Single Vortex Experiments in Superfluid Helium

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Superfluid Helium

Near T = 0 (transition at 2.17 Kelvin)

Quantum fluid, described by *single-particle* wave function

Zero viscosity

$$\psi(\vec{r}) = A(\vec{r})\, e^{i\phi(\vec{r})}$$

$A(\vec{r})$: varies slowly, related to superfluid fraction

$\phi(\vec{r})$: related to velocity

Film flow

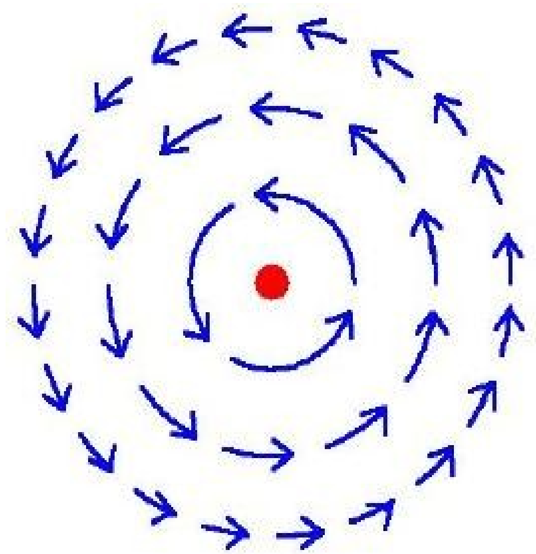
Quantized circulation

$$\kappa = \oint \vec{v} \cdot d\vec{\ell} = \oint \frac{\hbar}{m} \vec{\nabla}\phi \cdot d\vec{\ell}$$

$$= \frac{\hbar}{m}\Delta\phi = \frac{h}{m} n$$

a single-valued wave function always yields some quantized quantity – in this case it's circulation

Superfluid Vortices



Quantization means vortices well-defined

1/r velocity field around infinite straight core (more generally, can calculate velocity from Biot-Savart law)

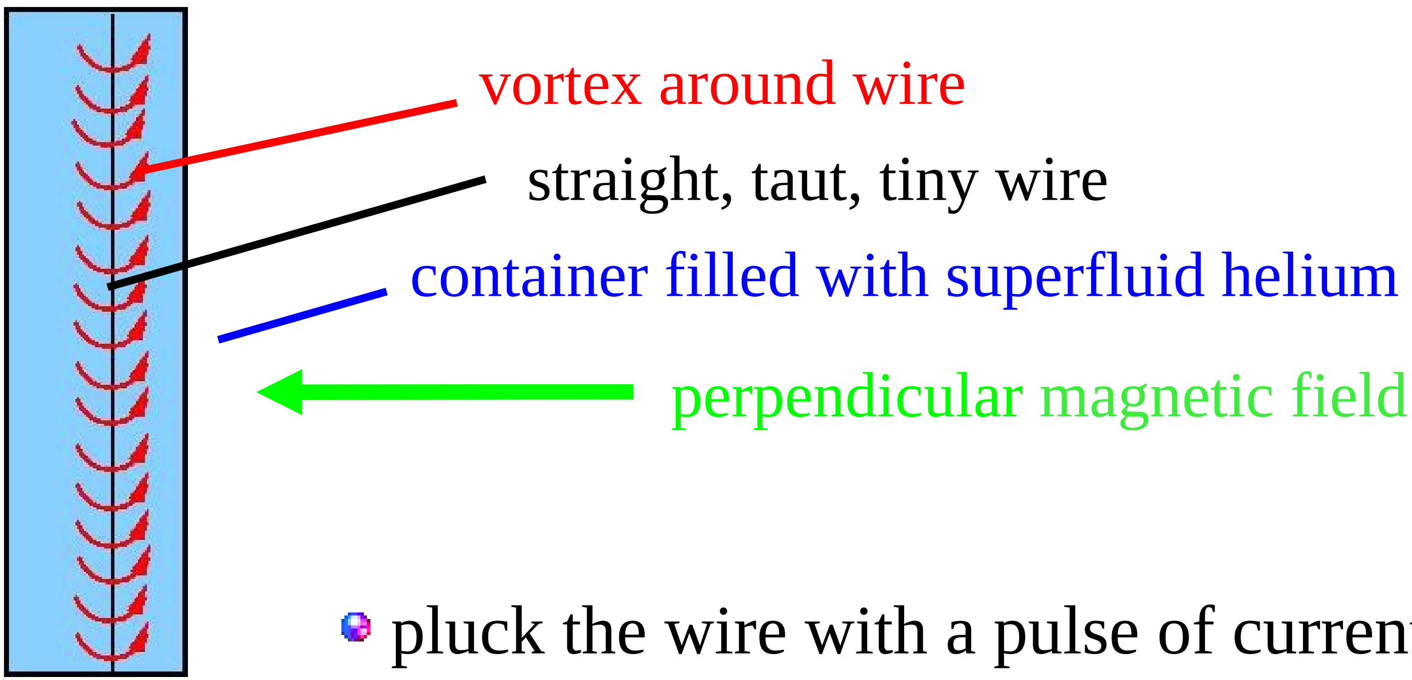
Near-ideal vortices: core diameter for free vortex is less than 3 angstroms!

Circulation is constant with time

Vortices have an energy per length: hence there is a line tension, and large cores are favored

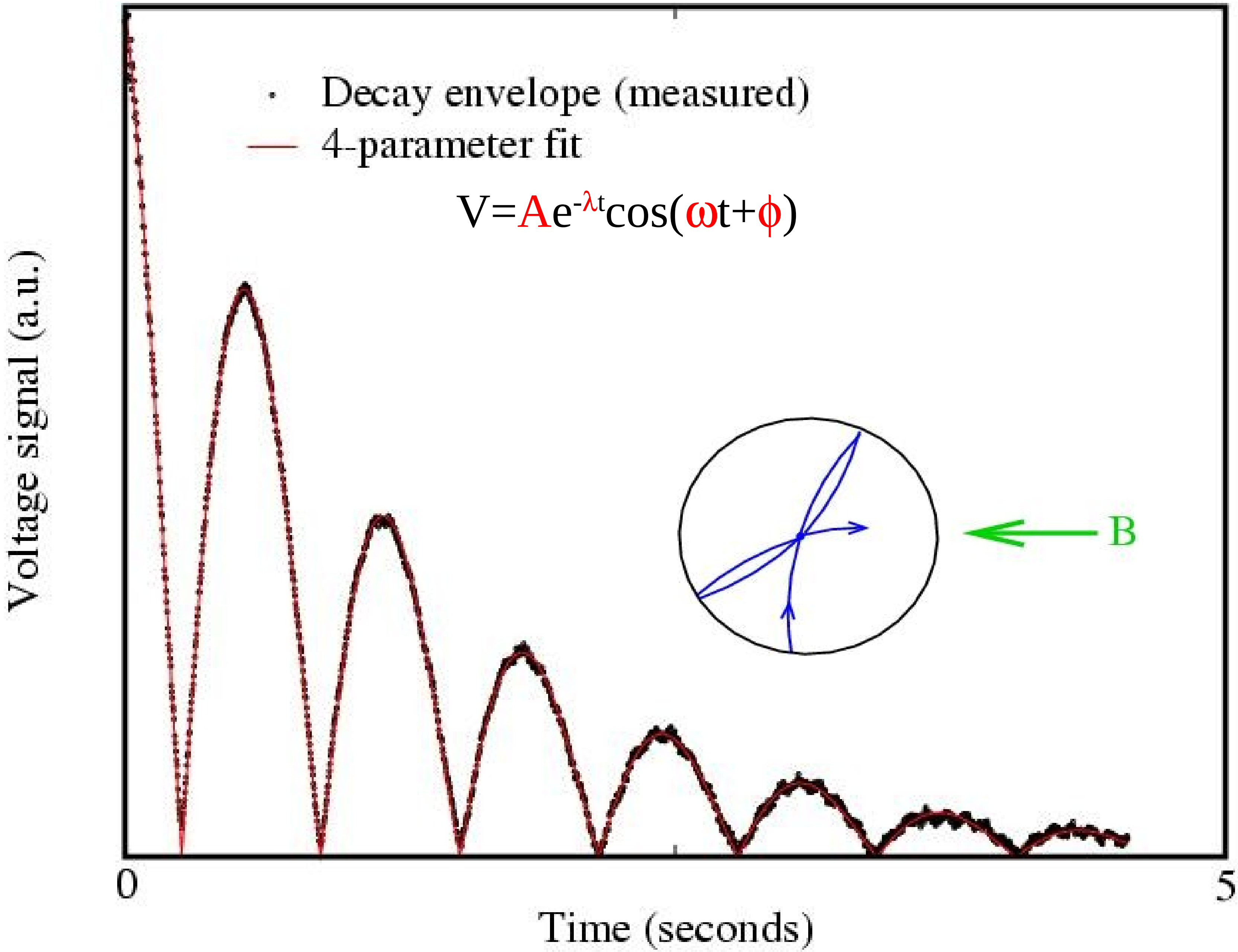
Vortex cores move at local superfluid velocity

Watching One Vortex

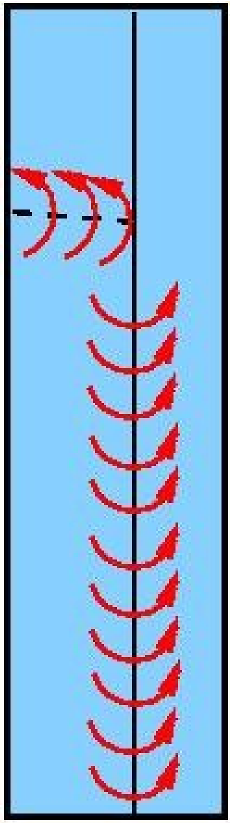


- pluck the wire with a pulse of current
- monitor voltage as it moves in magnetic field
- circulation changes the vibrational modes
- splitting of modes causes beats in signal

Typical Signal



Partially Attached Vortex



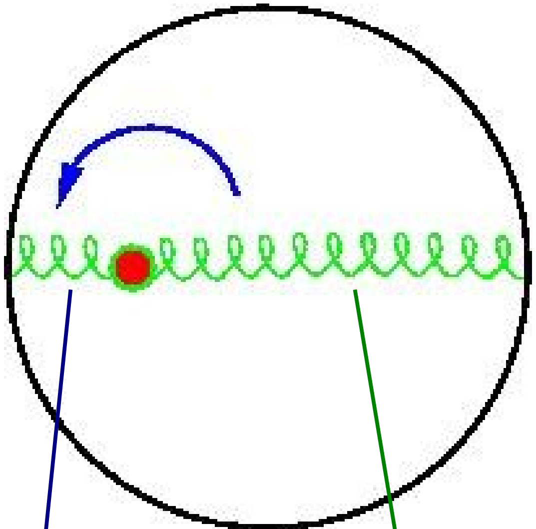
A classical analog

Partial vortex has intermediate effect on normal modes of wire

Can use wire beat frequency to measure attachment point of vortex

Most sensitive near middle of wire (vertically), where wire's velocity is fastest

Vortex Precession

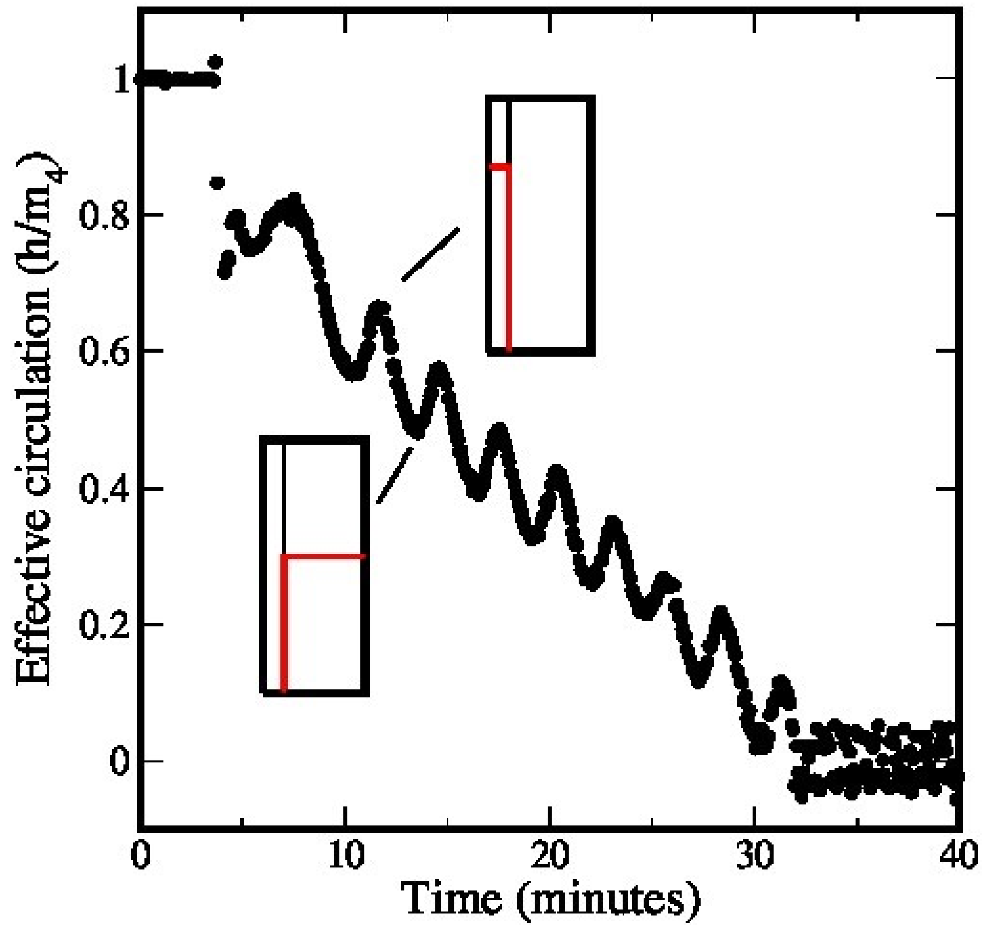


Vortex core moves with the fluid.

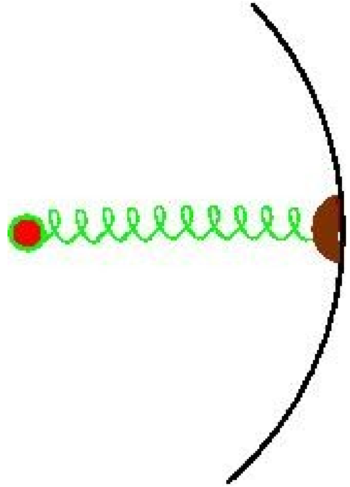
portion on wire shorter (minima)

portion on wire longer (maxima)

<u>energy conservation!</u>

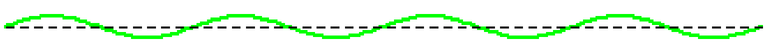


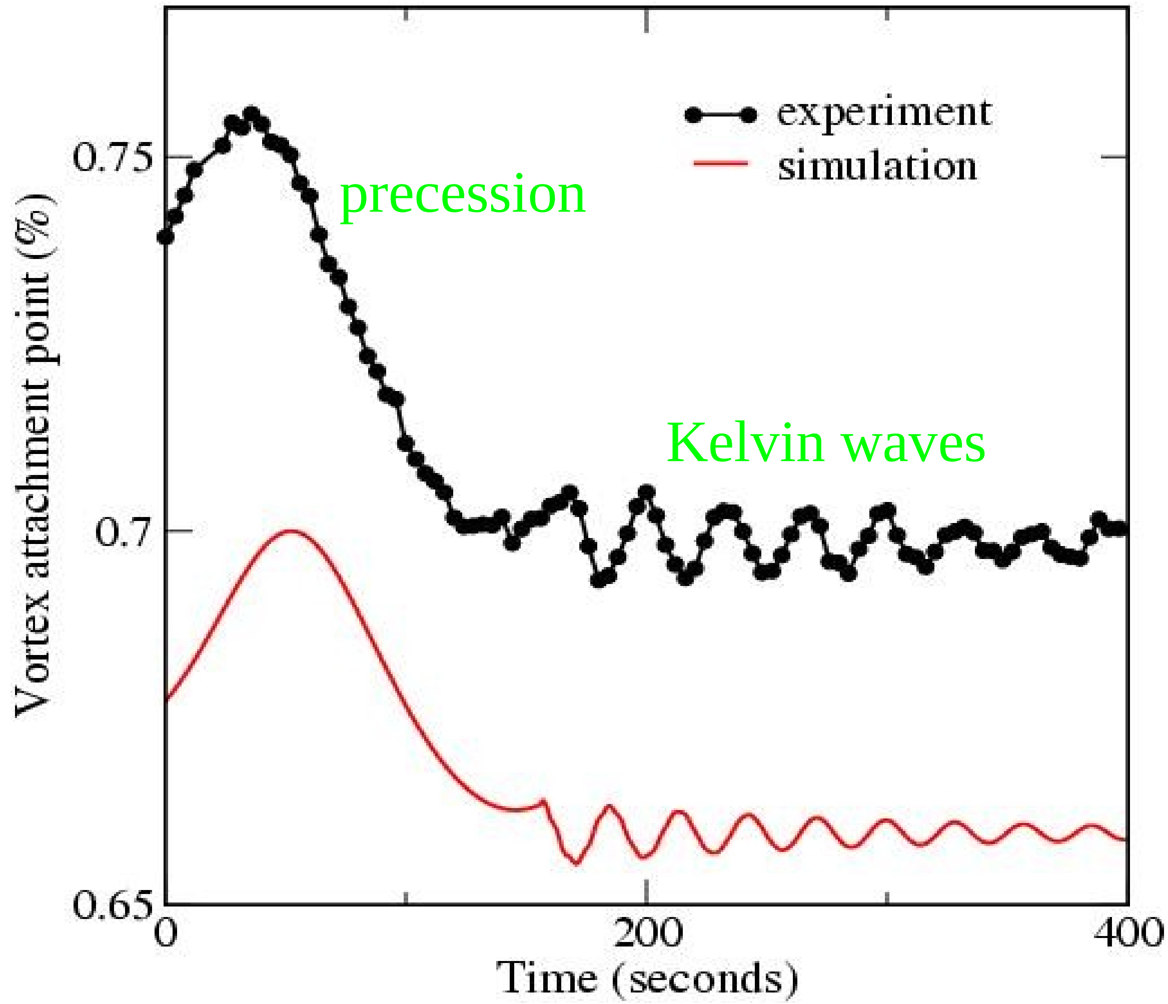
Pinning



Roughness (a “bump”) on wall “pins” vortex in place.

Vortex oscillates as
it settles into position.





Kelvin waves:

$$\omega = -\frac{\kappa k^2}{4\pi} \ln(ka)$$

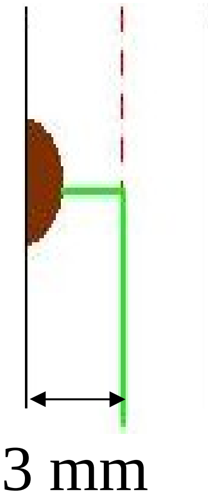
$$k = \frac{\pi n}{2d}$$

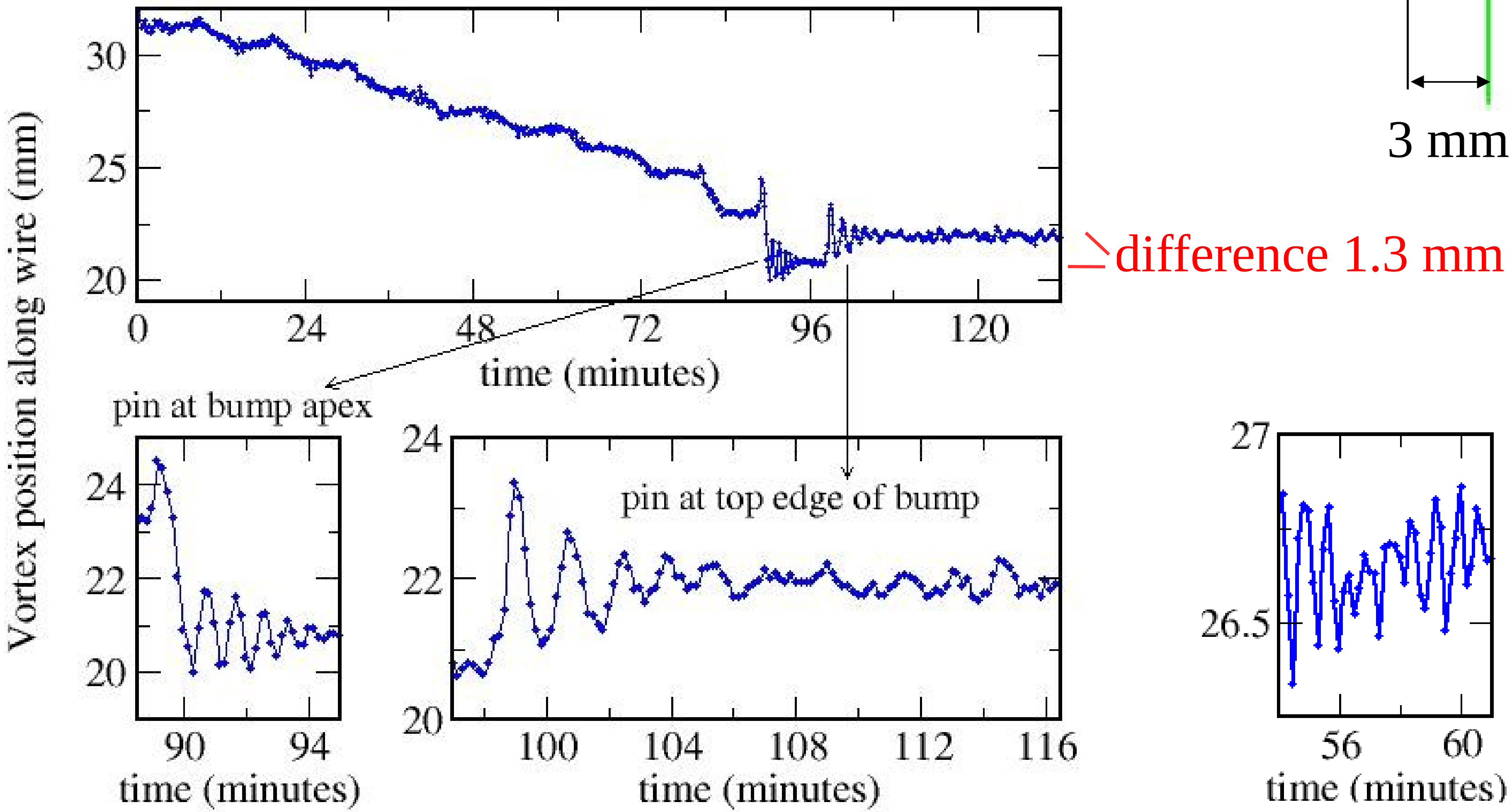
wire-bump distance

Deliberate Pinning: Macroscopic Bump

h = 1.3 mm

d = 3.0 mm



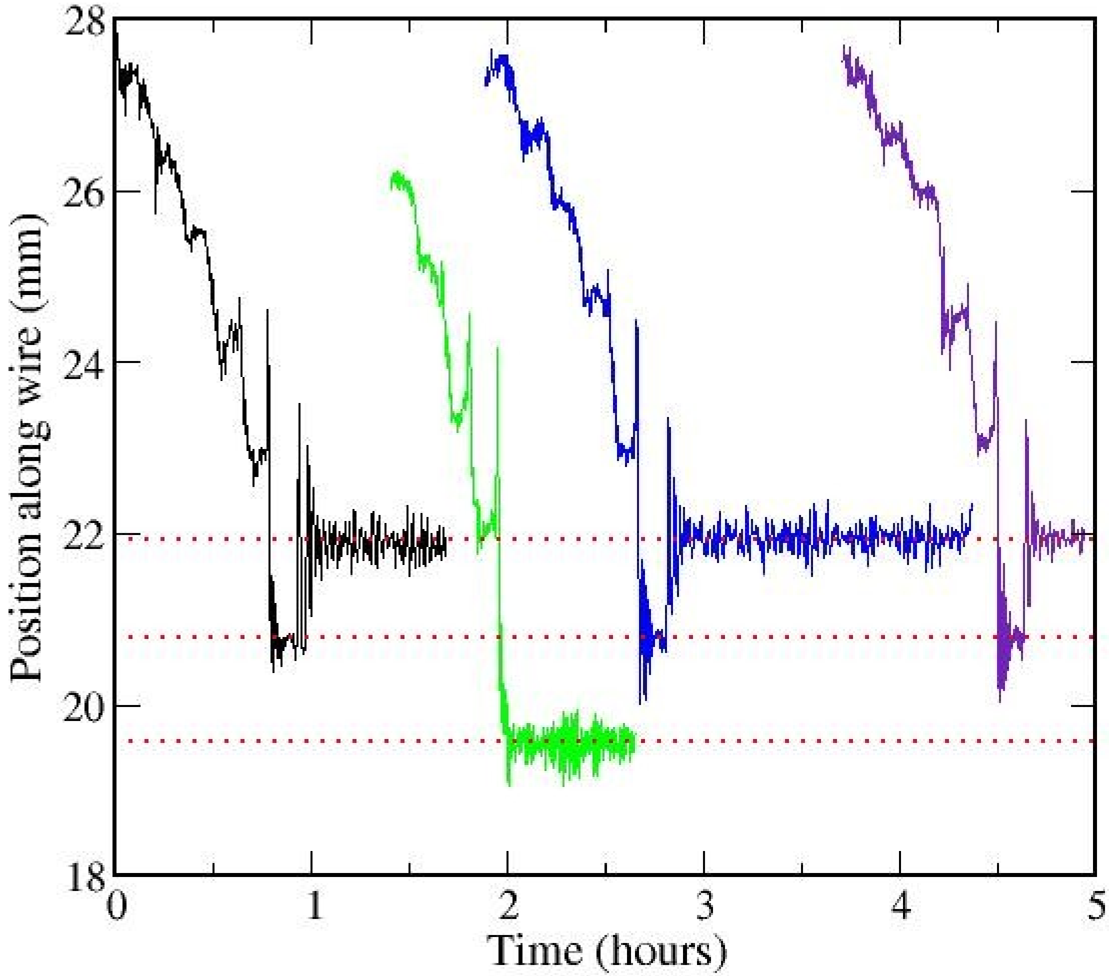


48 s, or 1.5 mm

98 s, or 2.2 mm

42 s; about 3 mm
(longer but moving)

Repeatability of pins



Oscillation period

Vertical position

Free vortex length

21.7 mm (98 s/ 2.2 mm)

20.4 mm (48 s/ 1.5 mm)

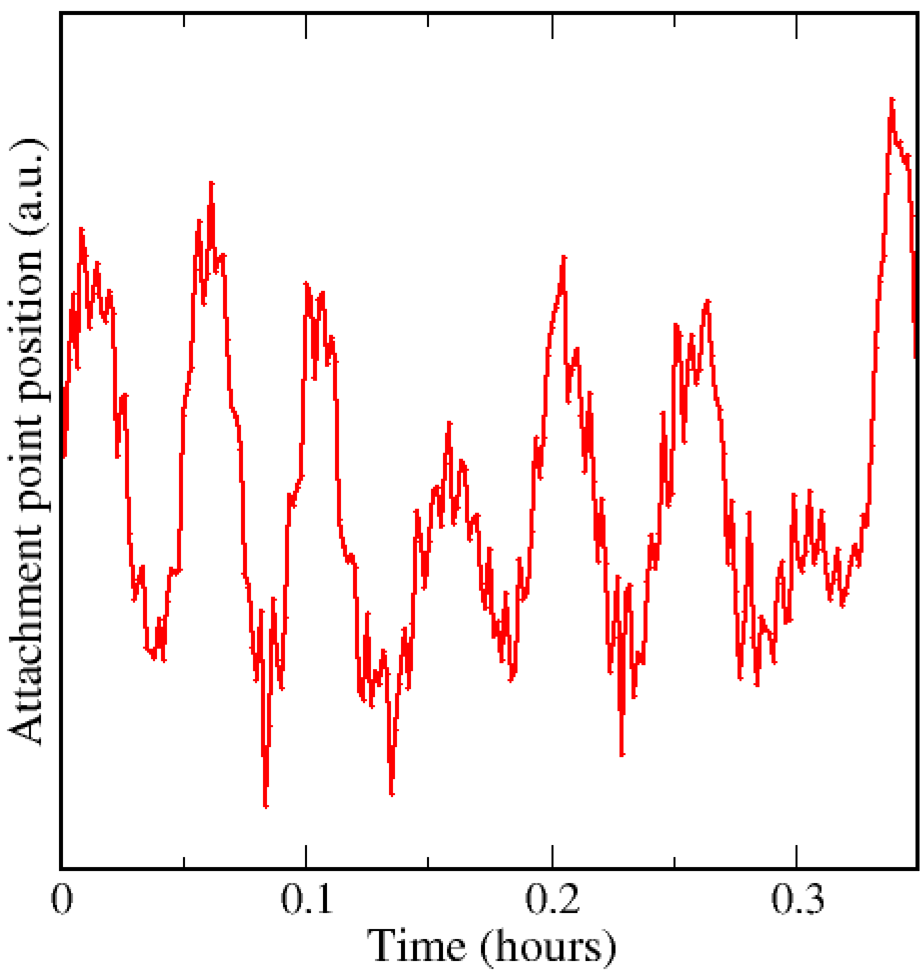
19.9 mm (64 s/ 1.8 mm)

Consistent with highly repeatable vortex pinning at three distinct locations.

Spikes: from vortex traversing bump

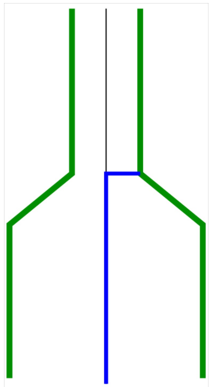
Higher Harmonics

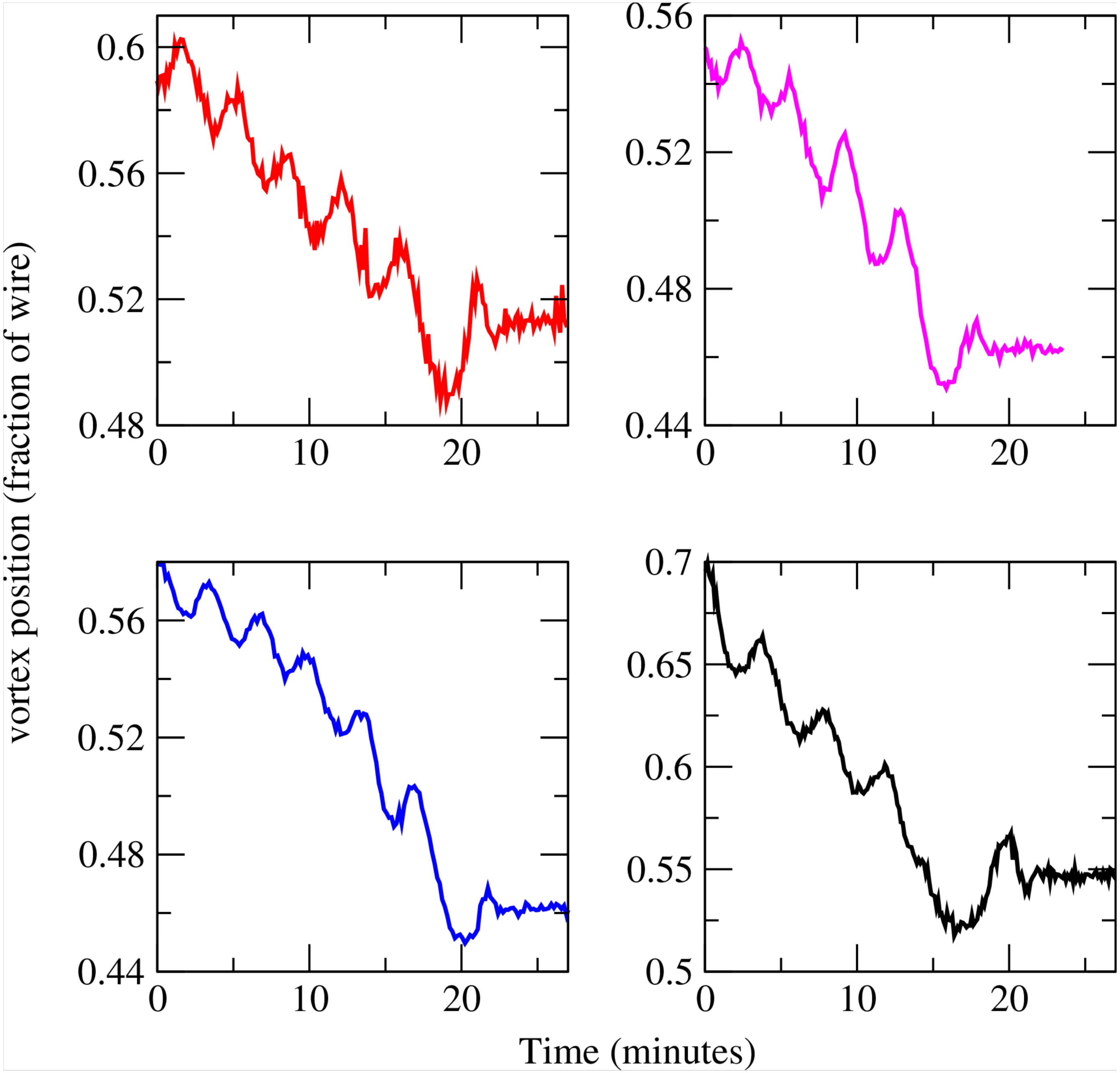
Using larger diameter cell, smaller bump, and displacing wire away from the bump – so longer free vortex!



- Vortex pinned near cell midpoint
- Lowest Kelvin mode period about 3 minutes (amplitude ~ 1 mm)
- Additional oscillation, 8-9 times faster, looks like third harmonic
- Hope to see onset of non-linear behavior and test dispersion relation
- Also working on other measurement techniques to reach higher frequencies

Pinning at a Diameter Change

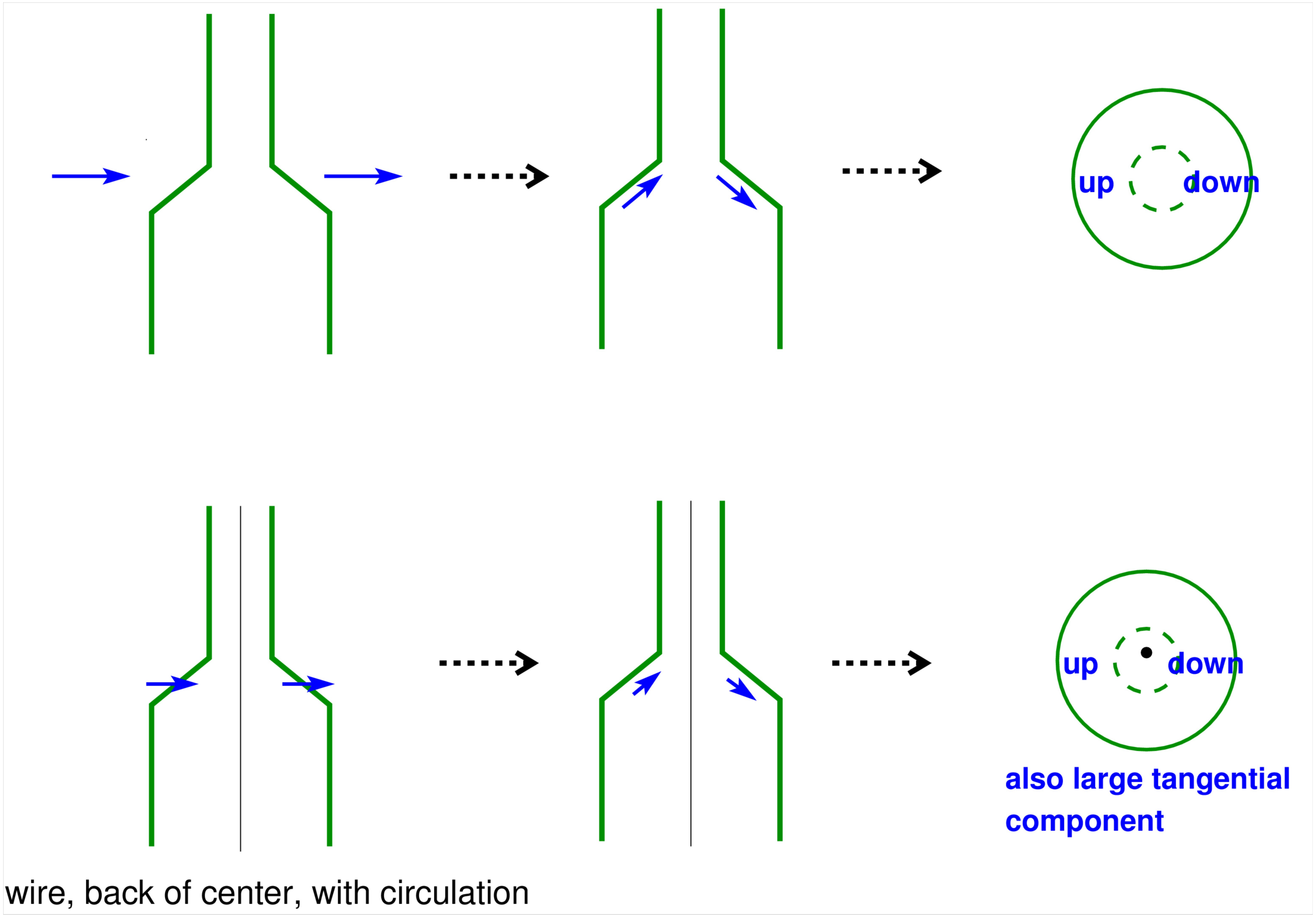




- Precession approach, on thin side of cell
- Vortex pins near edge of slope
- Often see large dip immediately before pin (3 cells shown)

Velocity Field Near Slope

Any horizontal deviation from circular symmetry generates a vertical velocity component.

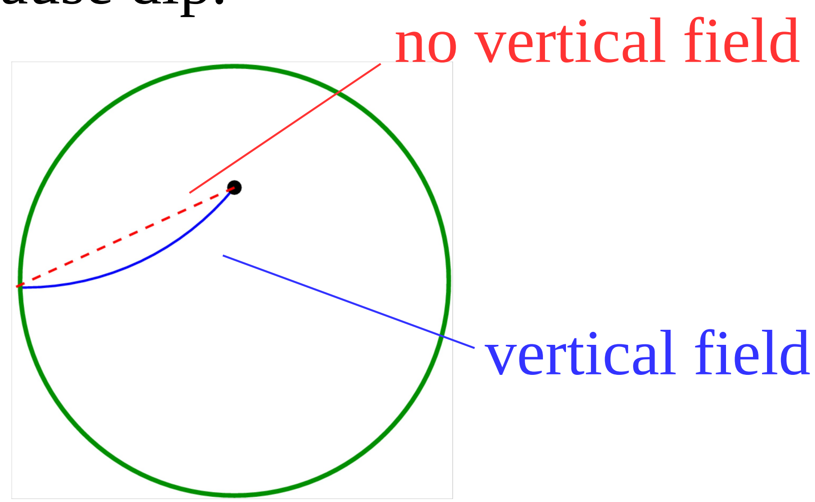


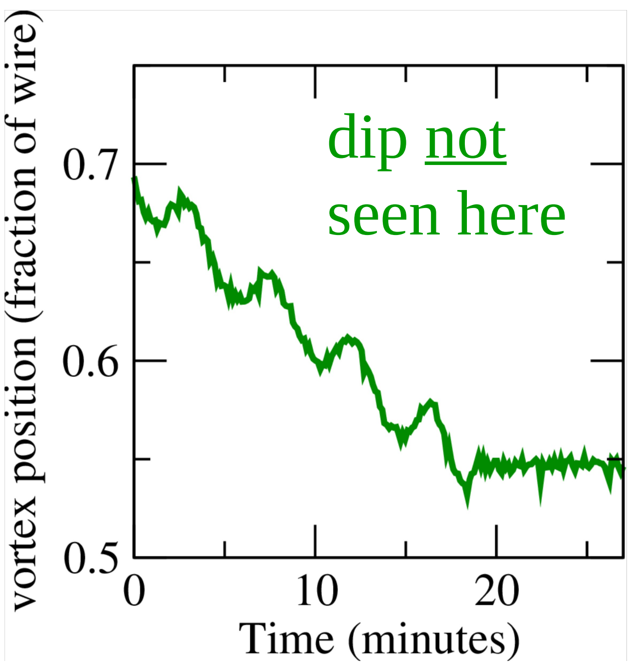
Vortex Distortion from Vertical Velocity?

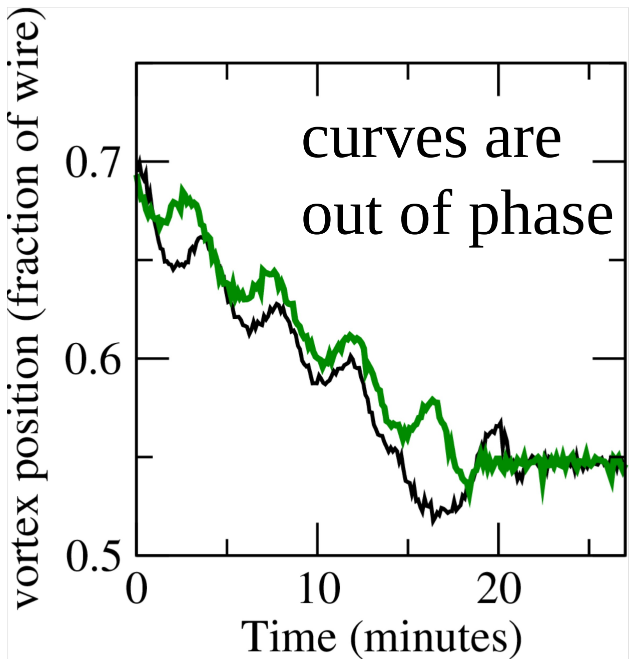
Free vortex distorts (therefore lengthens) to cancel vertical field component, so portion on wire shrinks to cause dip.

May also help stabilize the pinning by angle of approach to wall.

Different signatures stem from vortex phase on approaching the slope.







Conclusions

- We can track single vortex lines in a superfluid.
- Vortices really do move at the local superfluid velocity!
- We can excite and observe Kelvin waves with our vibrating wire – next up, non-linearities.
- The vortex pins reliably at macroscopic features on the cell wall; we can also measure how the vortex and wall structures interact.