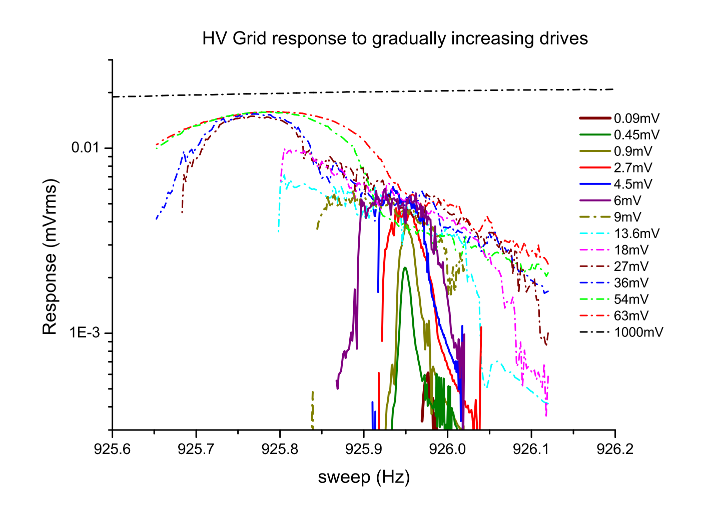
- Is not really resonant
- Displays huge jumps

After excitation to 63 mV (points) response –

- Is "well-behaved", reproducible, with no hysteresis
- Has $Q \sim 50,000$



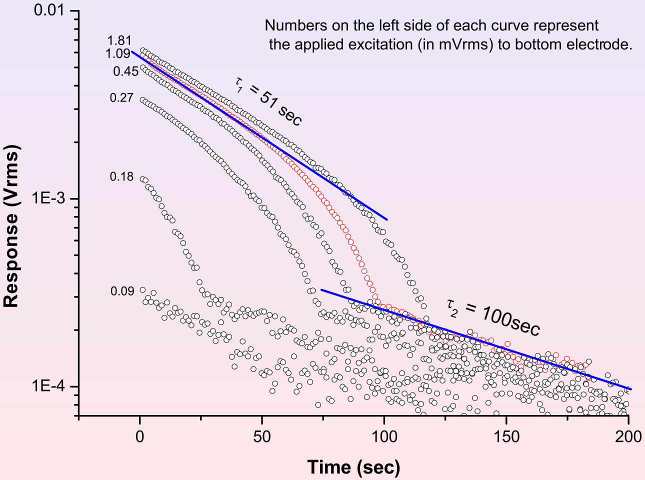
Summary of resonance data



Free decay measurements

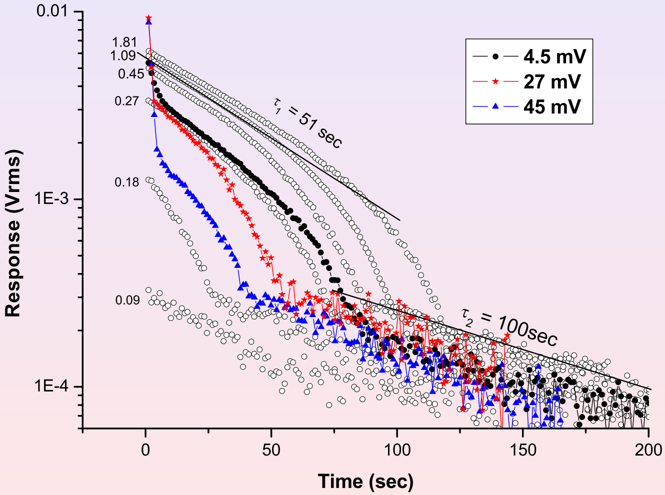
- Procedure –
  - Drive grid on (or very close to) resonance.
  - Switch off drive.
  - Monitor the decay of the oscillations.
- Advantages –
  - Unaffected by instability of the resonant frequency.
  - Hence separates changes in damping from changes in frequency.

Free decay after low-drive excitation



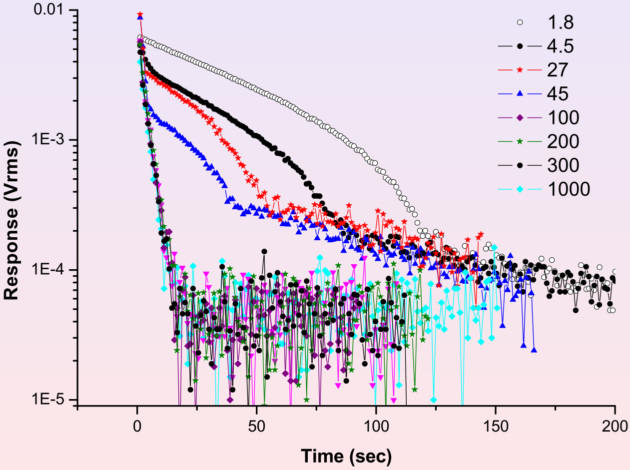
- For very lowest drive: a single, exponential, decay process with $\tau \sim 100\,\mathrm{s}$.
- For slightly larger drives: an initial, faster, non-exponential, decay.

Free decay after medium-drive excitation



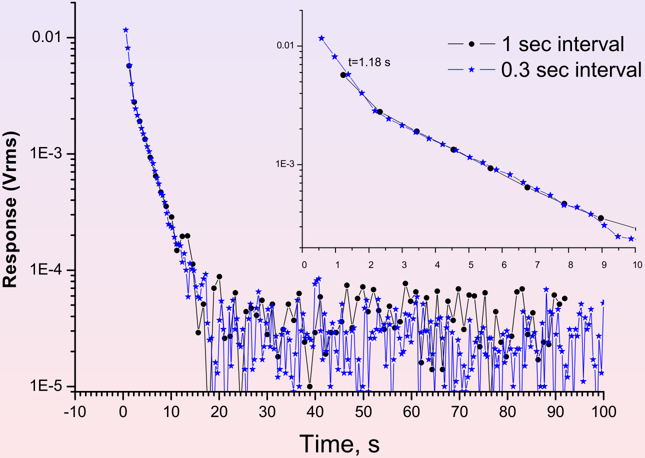
- After medium drives: an initial, fast, decay process appears.
- Then the same two processes as after low drives.

Free decay after high-drive excitation



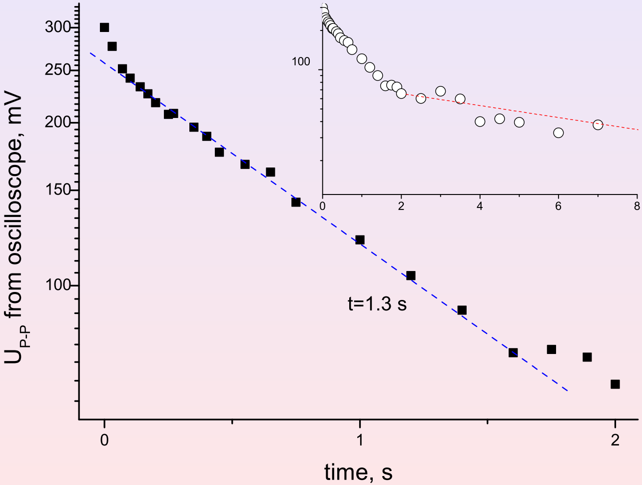
- After high drives: the fast process dominates and the two slower processes vanish.
- So examine initial decay more closely...

Initial free decay after high-drive excitation



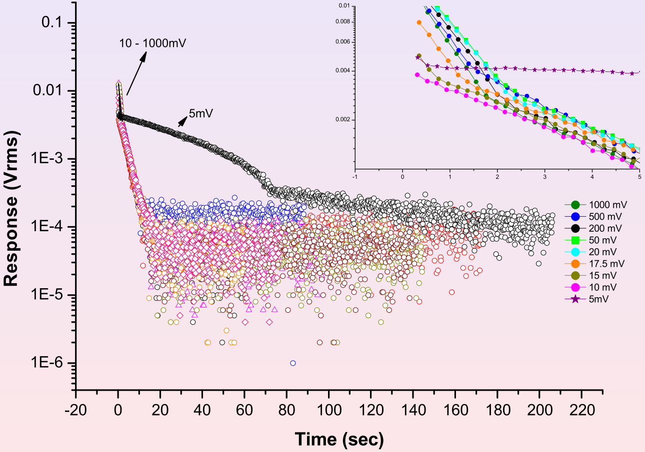
- The initial decay consists of two processes – very fast, then fast.
- Looks like straight lines of different slope...

Initial free decay after high-drive excitation II



- Expansion of first 2 s, inset to 8 s.
- Points to two separate processes.
- Change-over at $\sim$2 s.

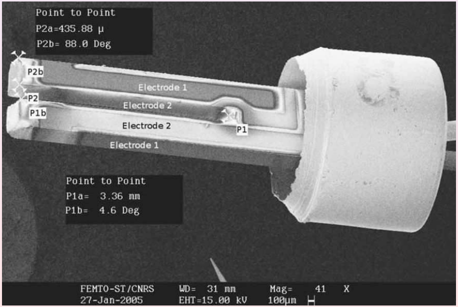
Behaviour after very high-drive excitation



- Decays from lower drives *after* very high drive.
- Earlier medium drive decays vanished.
- The 5 mV curve restored after ∼2 hours.

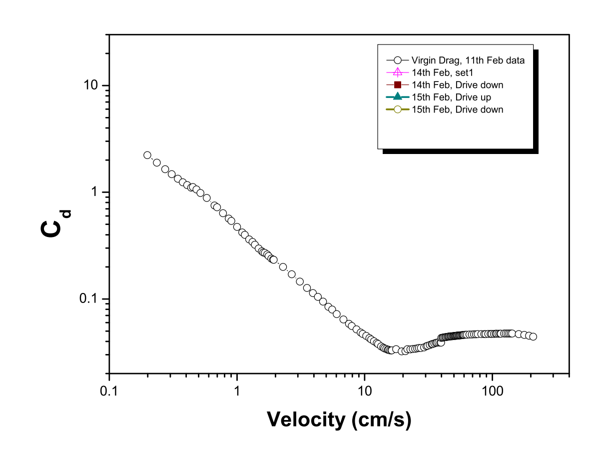
Quartz forks

- Huge range of sizes, frequencies.
- Very high Q s.
- Can use for the creation of QT.
- Maybe also for the detection of QT?

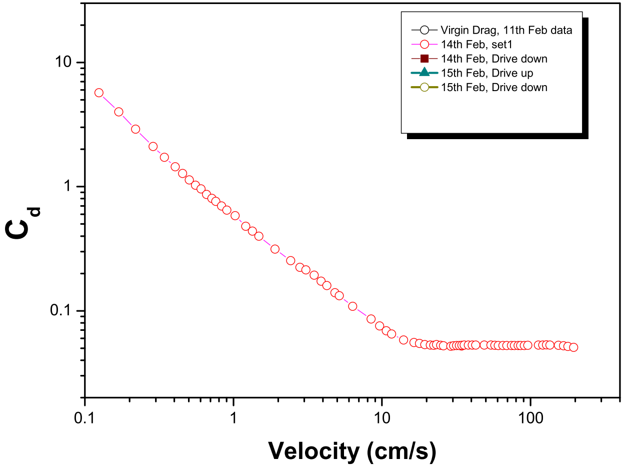


Drag coefficient at 20 mK – virgin response

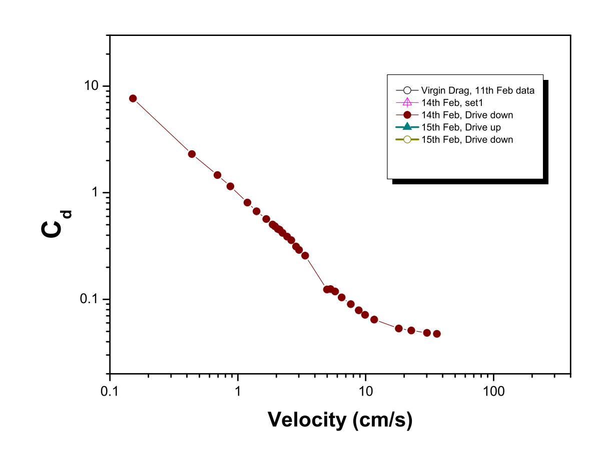
- The virgin response exhibits a minimum in $C_d(v)$.
- Discontinuity near $v = 40$ cm/s is an artifact.
- But when measurements were repeated...



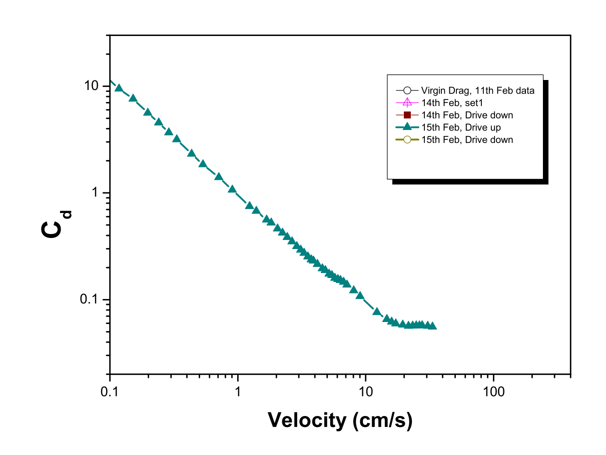
Drag coefficient – repeat, increasing, 14/02/2009



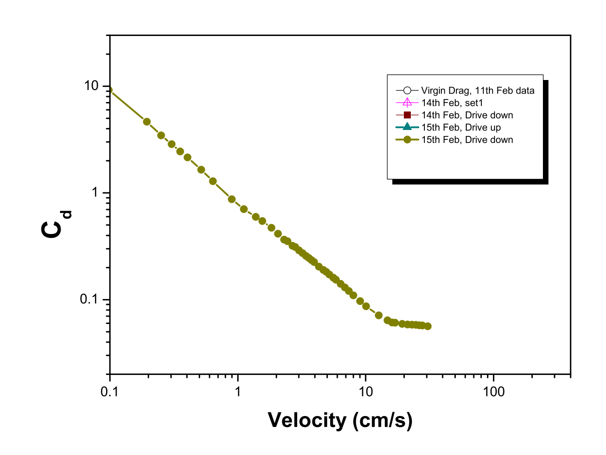
Drag coefficient – repeat, decreasing, 14/02/2009



Drag coefficient – repeat, increasing, 15/02/2009

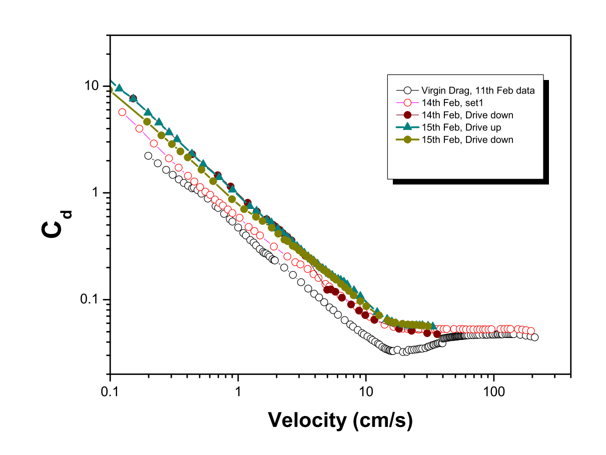


Drag coefficient – repeat, decreasing, 15/02/2009



Comparison of different results

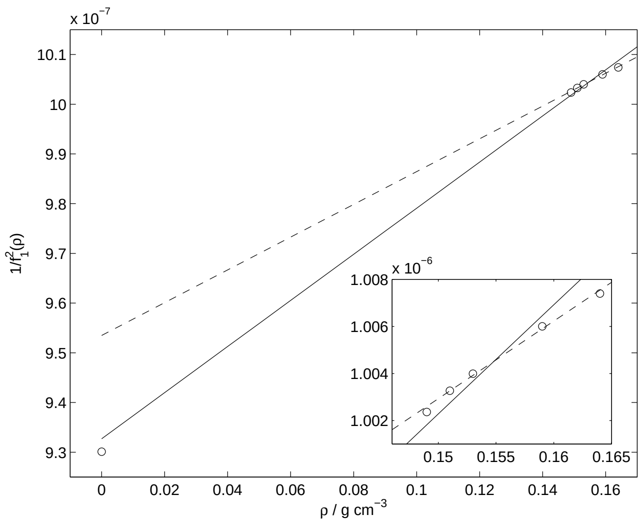
- A minimum is only seen for the virgin response.
- Subsequently, the minimum is absent, even if one waits for a day.
- Warming above 1 K restores the virgin behaviour



Time-dependences, instabilities

- Both for grid and forks, history-dependences, and very long relaxation times –
  - Small frequency shifts, often without change of width for small drives.
  - As with Grid No. 2, sometimes achieved well-behaved low-drive response after “cleaning” at higher drives.
  - Waiting a week does not restore “virgin” responses.
- Free decay data indicate at least two critical velocities.
- Frequency shifts imply changes in effective mass –
  - Probably not caused by “dirt”!
  - Pressure-dependence of Grid No. 2 resonant frequency suggested a permanently enhanced mass in He II...

"Anomalous" hydrodynamic effective mass? *PRE* **74** 036307 (2006).



- Plot of $\left(\frac{1}{f}\right)^2$ against density ρ.
- Very-low amplitude.
- Line misses vacuum resonance.
- Remanent vorticity: a "fur" of small loops?
- Vibrating wire, *cf.* Yano.

Tentative conclusions

1. For both grids and forks, measurements in He II near 20 mK exhibit –
   - History-dependence
   - Very slow relaxation
   - Jumps (grid only)
2. There are at least three distinct dissipation regimes for a free decay of the grid vibrations.
3. Hypothesis: shifts in resonant frequencies may be due to changes in effective mass associated with pinned vortices.

Acknowledgements & selected references

We are grateful to EPSRC/NSF WMN for financial support.

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3. H A Nichol, L Skrbek, P C Hendry and P V E McClintock, “Flow of He II due to an oscillating grid in the low temperature limit”, *Phys. Rev. Lett.* **92**, 244501 (2004).
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