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Andrei Golov

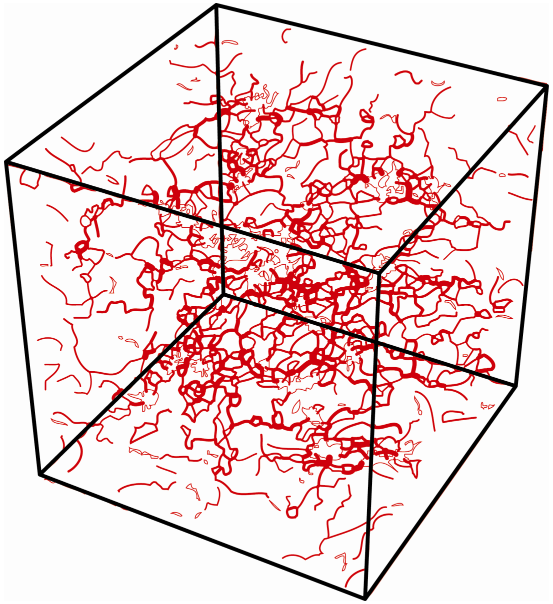
Saclay, September 2015

(1) Injected ions in superfluid helium as detectors of quantized vortices

(2) New measurements of the rate of dissipation of QT in the *T*=0 limit

Quantum Turbulence (QT) in the *T*=0 limit

($T < 0.5$K for ^{4}He, $T < 0.1$-0.3mK for ^{3}He-B)

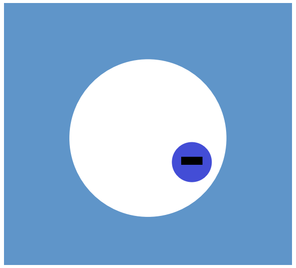


No normal component
Fractal vortex lines
Broad range of length scales involved
Free-slip BC?

-Methods of forcing?

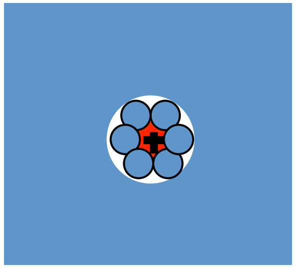
- Probes/tags?

Injected ions and molecules: structure



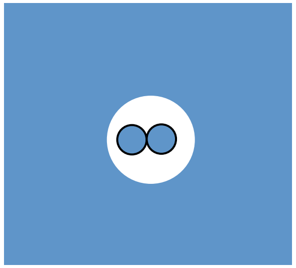
Negative ion: bare electron in a bubble (Atkins 1959) :

p	0 bar	25 bar	
R_-	17 Å	12 Å	
m_-	243 m_{He}	87 m_{He}	(Ellis, McClintock 1982)



Positive ion: cluster ion (“snowball”) (Ferrell 1957) :

p	0 bar	25 bar
R_+	7 Å	9 Å
m_+	~30 m_{He}	~50 m_{He}



Excimer molecule He_2^* in a bubble, lifetime ~13s:

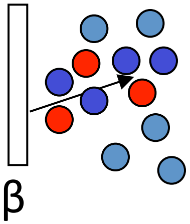
p	0 bar
R_*	~ 7 Å
m_*	~20 m_{He}

Ions - can be pulled by external force and easily detected

Molecules are neutral, fluorescent

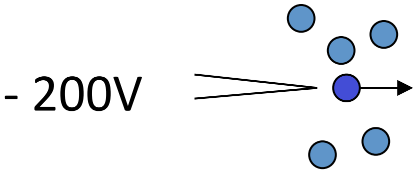
By changing pressure and species, one can cover R = 7–17 Å, m/m_{He}= 30-240.

How to inject ions and molecules?

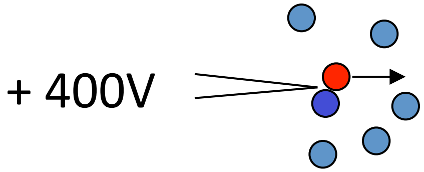


- radioactive ionization (α or β) sources
(easy to use but can't be switched off: excess heating)
Example: ^{3}H emits β-particles of average energy 5 KeV

- sharp metal tips (radius of curvature ~ 100-1000 Å):

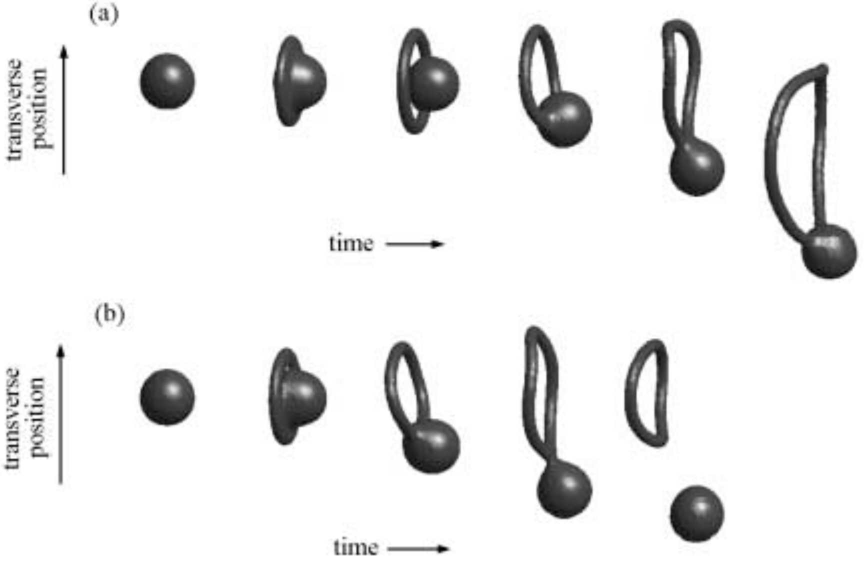


field emission: negative ions



field ionization: positive ions

Vortex nucleation by a moving ion at $v_c \sim R^{-1}$



Depending on the pull, the ion will then either stay with the ring or leave:

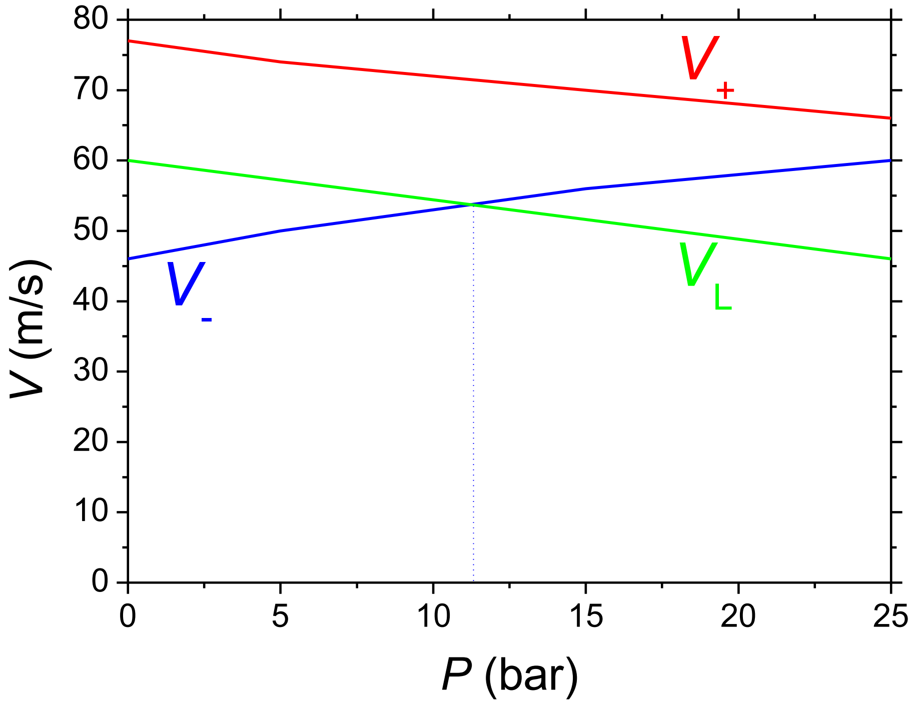
Experiment: Rayfield and Reif (1964)
McClintock, Bowley, Nancolas, Stamp, Moss (1980, 1982, 1985)

Theory for V_c: C.M.Muirhead, W.F.Vinen, R.J.Donnelly, Phil. Trans. R. Soc. A**311**, 433 (1984)

Simulations:

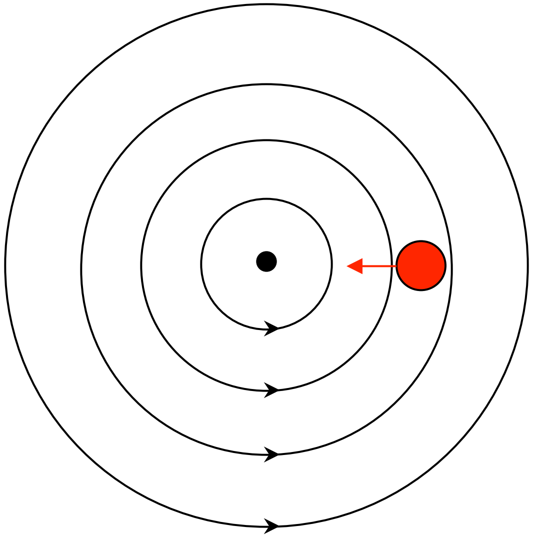
T.Winiecki and C.S.Adams, Europhys. Lett. **52**, 257 (2000)

Berloff abd Roberts (2000)



Charged vortex rings (CVRs) automatically nucleate only for negative ions at $p < 13$ bar

Ion–vortex interaction (rigid vortex)

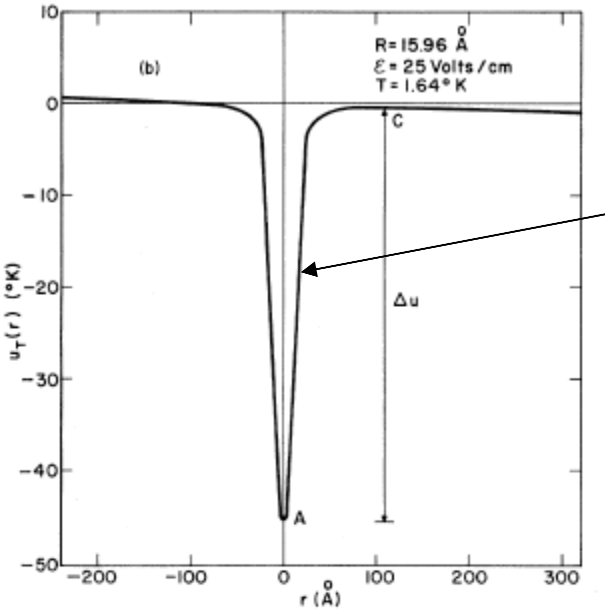


Energy of interaction = missing kinetic energy of superflow (roughly proportional to ion's volume)

Calculated binding energy ΔV (p=0):

Positive ions: ΔV = 16 - 46 K

Negative ions: ΔV = 55 - 66 K



slope ~ 10 K / 10 Å = 1 K/Å

e.g. eE = 1 K/Å at E = 10 KV/cm

Theory:

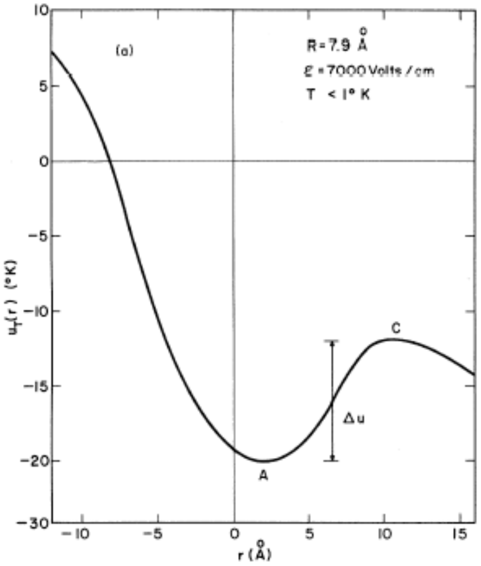
Parks and Donnelly (1966):

Donnelly & Roberts (1969):

Berloff, Roberts (2000)

Chances of escape (Brownian particle in a well)

High field $E > 10^4$ V/cm
might help liberate the ion:

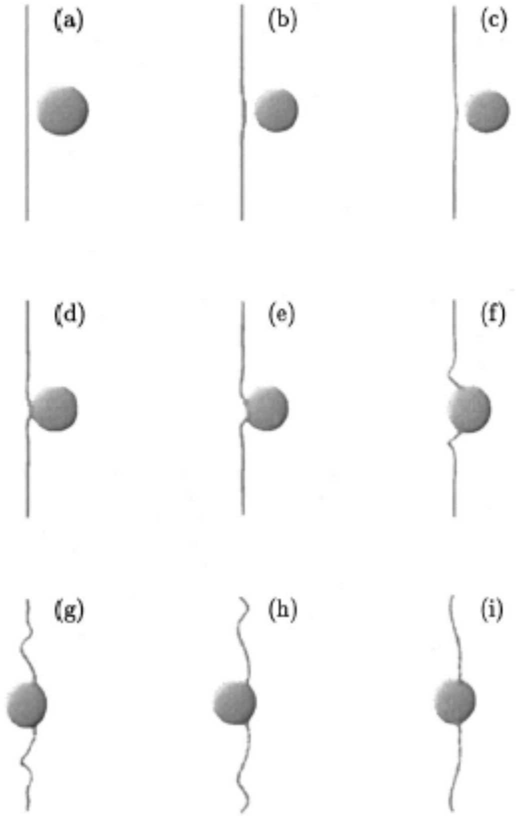


In low fields, $E \ll 10^4$ V/cm, no escape at low T :
- for negatives, at $T < 1.7$ K,
- for positives, at $T < 0.8$ K,
- for excimers, apparently, at $T < 0.2$ K.

While trapped, ions can slide along the vortex line, but the mobility is reduced – this can be used to probe Kelvin waves , etc.

Donnelly, Glaberson, Parks (1967), Ostermeier and Glaberson (1976), Walmsley *et al*. (ongoing)

Capture by vortex line at T=0



Capture of a stationary ion from distance ~ R:
Kelvin waves help remove excess energy
N.G.Berloff and P.H.Roberts, Phys. Rev. B 63, 024510 (2000).

As stretching a vortex line by just 10 Å increases its energy by some 30 K, this is effective.

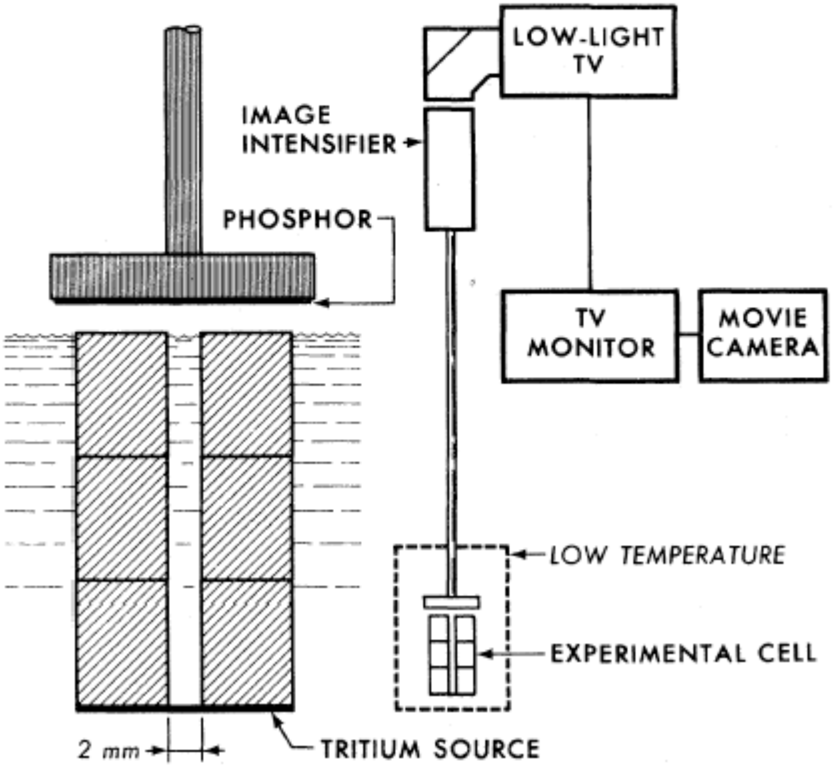
More calculations are needed to figure out how a **moving** ion will interact with the vortex.

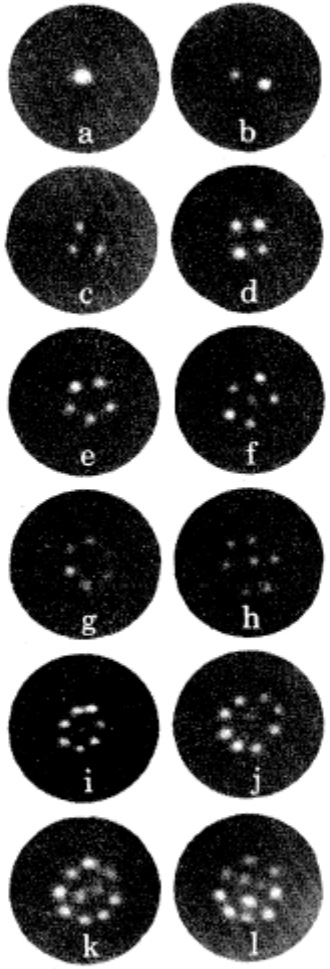
VOLUME 43, NUMBER 3 PHYSICAL REVIEW LETTERS 16 JULY 1979

Observation of Stationary Vortex Arrays in Rotating Superfluid Helium

E. J. Yarmchuk and M. J. V. Gordon[a]
Physics Department, University of California, Berkeley, California 94720
and
R. E. Packard[b]
Physics Department, University of Sussex, Brighton, England

(Received 29 May 1979)





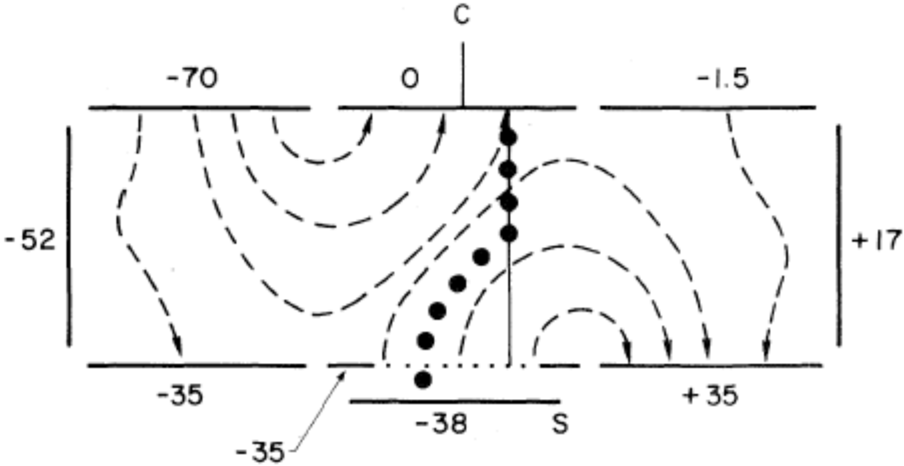
$\Omega = 0.30 - 0.86\ s^{-1}$

Observation of a Remanent Vortex-Line Density in Superf

D. D. Awschalom and K. W. Schwarz
IBM Thomas J. Watson Research Center, Yorktown Heights, New

(Received 23 September 1983)

Sensitive ion-trapping measurements show that superfluid ^{4}He at rest
stantial number of quantized vortex lines, metastably pinned between the
container. This remanent line density appears to be history independent
lished upon going through the lambda point.



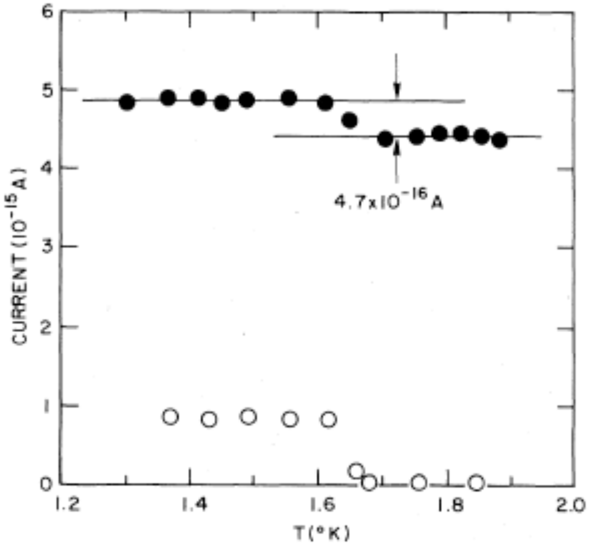


FIG. 2. Solid circles: current measured at C in undisturbed helium. Open circles: 1/100 of the current observed at C when the helium is turbulent, with $L = 9\times 10^3\ \mathrm{cm}^{-2}$.

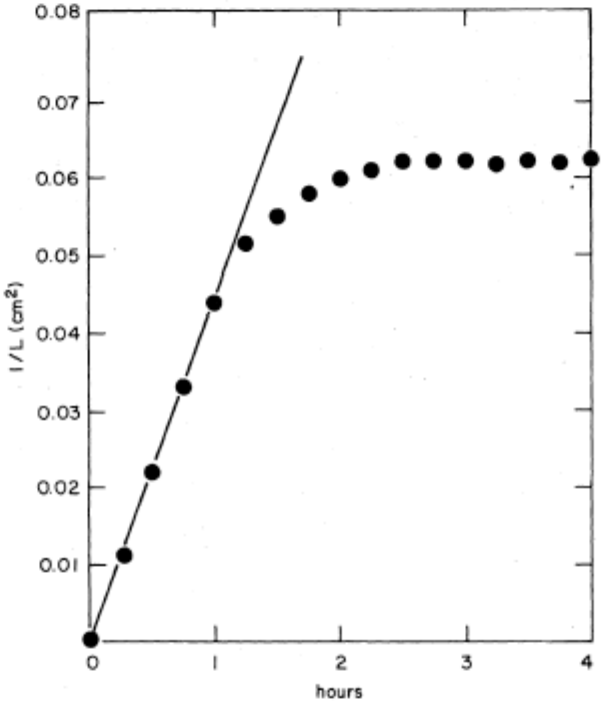


FIG. 3. Free decay from an initial line-length density $L = 9\times 10^3\ \mathrm{cm}^{-2}$ to the remanent density $L \simeq 15\ \mathrm{cm}^{-2}$ when the turbulence driver is turned off. The straight line corresponds to the behavior $\dot{L} = -\mathrm{const} \times L^2$, as observed in Ref. 12.

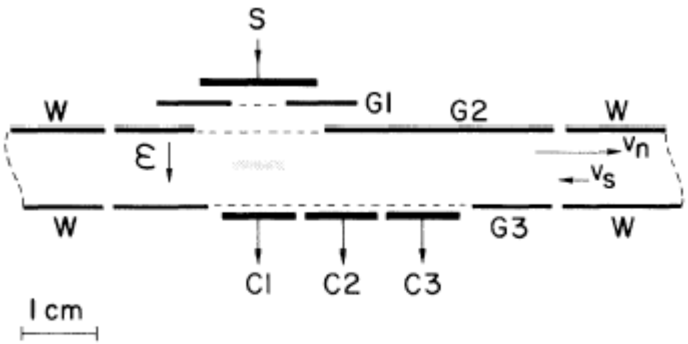
VOLUME 53, NUMBER 14 PHYSICAL REVIEW LETTERS 1 OCTOBER 1984

Properties of Superfluid Turbulence in a Large Channel

D. D. Awschalom, F. P. Milliken, and K. W. Schwarz
IBM T. J. Watson Research Center, Yorktown Heights, New York 10598

(Received 28 June 1984)

Pulsed-ion techniques are used in a 1-cm × 2.3-cm channel to obtain the first spatially resolved measurements of the vortex-line length-density distribution and the normal-fluid velocity field in turbulent counterflow. Also, an upper limit to the structural anisotropy of the vortex tangle is obtained which contradicts earlier claims.



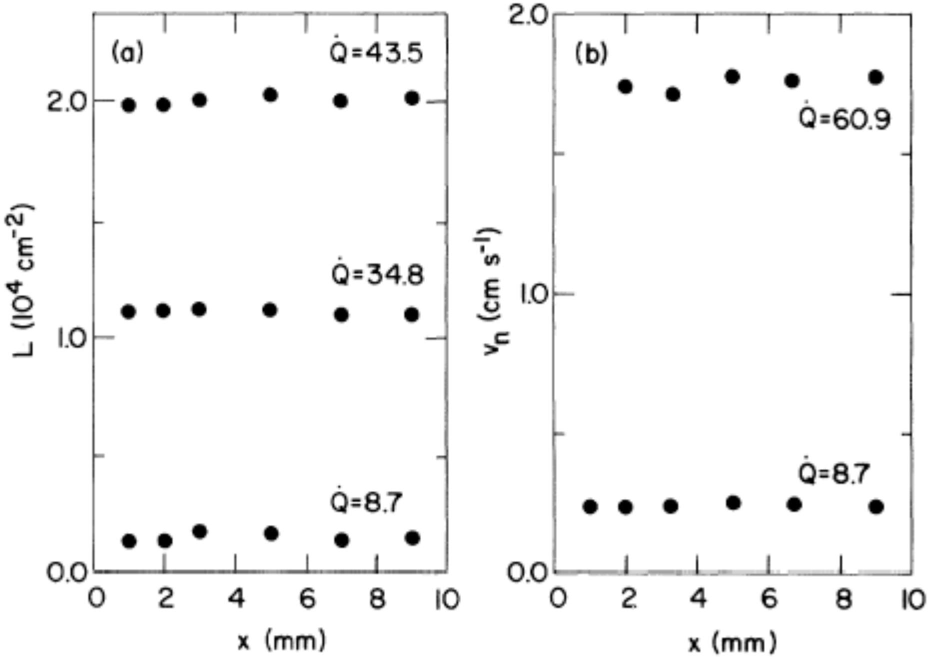


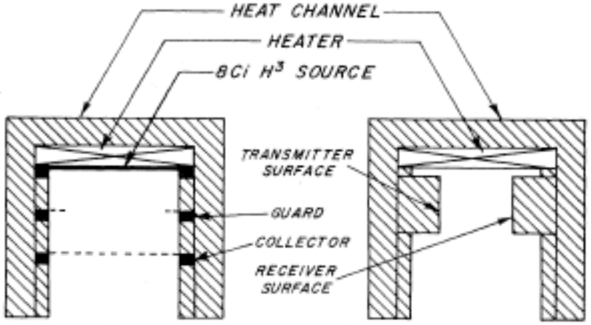
FIG. 3. (a) Line-length-density profiles and (b) normal-fluid velocity profiles as a function of distance across the channel. Heat flux levels are in milliwatts per square centimeter. At $T = 1.45$ K where these data were taken, $v_n = 28.6\dot{Q}$ and $v_{ns} = 31.6\dot{Q}$.

Noise from Vortex-Line Turbulence in He II

Henry Hoch, Lynda Busse, and Frank Moss
Department of Physics, University of Missouri at St. Louis, St. Louis, Missouri 63121

(Received 18 November 1974)

The first measurements of fluctuations observed with both negative-ion and second-sound probes in turbulent He II are reported. Data on the distributions are well matched by Gaussian functions. An ω^- component, and well-defined relaxation times which depend on the heat flux, are found in the spectral intensity.



(a) (b)

FIG. 1. (a) The IP consisting of a diode mounted in a cylindrical Lucite heat channel with inside diameter 2.5 cm. The source potential was -20 V with respect to the collector. The source-collector distance was 1 cm. (b) The SP with cavity dimensions 1.5 cm between transmitter and receiver by 2.5 cm deep by 1.27 cm thick. The transmitter film was acquadag plus silver with $R = 80\ \Omega$, and the receiver was acquadag with $R = 180\ \text{k}\Omega$ and temperature coefficient $0.3\ \text{K}^{-1}$ at 1.25 K.

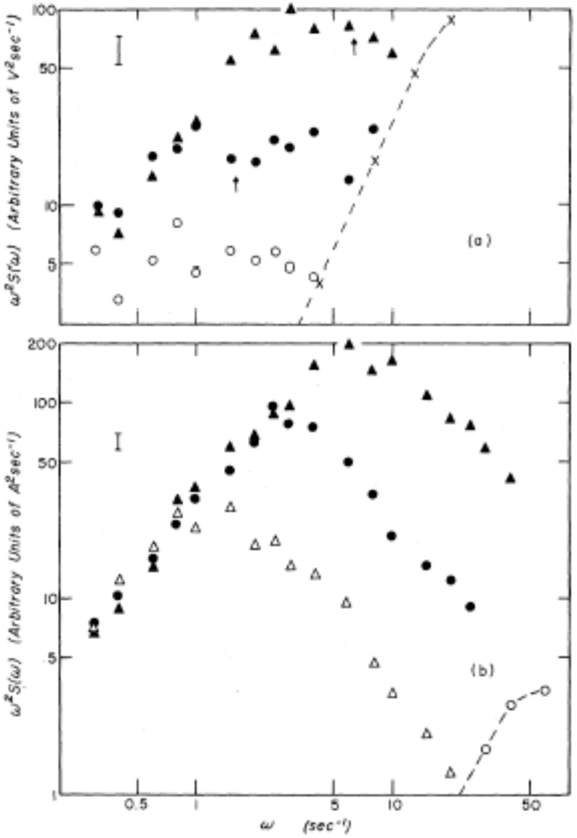


FIG. 4. Spectral intensity functions for $\dot{q} = 0$, open circles; $\dot{q} = 5\ \text{mW cm}^{-2}$, open triangles; $\dot{q} = 10\ \text{mW cm}^{-2}$; closed circles; and $\dot{q} = 20\ \text{mW cm}^{-2}$, closed triangles. (a) Measured with the SP. The crosses are the instrumental noise with the SP switched off. (b) Measured with the IP. The error bars and arrows are discussed in the text.

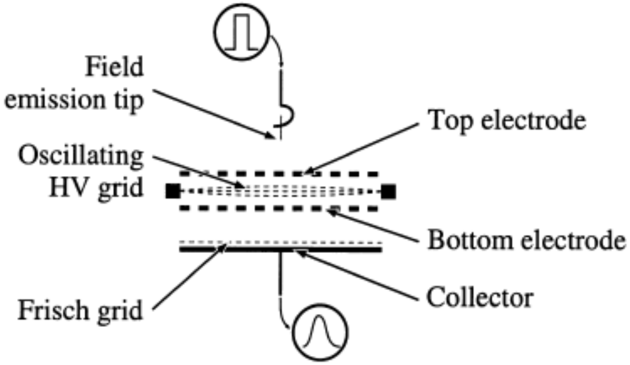
T=0 limit. Since 1970s, vibrating structures were used to force liquid helium, and charged vortex rings used to detect the produced vortices:

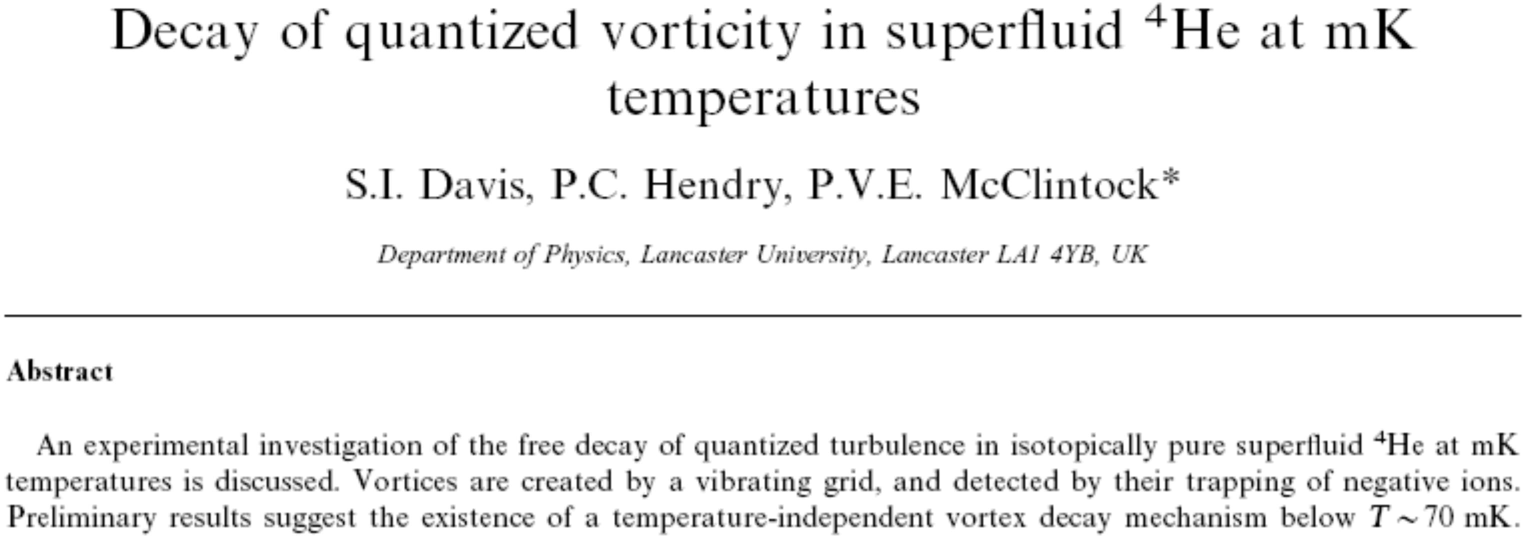
- Emission of individual rings is detected as well as of their tangles.
- Tangle's decay within several seconds observed.

G. Gamota, *Phys. Rev. Lett.* **31**, 517 (1973).
Experiment with an array of vibrating orifices (Nuclepore membrane, orifices diameters 5 um, resonance frequency 1.17 kHz) at 0.3 - 0.5 K to generate a beam of vortex rings of diameter 1.7 - 3.2 um (decreasing as the flow drive was increased) and detect them by a transverse beam of charged vortex rings

Observation of vortex tangles leaking from the ion emission region and decaying within a minute (McClintock et al. ~ 1974 - 1985)

Vibrating sphere was used by Schoepe *et al.* (90s),
and vibrating grid to generate and ions to detect QT were used (McClintock et al. 2000):





Decay of quantized vorticity in superfluid ^{4}He at mK temperatures

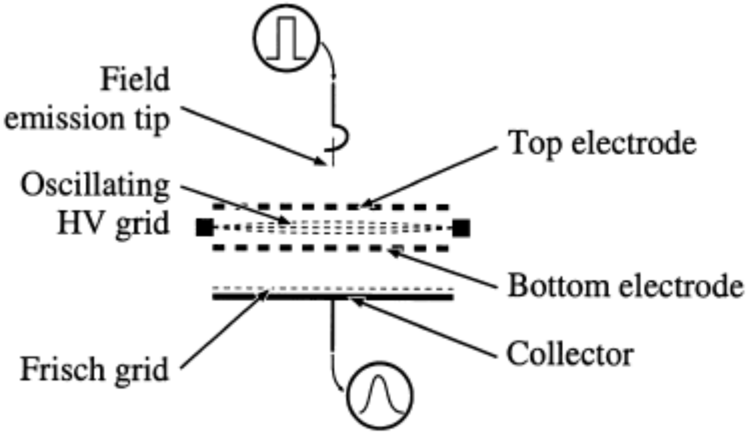
S.I. Davis, P.C. Hendry, P.V.E. McClintock*

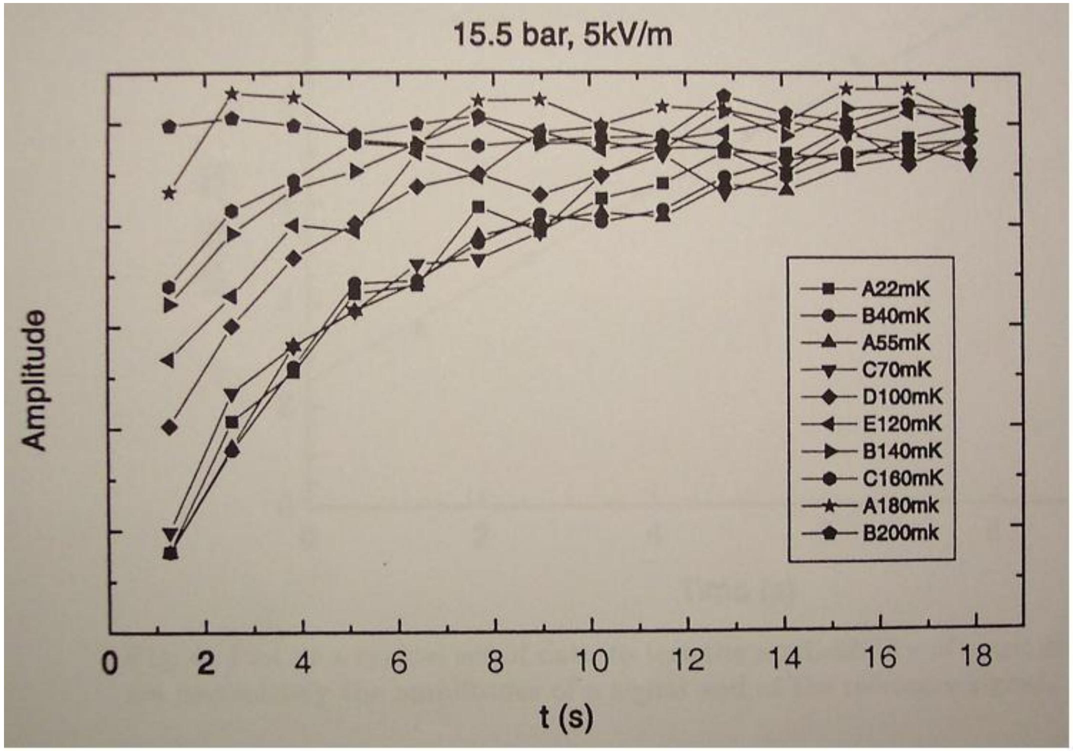
Department of Physics, Lancaster University, Lancaster LA1 4YB, UK

Abstract

An experimental investigation of the free decay of quantized turbulence in isotopically pure superfluid ^{4}He at mK temperatures is discussed. Vortices are created by a vibrating grid, and detected by their trapping of negative ions. Preliminary results suggest the existence of a temperature-independent vortex decay mechanism below $T \sim 70$ mK.

Physica B **280**, 43 (2000);

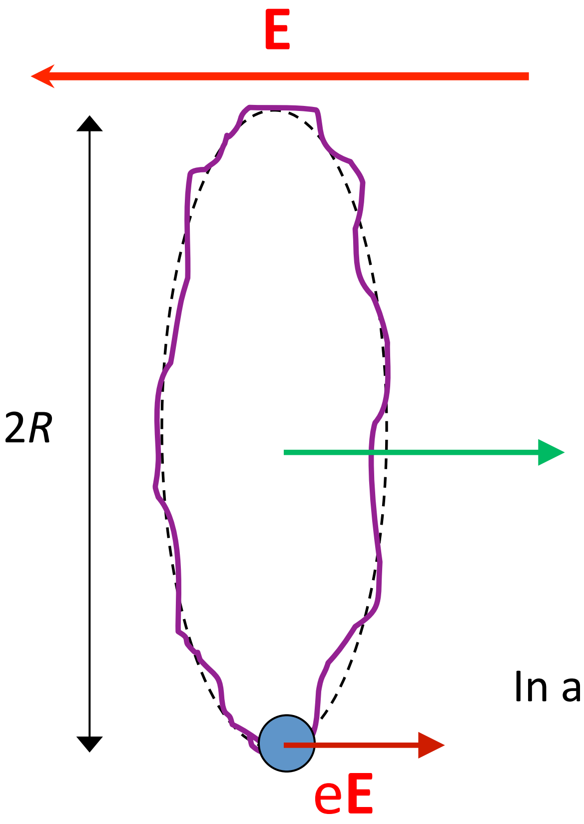




S.I.Davis, P.C.Hendry, P.V.E.McClintock, H.Nichol, in “Quantized Vortex Dynamics and Superfluid Turbulence”, ed. C.F.Barenghi, R.J.Donnelly and W.F.Vinen, Springer (2001).

Quantized Vortex Rings at T<0.5K

(first experiment: Rayfield and Reif 1964)



Velocity $\approx (\Lambda/4\pi)\kappa R^{-1}$

$\Lambda = \ln(8R/a_0) \approx 12$

Impulse $= \pi\rho\kappa R^2$

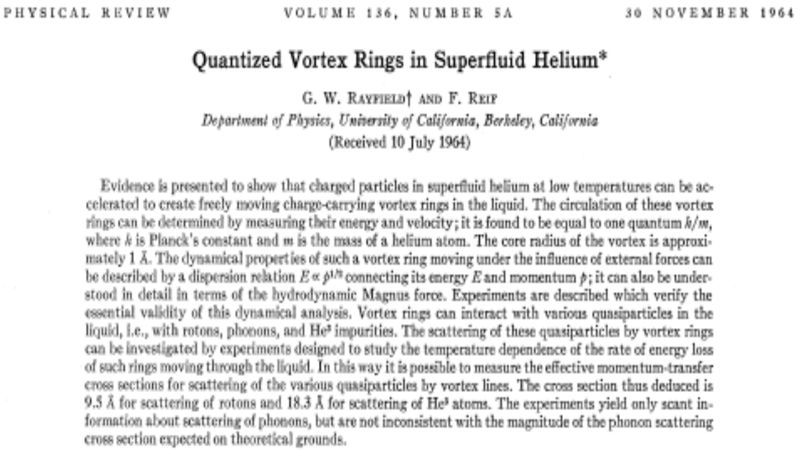
Energy $\geq \frac{1}{2}\Lambda\rho\kappa^2 R$

In a uniform electric field E, radius grows linearly:

$$R(x) \approx R_0 + (2e)/(\rho\kappa^2\Lambda)Ex$$

Theory of deformed charged vortex rings (CVRs):
Samuels & Donnelly (PRL 1991);Tsubota & Adachi (JLTP 2010)

Injected ions were used to create vortex rings, tag them and explore their dynamics at small fields and all $T < 1$ K. (Rayfield and Reif, 1964)



PHYSICAL REVIEW VOLUME 136, NUMBER 5A 30 NOVEMBER 1964

Quantized Vortex Rings in Superfluid Helium*

G. W. RAYFIELD† AND F. REIF
Department of Physics, University of California, Berkeley, California

(Received 10 July 1964)

Evidence is presented to show that charged particles in superfluid helium at low temperatures can be accelerated to create freely moving charge-carrying vortex rings in the liquid. The circulation of these vortex rings can be determined by measuring their energy and velocity; it is found to be equal to one quantum h/m, where h is Planck's constant and m is the mass of a helium atom. The core radius of the vortex is approximately 1 Å. The dynamical properties of such a vortex ring moving under the influence of external forces can be described by a dispersion relation $E \propto p^{1/2}$ connecting its energy E and momentum p; it can also be understood in detail in terms of the hydrodynamic Magnus force. Experiments are described which verify the essential validity of this dynamical analysis. Vortex rings can interact with various quasiparticles in the liquid, i.e., with rotons, phonons, and He^3 impurities. The scattering of these quasiparticles by vortex rings can be investigated by experiments designed to study the temperature dependence of the rate of energy loss of such rings moving through the liquid. In this way it is possible to measure the effective momentum-transfer cross sections for scattering of the various quasiparticles by vortex lines. The cross section thus deduced is 9.5 Å for scattering of rotons and 18.3 Å for scattering of He^3 atoms. The experiments yield only scant information about scattering of phonons, but are not inconsistent with the magnitude of the phonon scattering cross section expected on theoretical grounds.

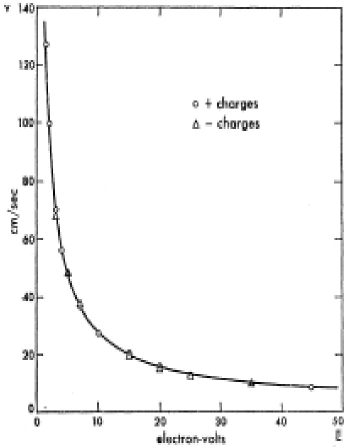


FIG. 2. Relation between the velocity v and energy E of a vortex ring. The points are experimental data for positive and negative charge carriers. The curve is the theoretical relation following from (5) and (6) with $\kappa = h/m$ and $a = 1.2$ Å.

$$E = \tfrac{1}{2}\rho\kappa^2 R[\eta - (7/4)],$$

$$v = (\kappa/4\pi R)(\eta - \tfrac{1}{4}),$$

$$\eta \equiv \ln(8R/a).$$

$$E = \tfrac{1}{2}\rho\kappa^2 R[\ln(8R/a) - \tfrac{3}{2}] \;,$$

$$v = (\partial E/\partial p)_a = (\kappa/4\pi R)[\ln(8R/a) - \tfrac{1}{2}] \;,$$

$$p = \rho\kappa\pi R^2 \;.$$

Proper relations:
Roberts and Donnelly, Phys. Lett. **31A**, 137 (1970).

Theory of deformed charged vortex rings (CVRs):
Samuels & Donnelly (PRL 1991); Tsubota & Adachi (JLTP 2010)

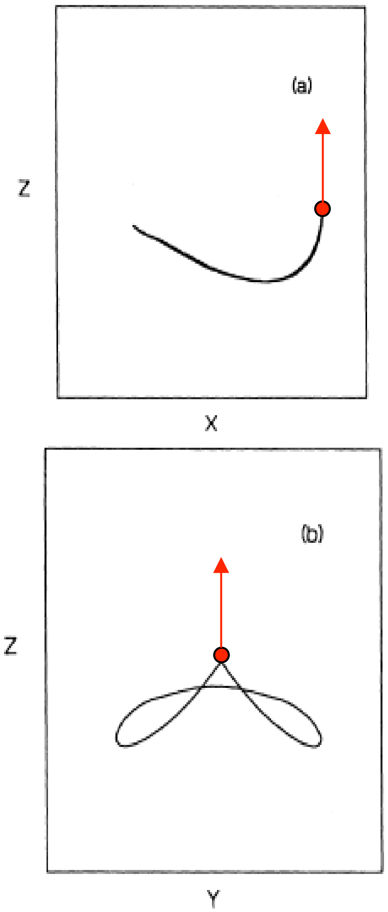


FIG. 1. The final shape of a vortex ring with a fixed ion moving in the *z* direction in an electric field. The ion is located at the cusp seen in (b). The *z* axis is exaggerated by a factor of 10.

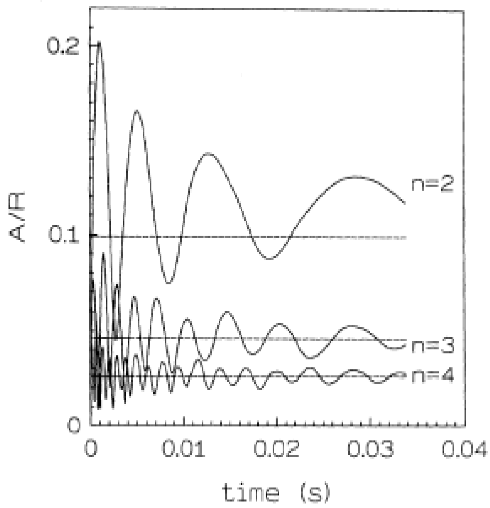
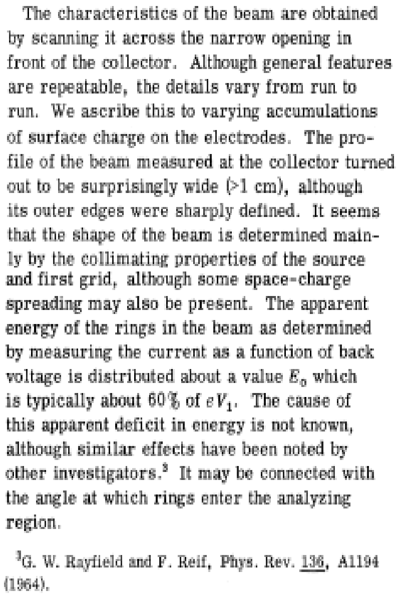


FIG. 2. Amplitudes of the lowest three harmonics vs time. The dashed lines are the amplitudes predicted from Eq. (12).

Simulations for $E = 10^5$ V/cm
Samuels and Donnelly, PRL **67**, 2505 (1991).

Charged vortex rings were used to detect vortices since 1966

Schwarz, Donnelly, Phys. Rev. Lett. **17**, 1088 (1966) Quantized Vortex Rings in Rotating Helium II
Schwarz, Phys. Rev. **165**, 323 (1968) (T = 0.3 K)



The characteristics of the beam are obtained by scanning it across the narrow opening in front of the collector. Although general features are repeatable, the details vary from run to run. We ascribe this to varying accumulations of surface charge on the electrodes. The profile of the beam measured at the collector turned out to be surprisingly wide (>1 cm), although its outer edges were sharply defined. It seems that the shape of the beam is determined mainly by the collimating properties of the source and first grid, although some space-charge spreading may also be present. The apparent energy of the rings in the beam as determined by measuring the current as a function of back voltage is distributed about a value E_0 which is typically about 60% of eV_1. The cause of this apparent deficit in energy is not known, although similar effects have been noted by other investigators.[3] It may be connected with the angle at which rings enter the analyzing region.

[3] G. W. Rayfield and F. Reif, Phys. Rev. 136, A1194 (1964).

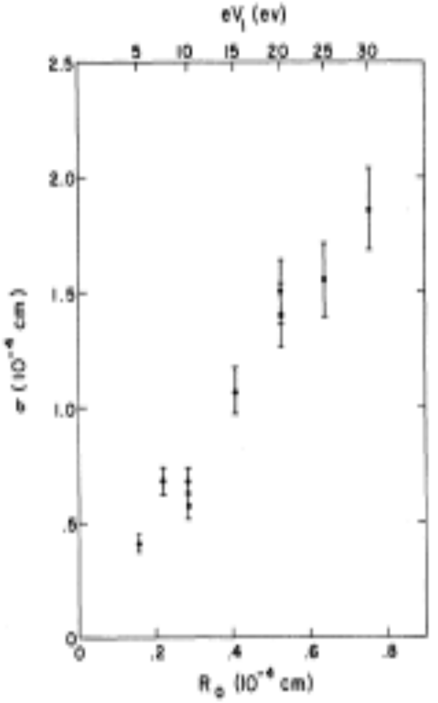
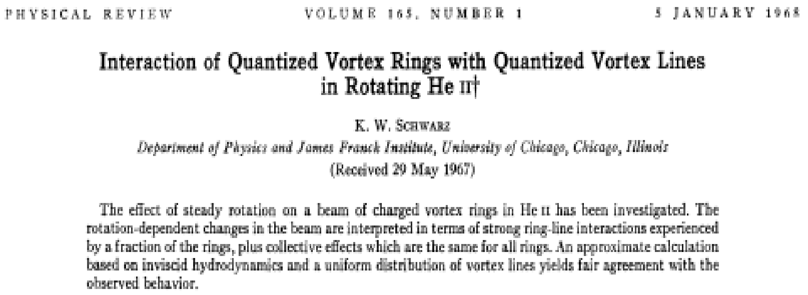


FIG. 2. Capture cross section for vortex rings incident on vortex lines as a function of the radius and energy of the rings.



PHYSICAL REVIEW VOLUME 165, NUMBER 1 5 JANUARY 1968

Interaction of Quantized Vortex Rings with Quantized Vortex Lines in Rotating He II†

K. W. SCHWARZ
Department of Physics and James Franck Institute, University of Chicago, Chicago, Illinois
(Received 29 May 1967)

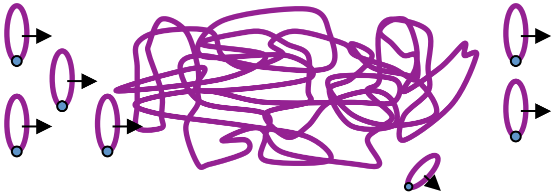
The effect of steady rotation on a beam of charged vortex rings in He II has been investigated. The rotation-dependent changes in the beam are interpreted in terms of strong ring-line interactions experienced by a fraction of the rings, plus collective effects which are the same for all rings. An approximate calculation based on inviscid hydrodynamics and a uniform distribution of vortex lines yields fair agreement with the observed behavior.

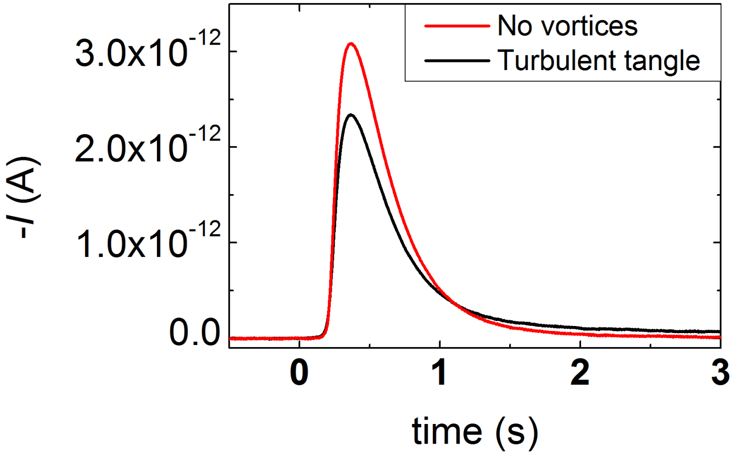
Detection Technique: Scattering of Charged Vortex Rings

In helium at $T < 0.7\text{K}$, an electron (inside bubbles of $R \sim 20\text{Å}$) nucleates a vortex rings and travels with it.

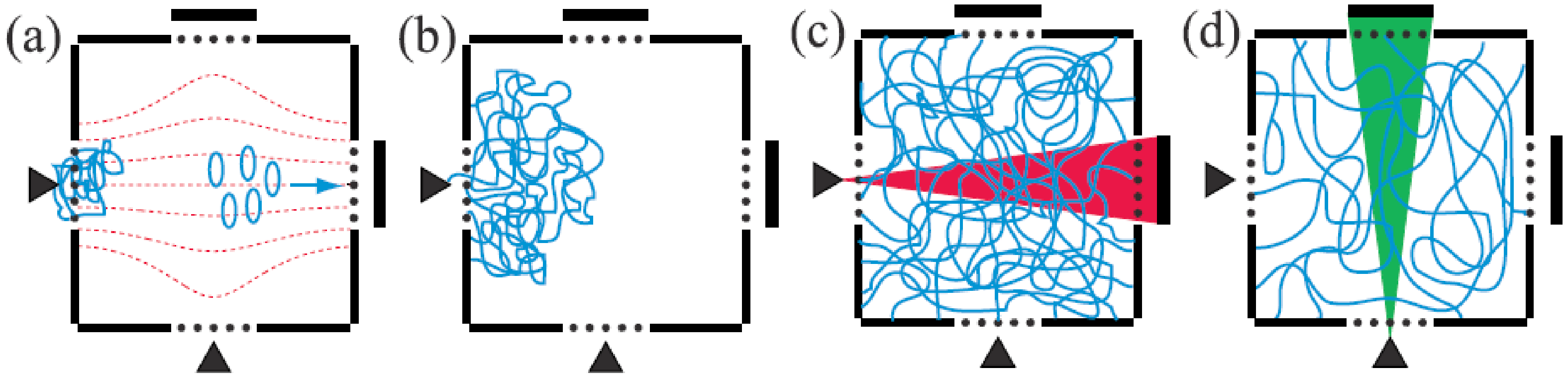
Charged vortex rings of suitable radius (~1 μm) are used as detectors of vortex length L

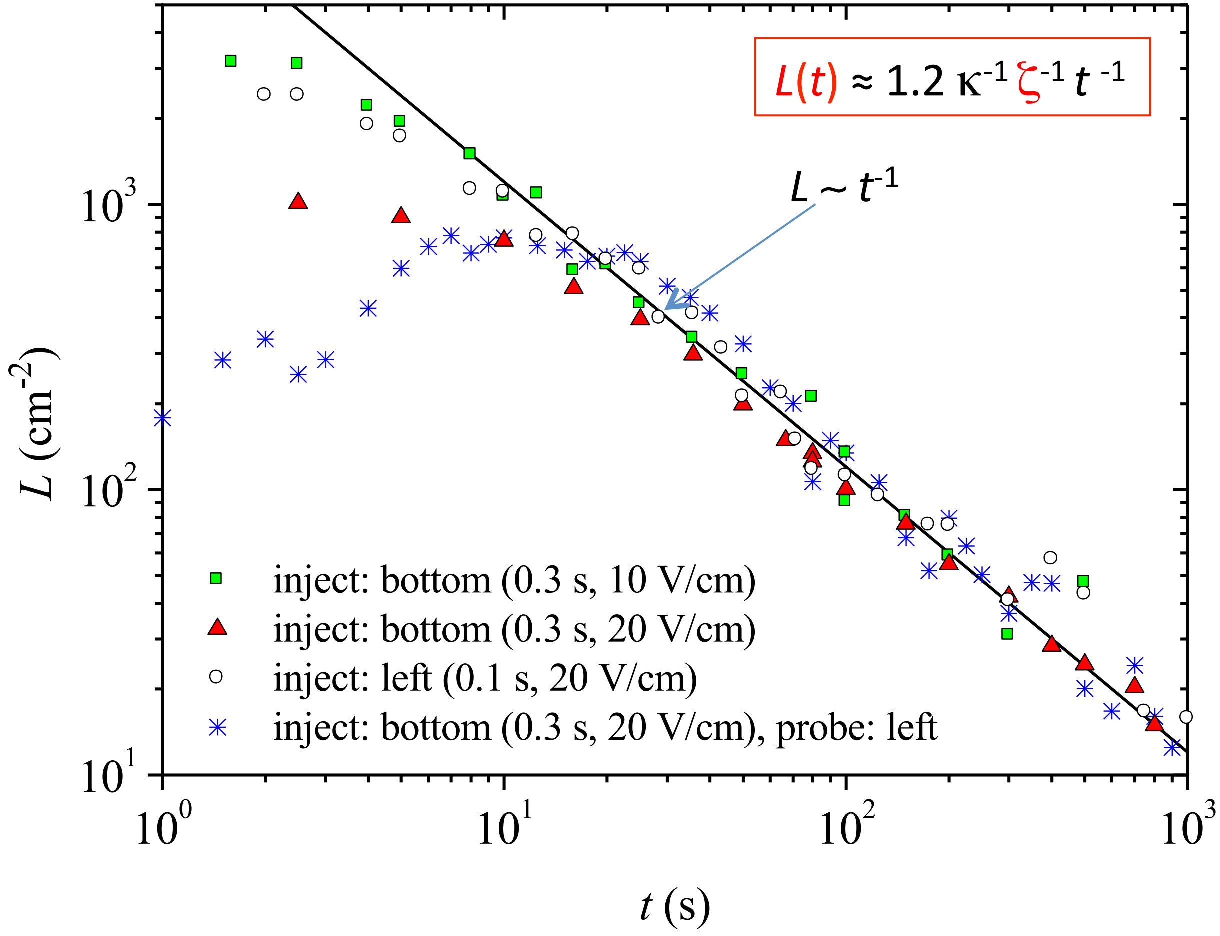
L can be calculated from attenuation of the electric current due to CVRs





Forcing (Vinen QT)





Short injection of charged vortex rings (<1 s).

Tangle fills volume in ~20s.

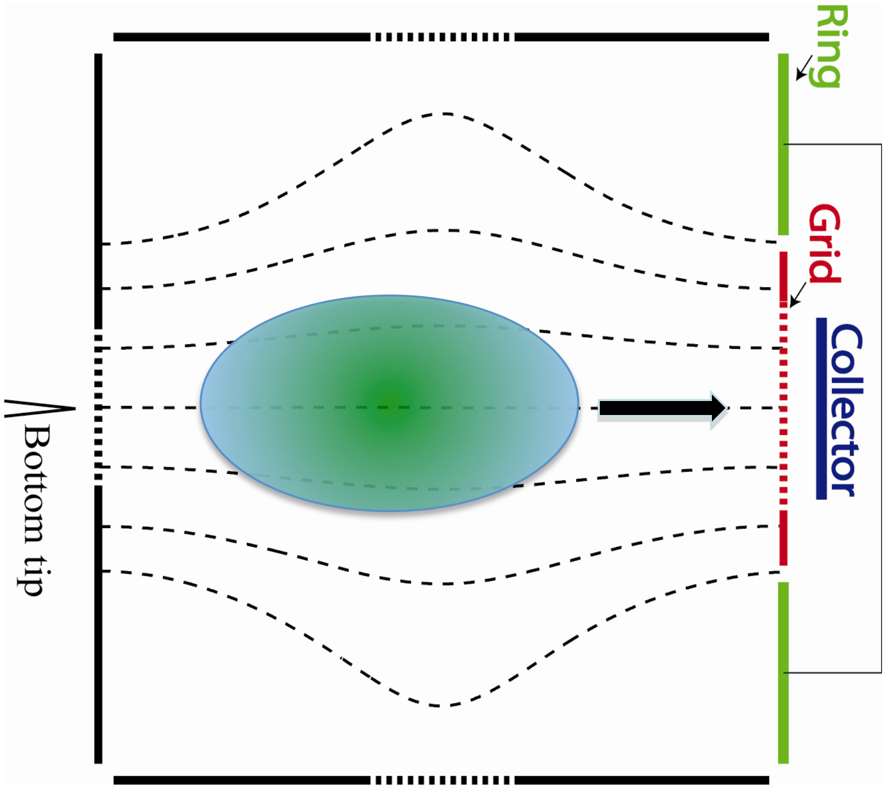
Late-time behaviour is identical for both directions of probing.

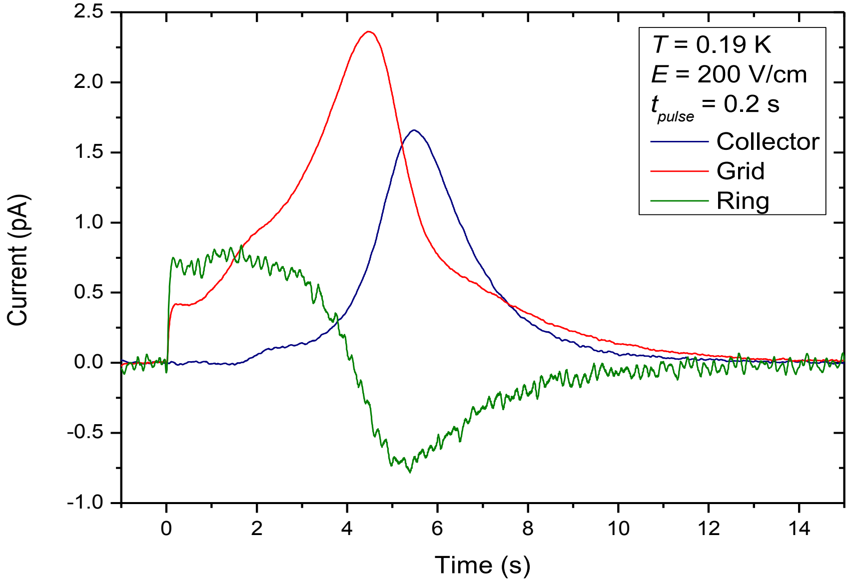
L~1/*t* indicates **ultraquantum** turbulence
- no large scale flow
- no classical analogue

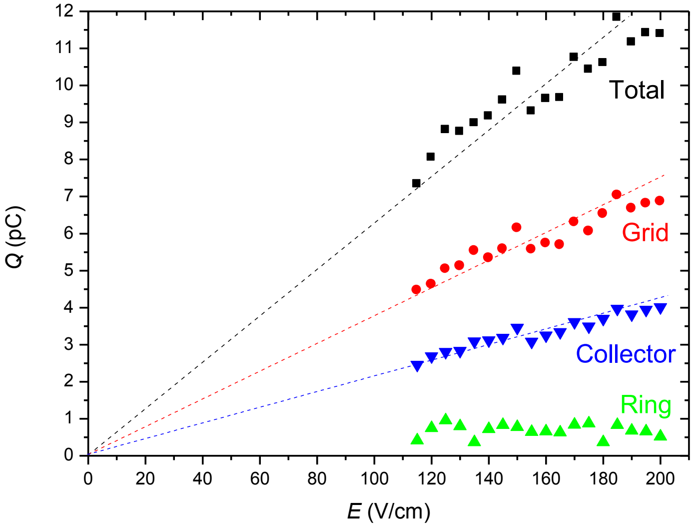
Walmsley & Golov, PRL (2008)

Spatial Extent of Charged Tangle

We can simultaneously measure the currents to three separate electrodes

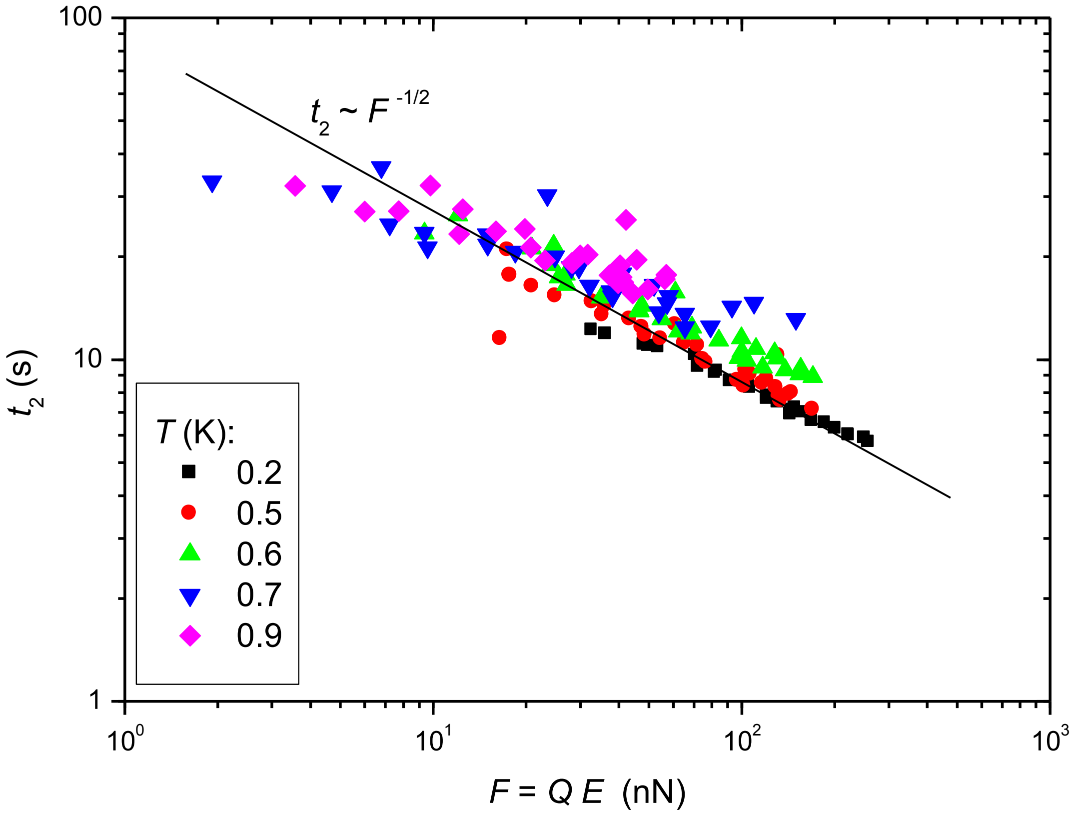


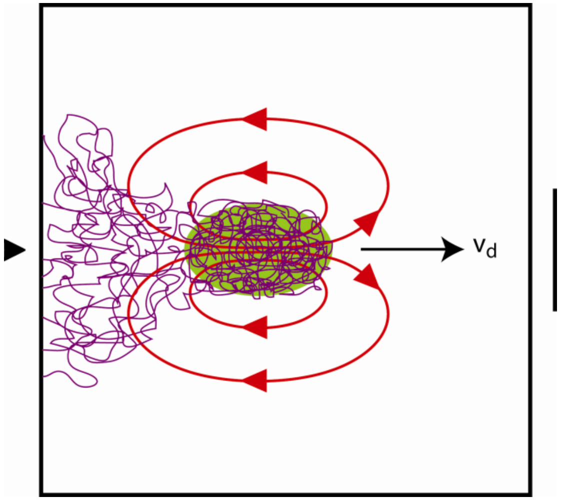




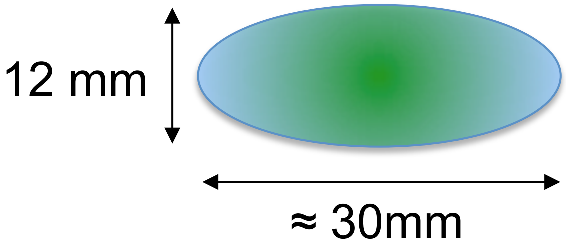
Main contributions to the currents to Grid and Ring electrodes are from *displacement current*

Forcing (quasi-classical QT)





Effective dimensions of the moving charged cloud:



Charged tangle likely to consist of polarized charged loops

$t_2 \sim F^{-1/2}$: uniform acceleration of a constant mass of fluid?

(1) Summary

- Ions (and molecules He_2^*) can be injected into helium, manipulated and detected.
- They can be trapped by vortex lines (and stay trapped if $T<0.1$K).
- Hence, by observing:
  - loss of ions,
  - transport of trapped ions,
  - deflection of current,
  - time-dependent fluctuations of current,

  one can learn about the presence and behaviour of vortices.

- By applying electric field to trapped ions, one can force QT.

MANCHESTER 1824
The University of Manchester

LANCASTER UNIVERSITY

UNIVERSITY OF BIRMINGHAM

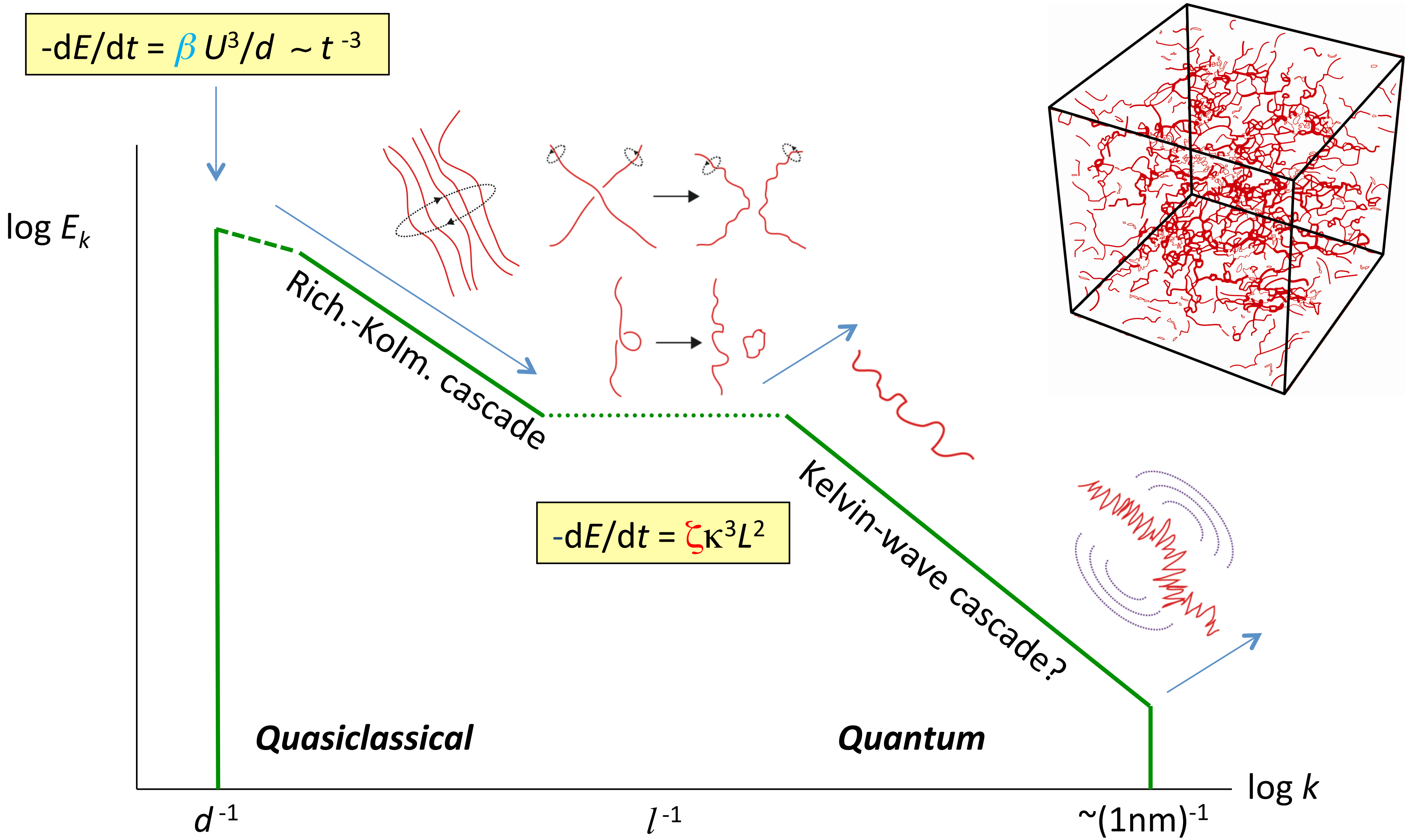
EPSRC

Dissipation of Quasi-Classical Quantum Turbulence in ^{4}He at $T \to 0$

D.E. Zmeev, P.M. Walmsley, A.I. Golov,
P.V.E. McClintock, S.N. Fisher, W.F. Vinen

Experiment: free decay of vortex line length $L(t)$

QT at T=0 was studied since 2000. Our *beliefs* after 15 years:

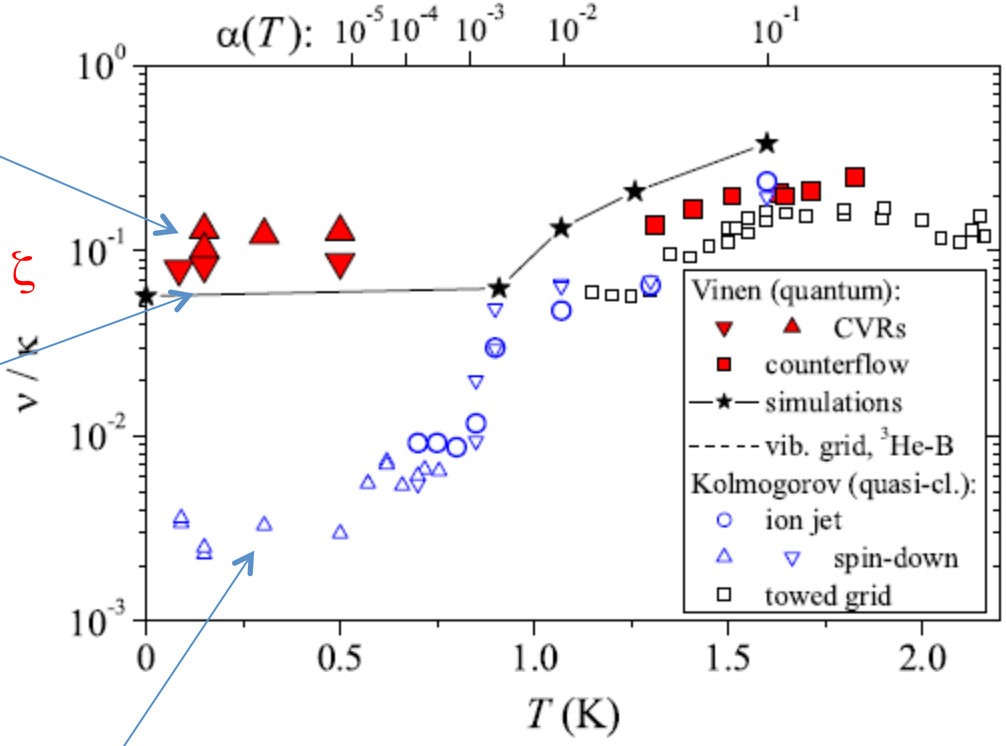


$-dE/dt = \beta U^3/d \sim t^{-3}$

$-dE/dt = \zeta \kappa^3 L^2$

Assumed energy spectrum of QT (HIT)

What we *believed* in 2008

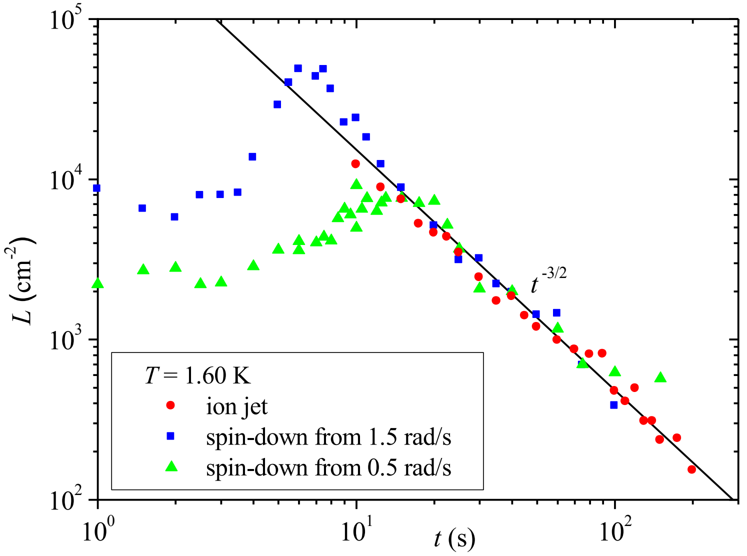


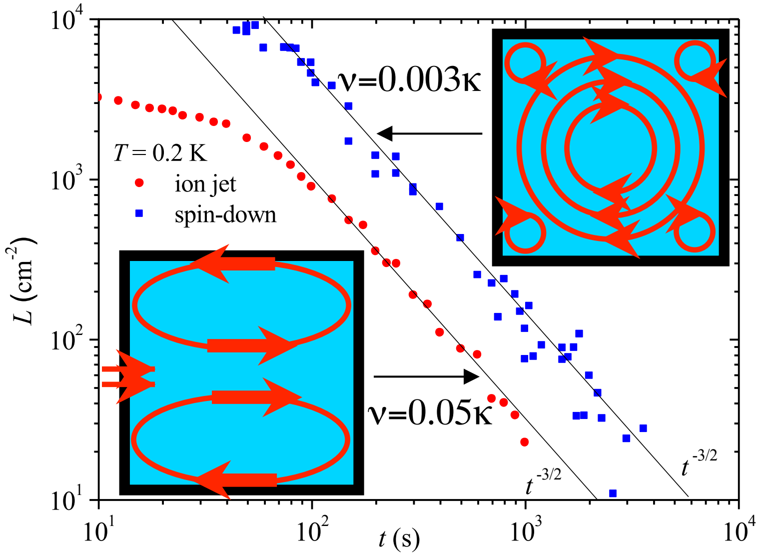
Unstructured (Vinen) QT
Walmsley and Golov 2008

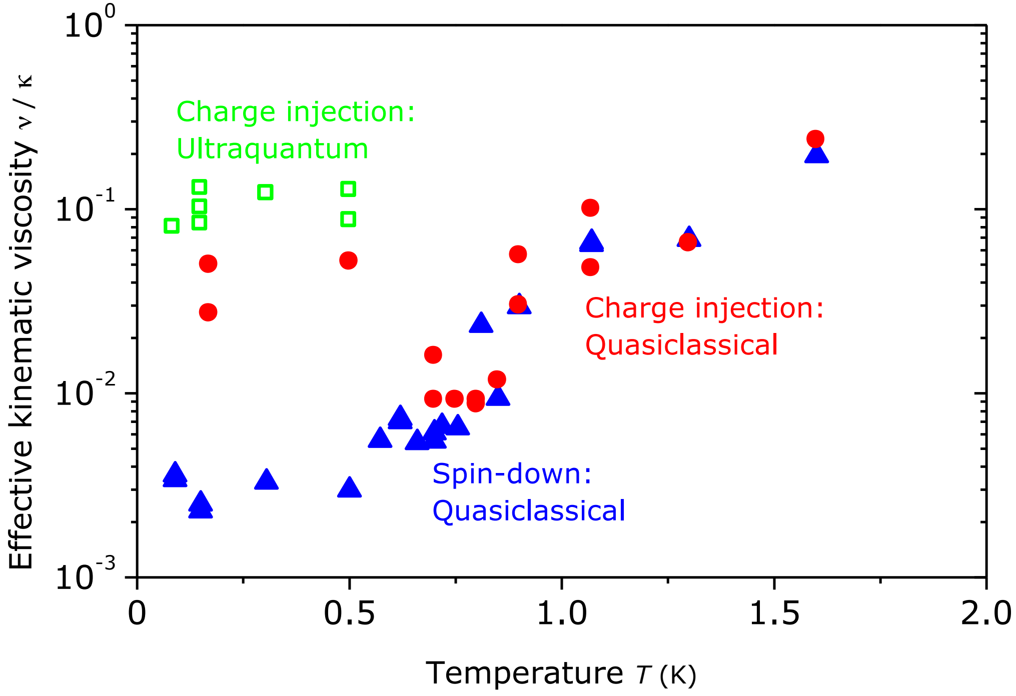
Simulations of decay
of unstructured tangle
Tsubota *et al.* 2000

Quasi-classical (structured) QT
from spin-down to rest
Walmsley *et al.* 2007

Slide from my talk in 2010







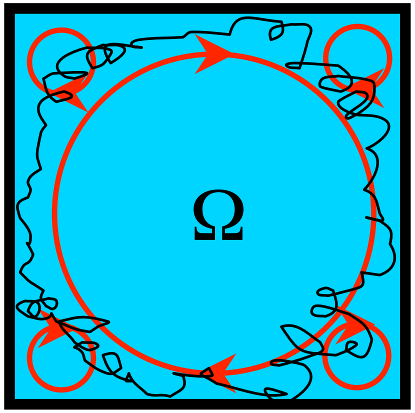
Only at T < 0.7 K, spin-down and ion jet result in quite different values of ν !

Quasi-classical turbulences of different spectra, both decaying as $L \sim t^{-3/2}$?

Means of generating turbulence

1. “Spin-down turbulence”: change of angular velocity of container

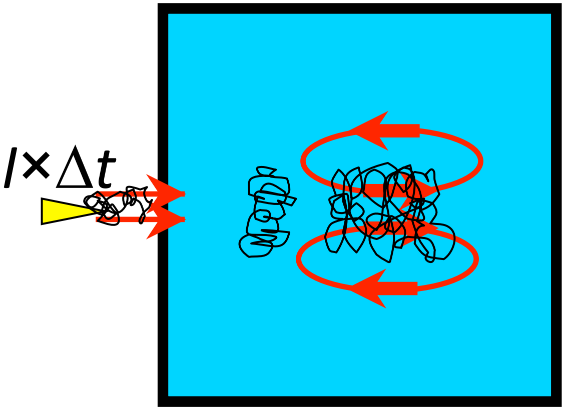
(impulsive spin-down to rest or AC modulation of Ω)



Non-zero angular momentum?

2. “Ion jet turbulence”: inject charged vortex rings and let them tangle

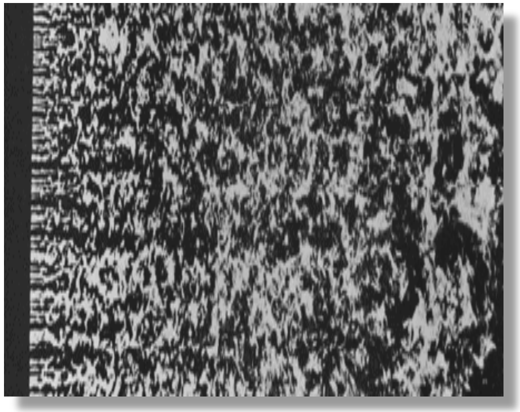
(injected impulse ~ *I*×Δ*t*)



Either ultraquantum or quasiclassical QT

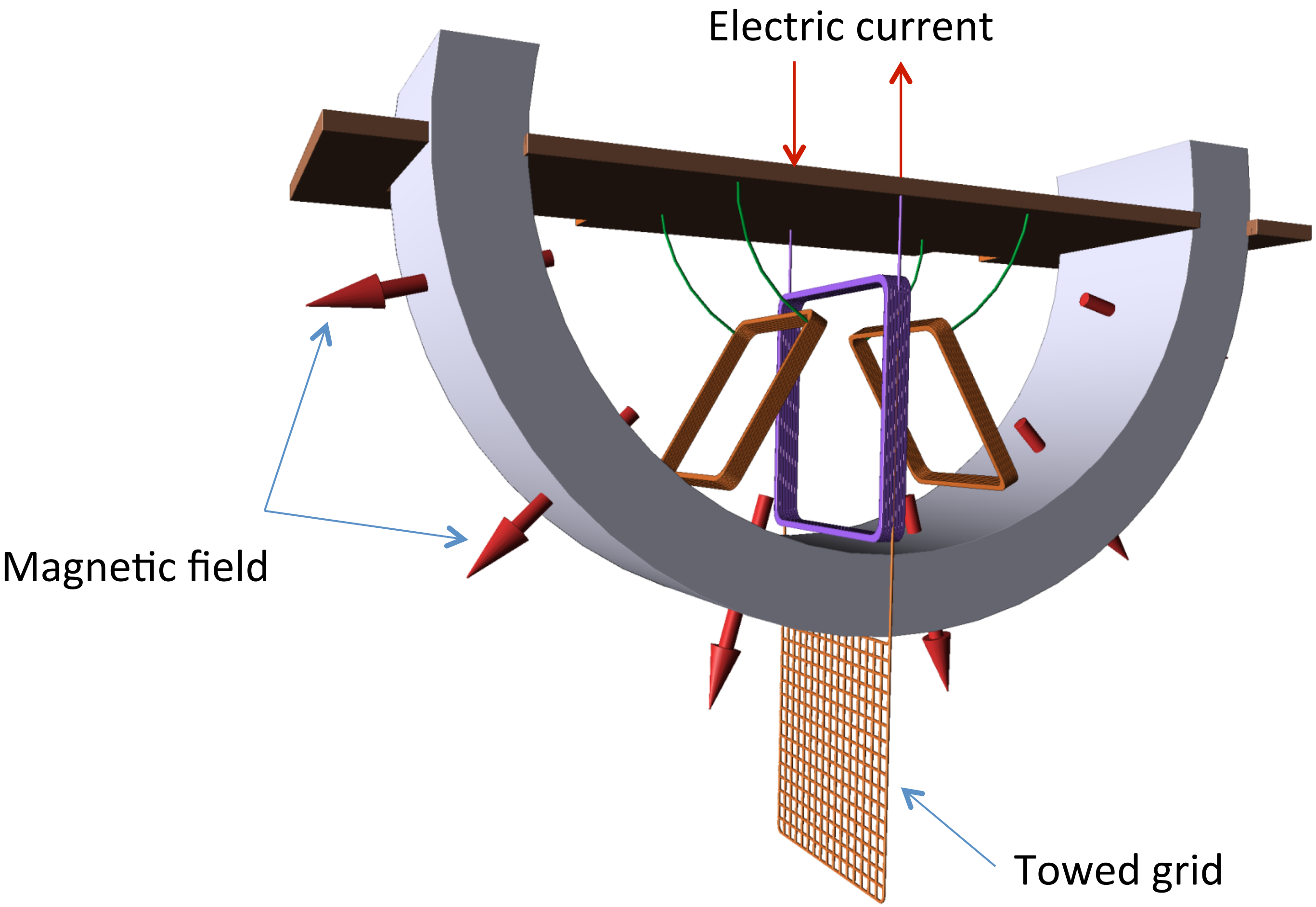
3. “Grid turbulence”

(tow a grid through stationary superfluid)

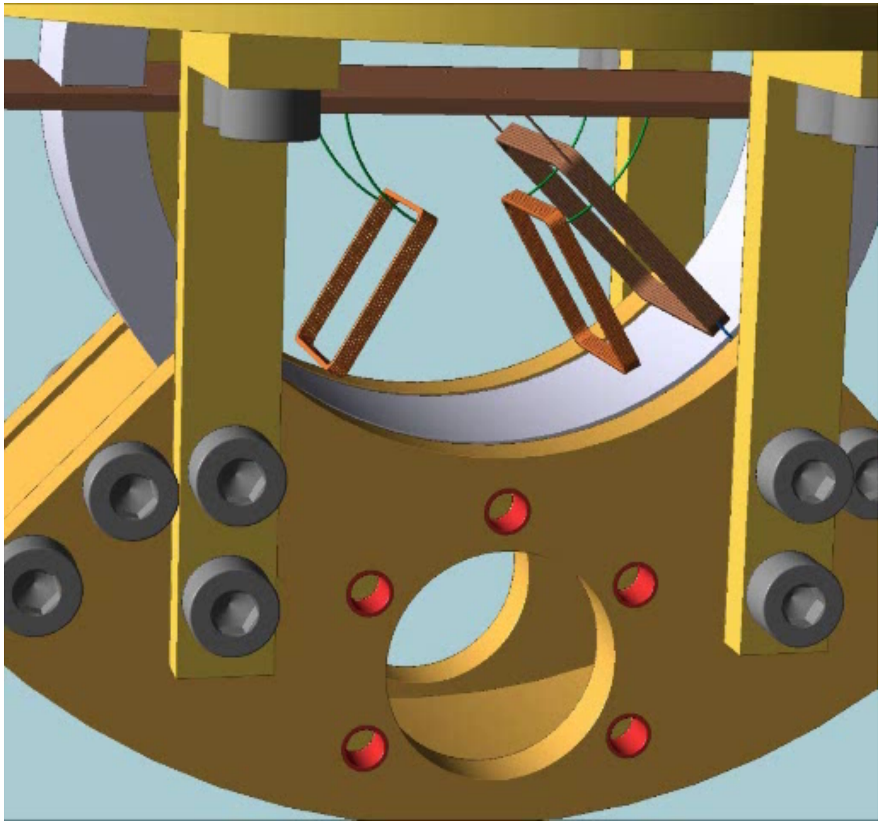


Nearly Homogeneous and Isotropic Turbulence (HIT)

Towed Grid



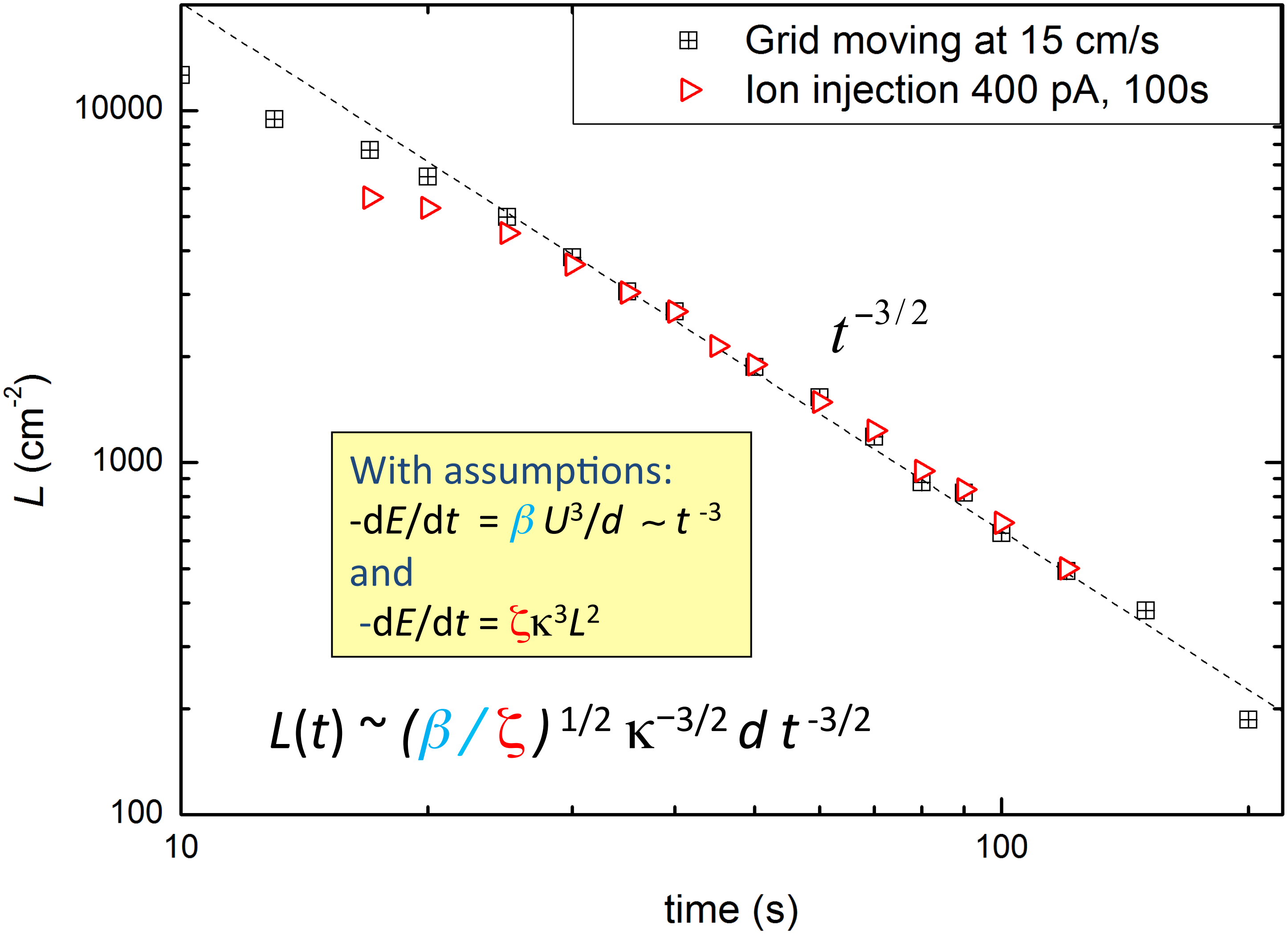
Towed Grid



We monitor the free decay of the turbulence after towing the grid through the channel.

Zmeev, J. Low Temp. Phys (2014)

Circumstantial evidence for quasi-classical cascade



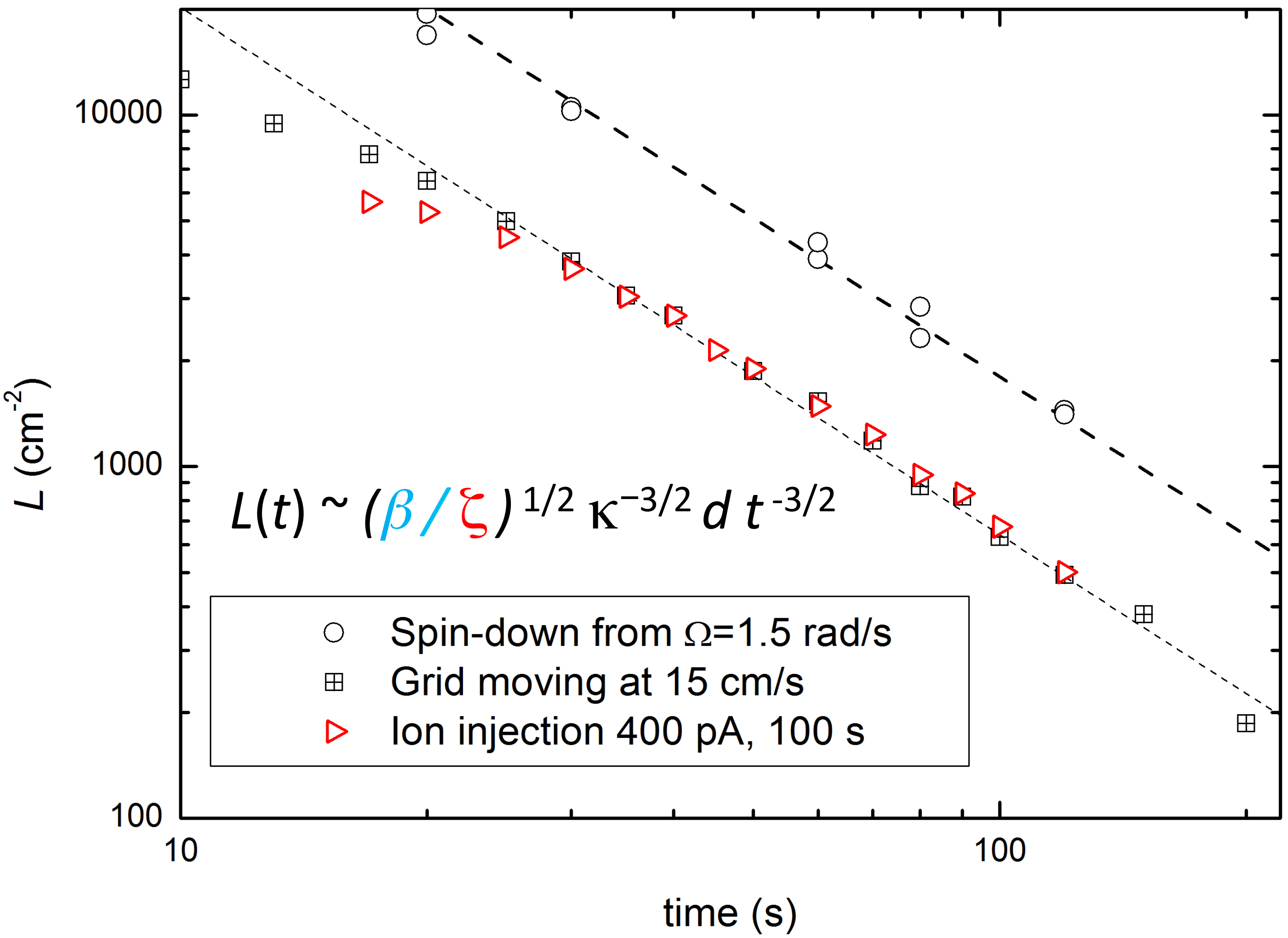
With assumptions:
$-dE/dt = \beta U^3/d \sim t^{-3}$
and
$-dE/dt = \zeta \kappa^3 L^2$

$$L(t) \sim (\beta / \zeta)^{1/2} \kappa^{-3/2} d\, t^{-3/2}$$

Free decay of QT
T=90 mK
P=0.1 bar

Zmeev *et al.*, to appear in PRL (2015)

Circumstantial evidence for quasi-classical cascade

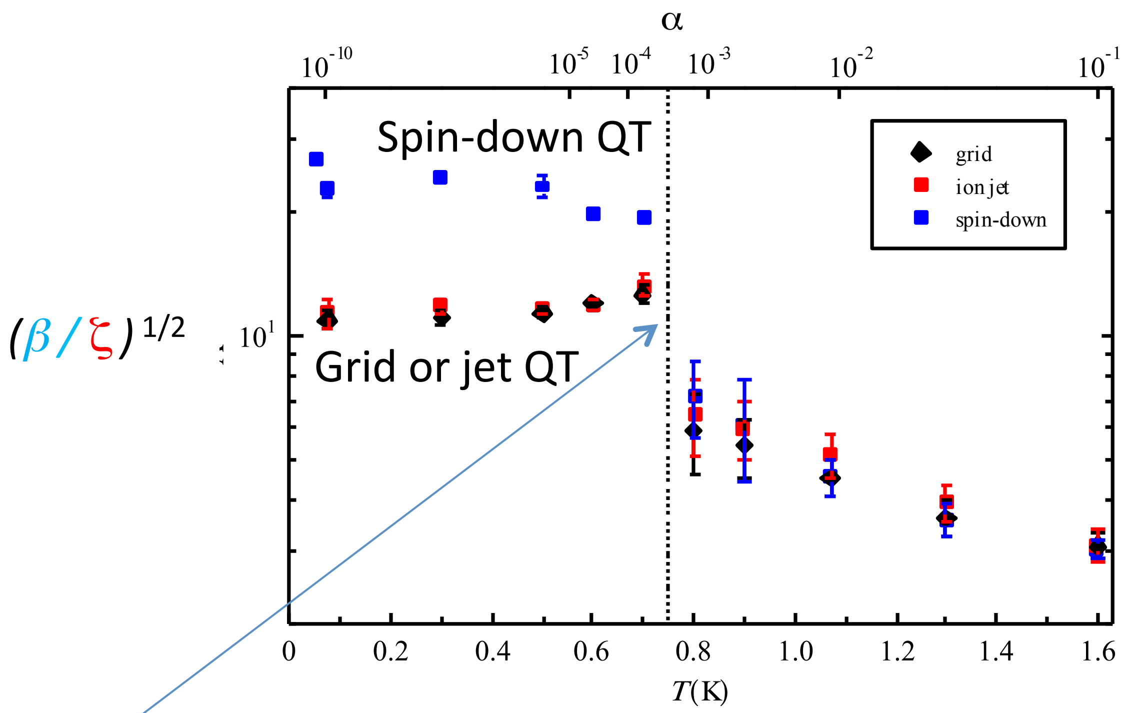


$$L(t) \sim (\beta / \zeta)^{1/2} \kappa^{-3/2} d\, t^{-3/2}$$

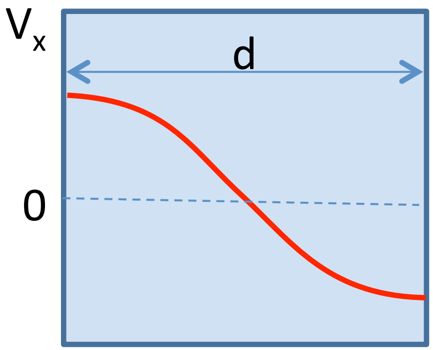
Free decay of QT
T=90 mK
P=0.1 bar

Zmeev et al., submitted to PRL (2015)

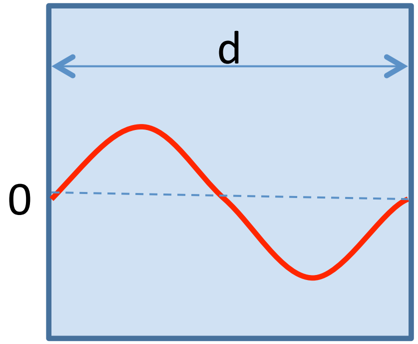
At $T < 0.8$K, spin-down turbulence differs from grid & jet turbulence



Hypothesis: boundary conditions change



Free slip



No slip

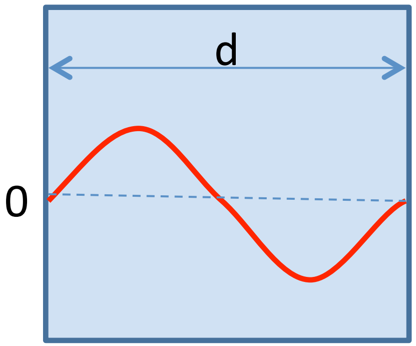
Interpretation in terms of $\nu=\kappa\zeta$ following Stalp *et al.*:

$$L(t) \sim (\beta/\zeta)^{1/2}\,\kappa^{-3/2}\,d\,t^{-3/2} \longrightarrow \boxed{L(t) = (3C\kappa^{-1})^{3/2} k_1^{-1}\,\zeta^{-1/2}\,t^{-3/2}}$$

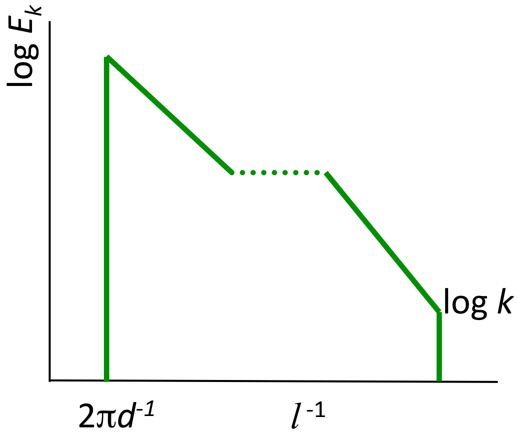
Largest eddy: velocity profile

Turbulence Spectrum

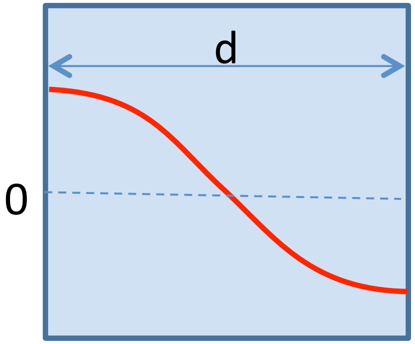
Stalp *et al*. 1999



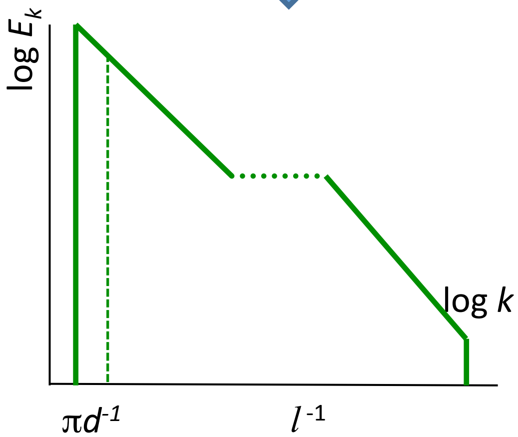
No-slip BC at *T*>0.8 K



k1 = 2π/d



Slip BC at *T*<0.8 K

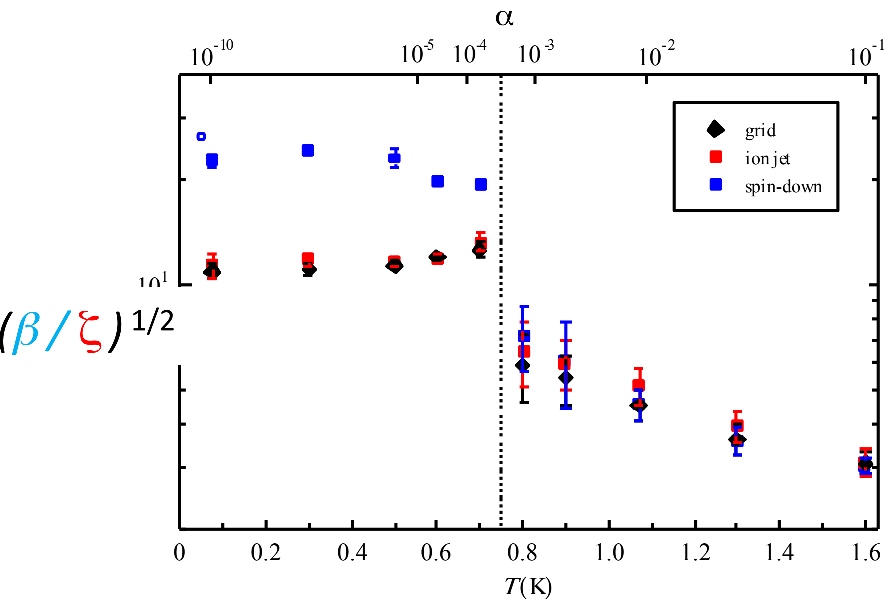


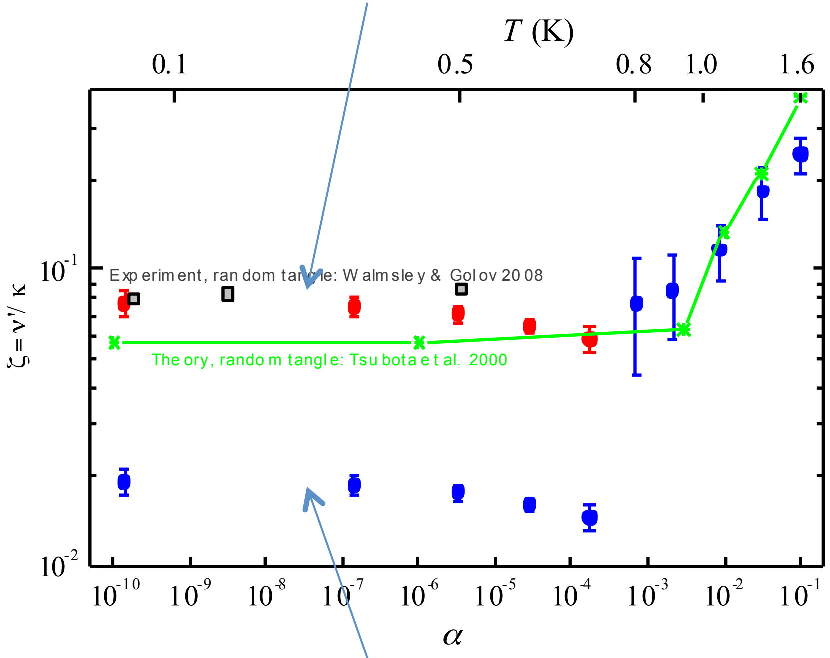
k1 = π/d

Effective viscosity for QHIT

$$\boxed{L(t) = (3C\kappa^{-1})^{3/2} k_1^{-1} \zeta^{-1/2} t^{-3/2}}$$

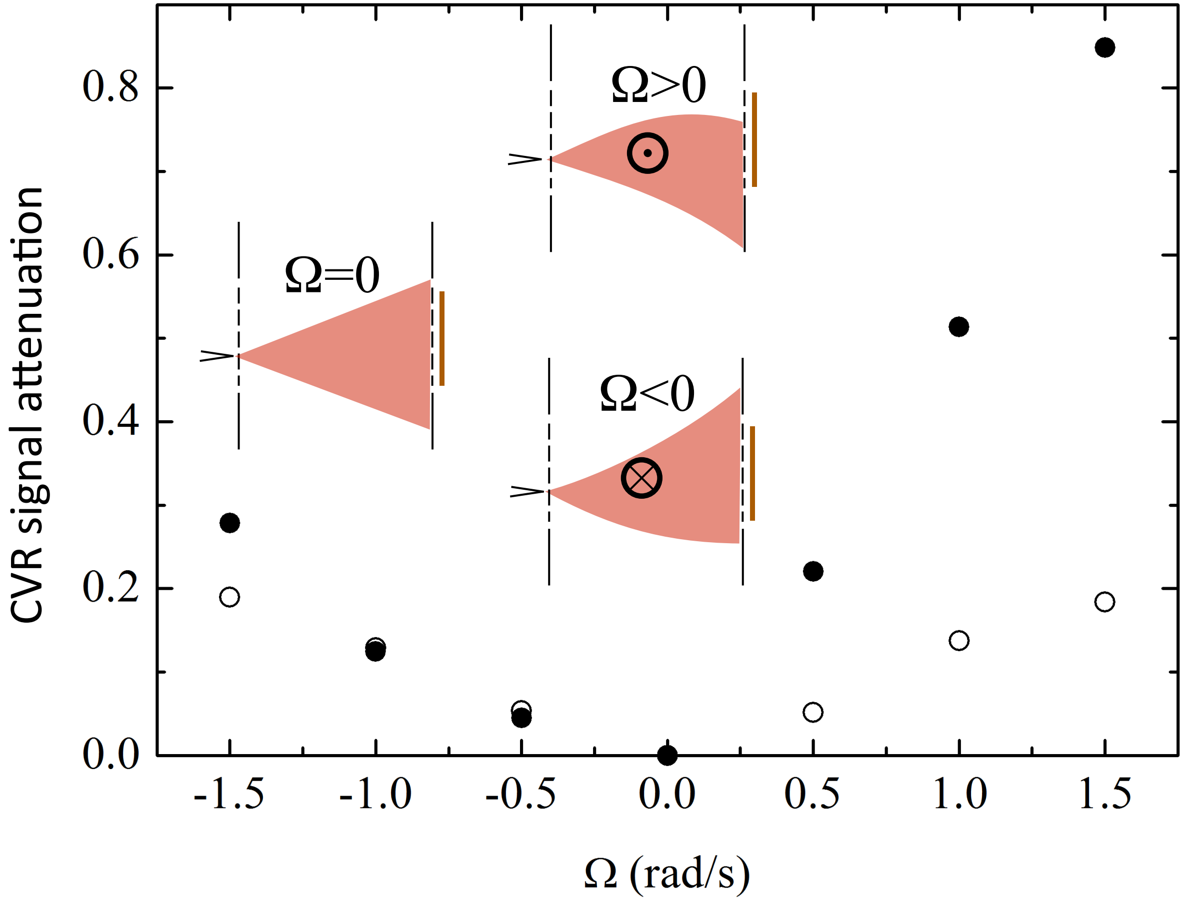
Quasi-classical QT (structured tangle), if $k_1 = \pi/d$ at $T < 0.8$K (free slip BC)





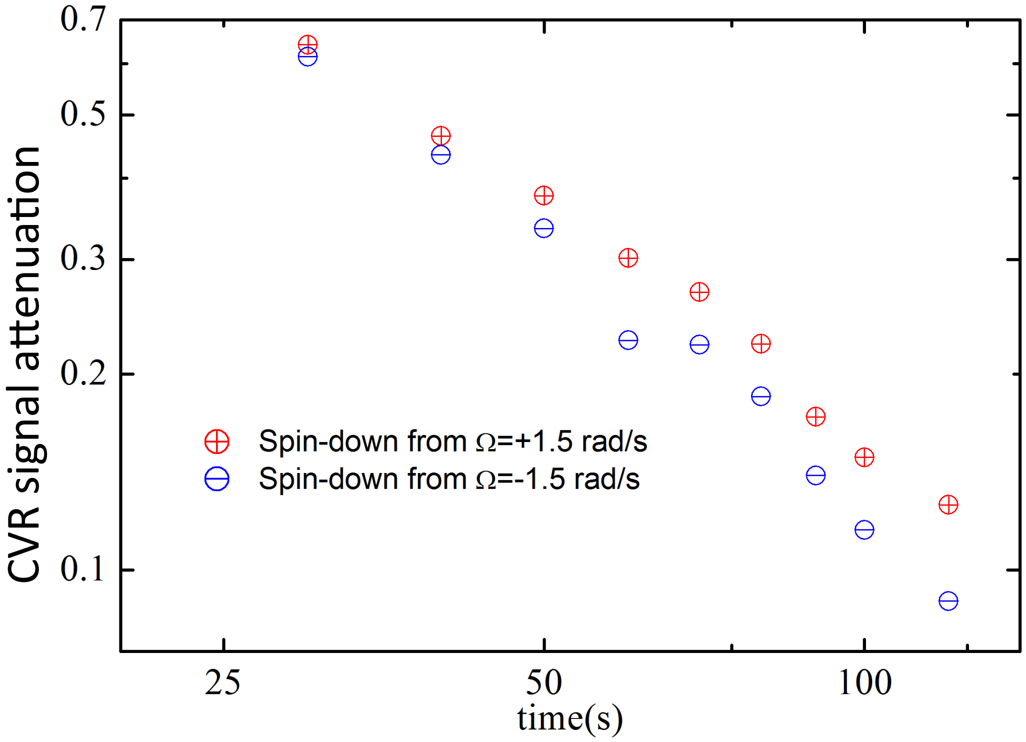
Quasi-classical QT (structured tangle), if $k_1 = 2\pi/d$ (no-slip BC)

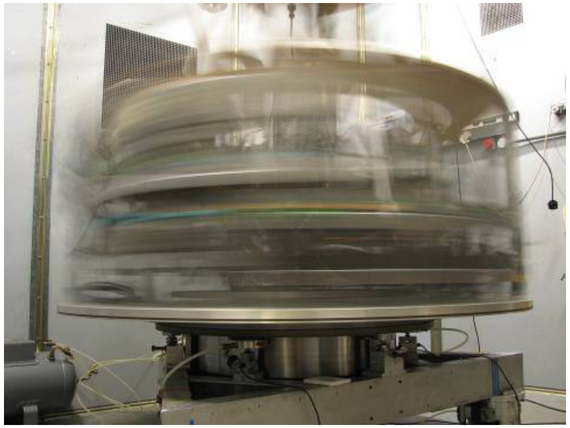
Polarization detector



- ✓ Ion source is off the symmetry plane
- ✓ We can focus or defocus the beam of CVRs
- ✓ Defocussed beam (●): can detect sense of rotation, therefore can serve as detector of **vorticity polarization**
- ✓ Focussed beam (○) was used to measure *L* (no dependence on sense of rotation)

Anisotropy of spin-down turbulence





- ✓ Conclusion: spin-down turbulence is anisotropic. Presence of large-scale circular flow is most probably responsible for the reduced value of the dissipation rate.

(2) Conclusions

1. We measured decay $L(t)$ of QT, generated by either towed grid or ion jet
2. Observed decay $L \sim t^{-3/2}$ is consistent with assumptions of quasi-classical behaviour $\varepsilon = Cu^3/d$ and energy flux $\varepsilon = \zeta\kappa^3 L^2$
3. BC switch to free-slip at $T < 0.8$K
4. Effective viscosity $\zeta\kappa \sim 0.1\kappa$ – same as for unstructured QT (hence, perhaps, no bottleneck between classical and quantum cascades)
5. Spin-down QT is different at $T < 0.8$K, albeit $L \sim t^{-3/2}$: some rotation persists, and $L(t)$ decays slower