Superfluid turbulence in rotating ^{3}He-B

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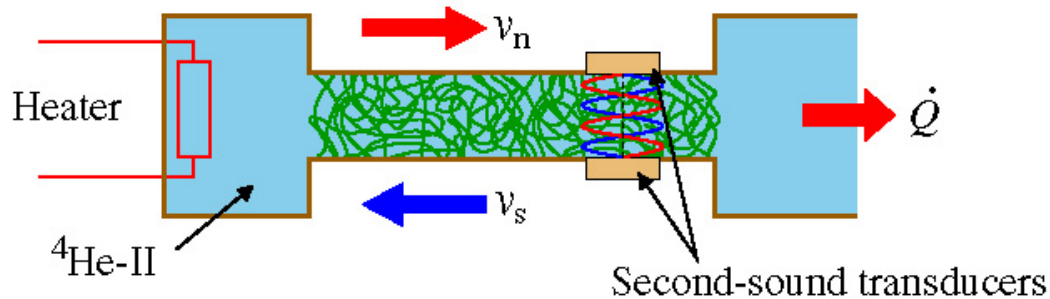
Overview

- Introduction to the experiment
- Experimental observations on:
  - Criteria for turbulence
    - Temperature
    - Velocity
    - Effect of initial vortex configuration
  - Sequence of events:
    1. Injection of vortex lines, start of turbulence
    2. How does turbulent network advance into vortex free flow
    3. Relaxation

Turbulence in superfluids

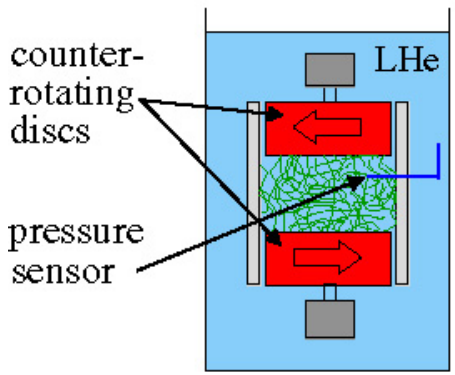
- Supefluid turbulence ≈ tangle of vortex lines (no strict definition)
- Discovered in thermal counterflow experiments in ^{4}He-II

Turbulence in thermal counterflow

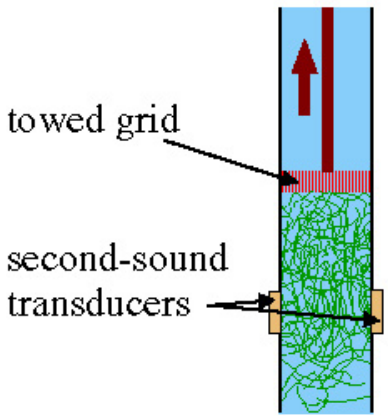


Turbulence driven in classical way

Pressure fluctuations
(Maurer & Tabeling, 1998)



Decay of vorticity
(Stalp, Skrbek & Donnelly, 1999)

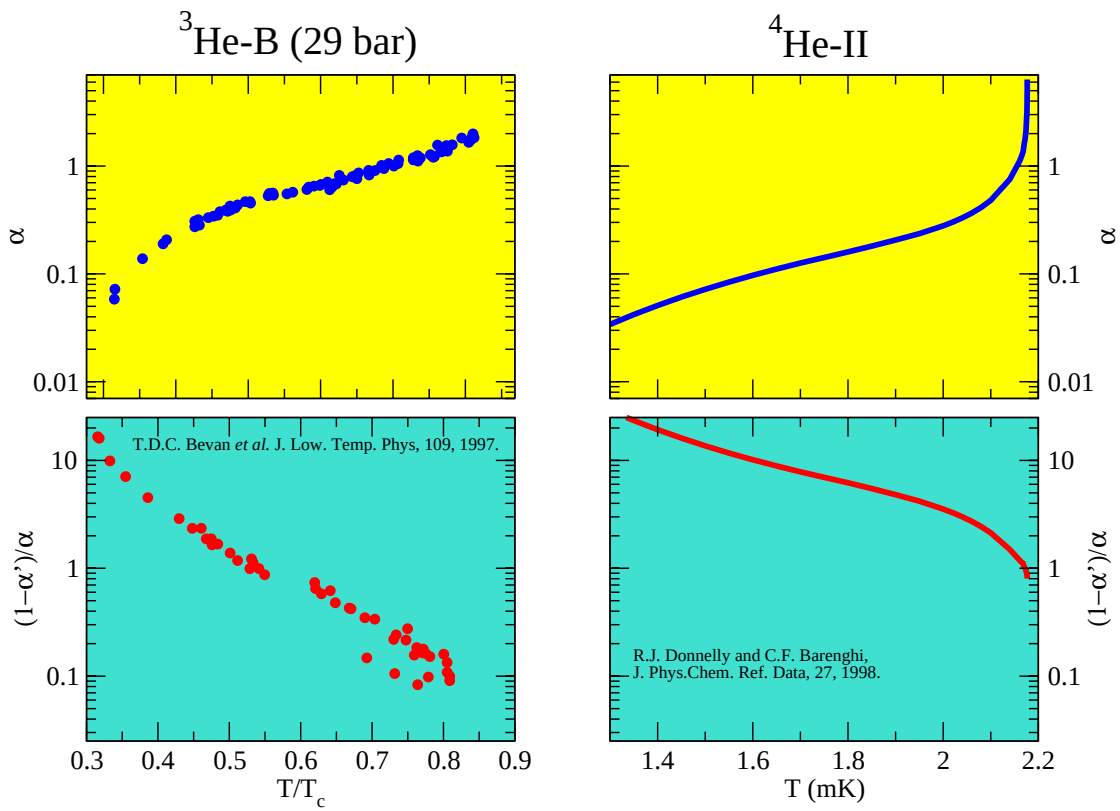


Hydrodynamics of ^{3}He and ^{4}He

In ^{3}He-B:

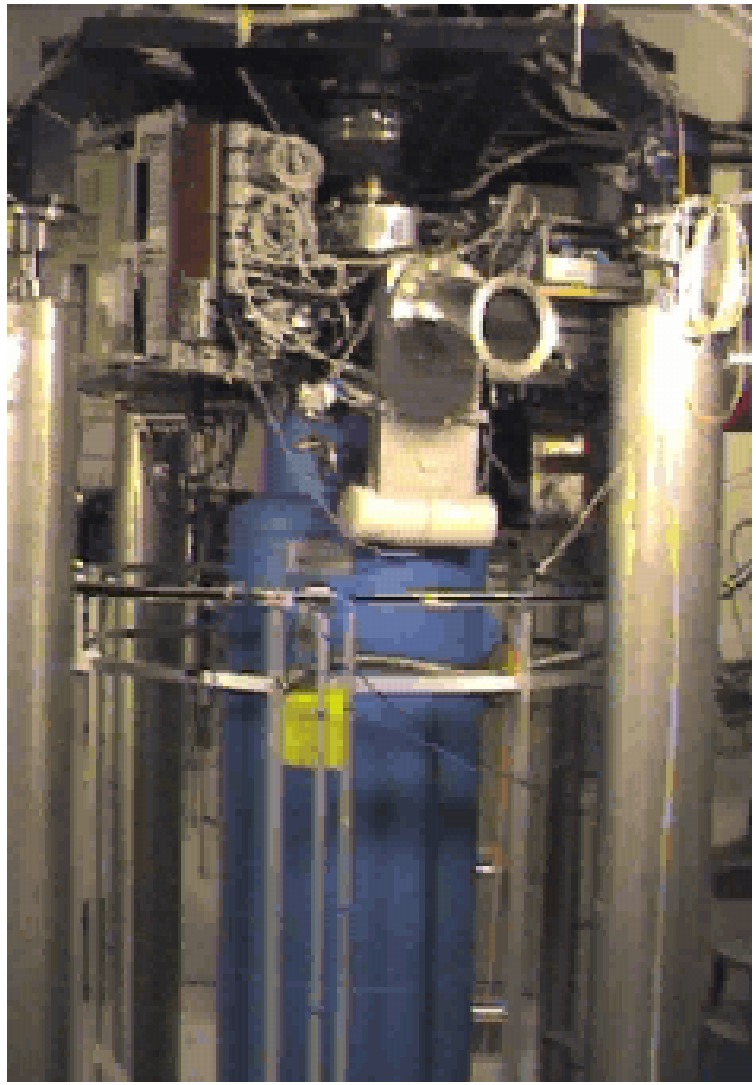
- Normal component ~10^4 more viscous
- Vortex formation under control
- Mutual friction covers different ranges, α and α' are the mutual friction parameters such that

$$v_L = v_s + \alpha \hat{s} \times (v_n - v_s) - \alpha' \hat{s} \times [\hat{s} \times (v_n - v_s)]$$



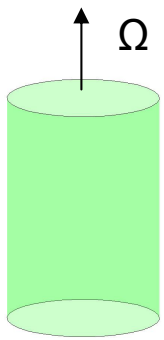
Rotating cryostat

- Dilution refrigerator for precooling
- Adiabatic nuclear demagnetization cooling for superfuid ^{3}He
- Creation of flow with rotation
    - normal component follows the container
    - superfluid at rest until vortices form



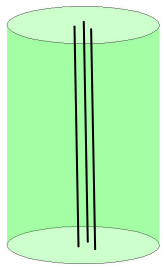
Rotating ^{3}He-B

vortex-free rotation



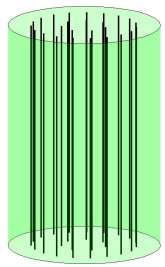
- maximum energy state
- normal component in corotation with the bucket
- superfluid stationary in laboratory frame

intermediate



- Cluster of vortex lines $0<N<N_{max}$

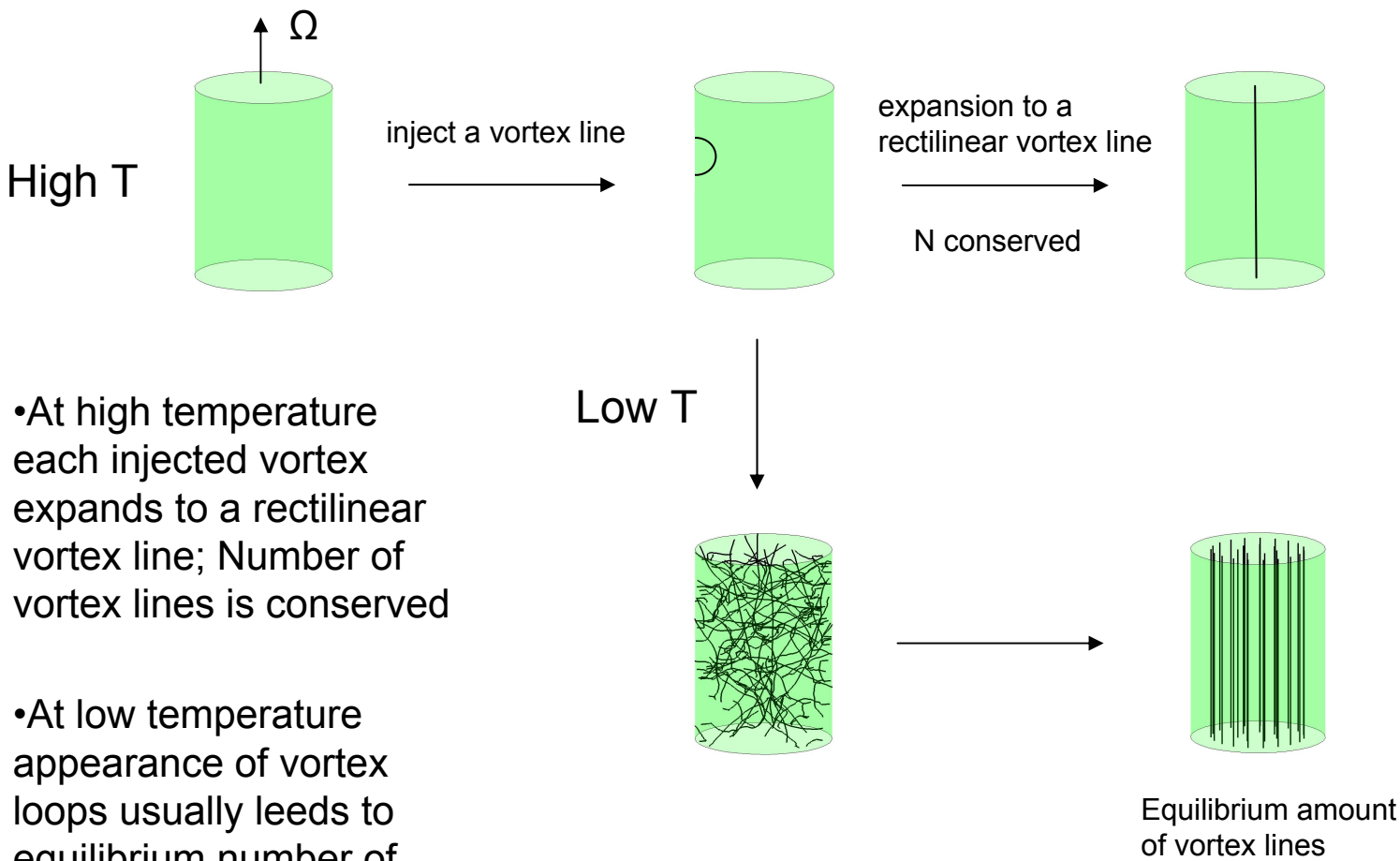
solid-body rotation



- minimum energy state
- superfluid mimics solid-body rotation
- total number of vortex lines:

$$N = \pi R^2 \frac{2\Omega}{\kappa}$$

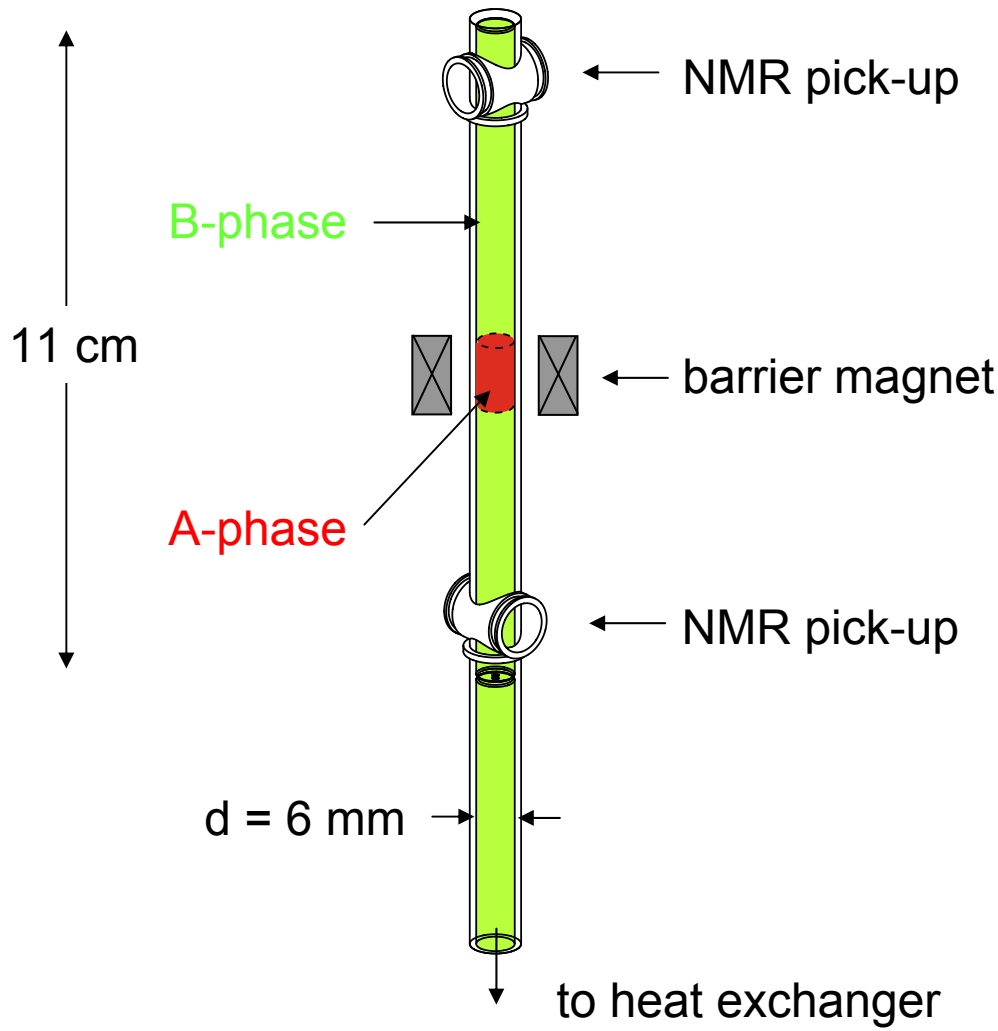
Overview of Experiment



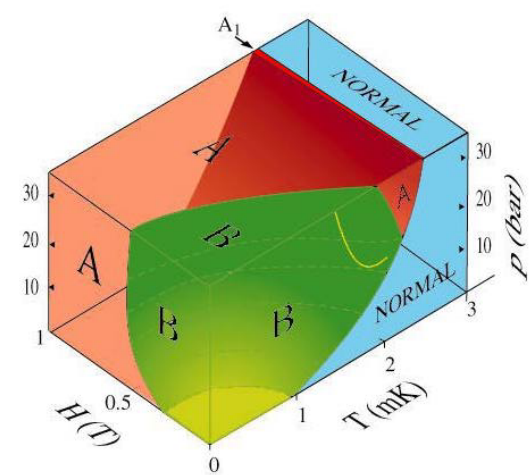
- At high temperature each injected vortex expands to a rectilinear vortex line; Number of vortex lines is conserved

- At low temperature appearance of vortex loops usually leeds to equilibrium number of vortex lines

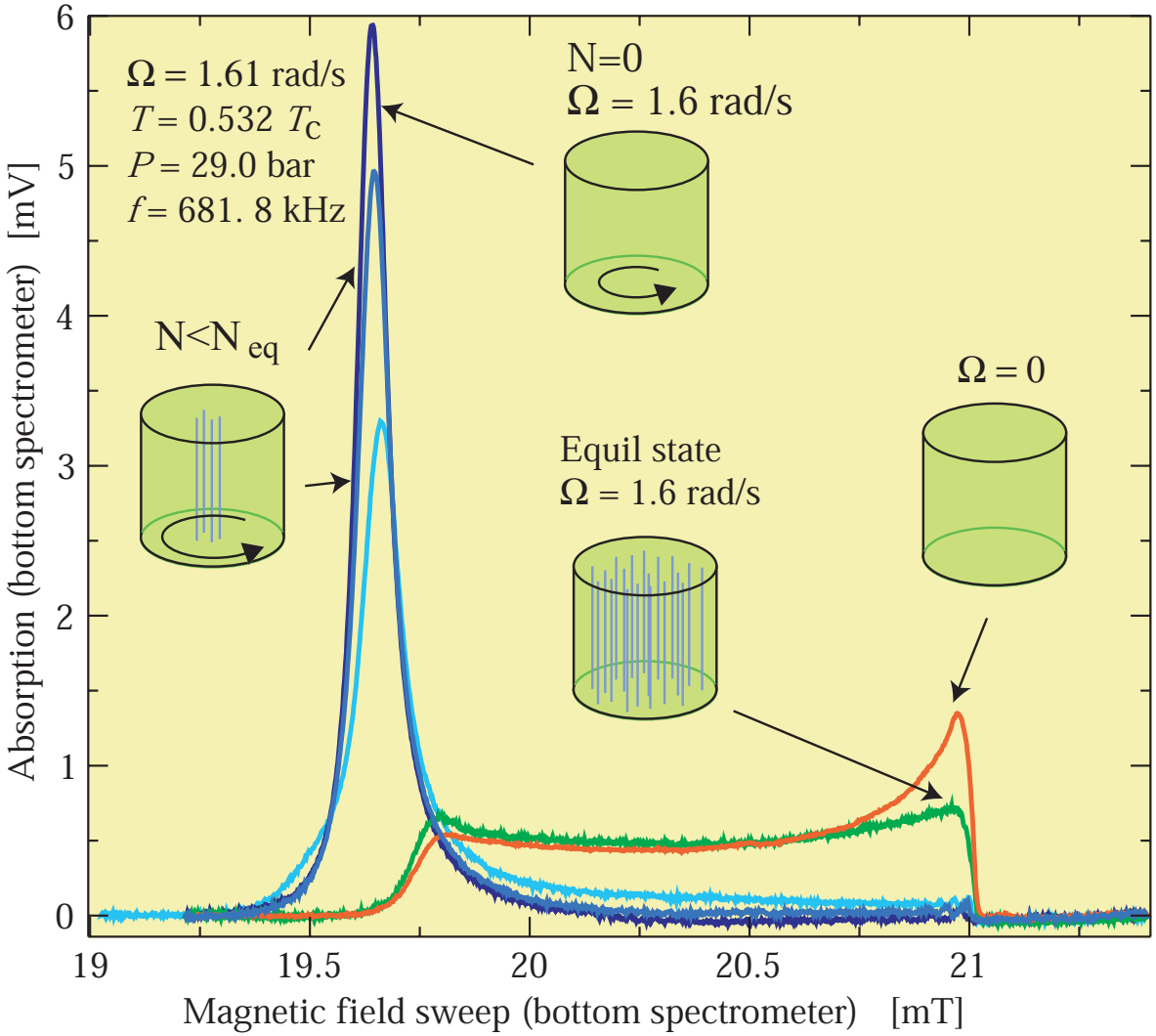
Experimental setup



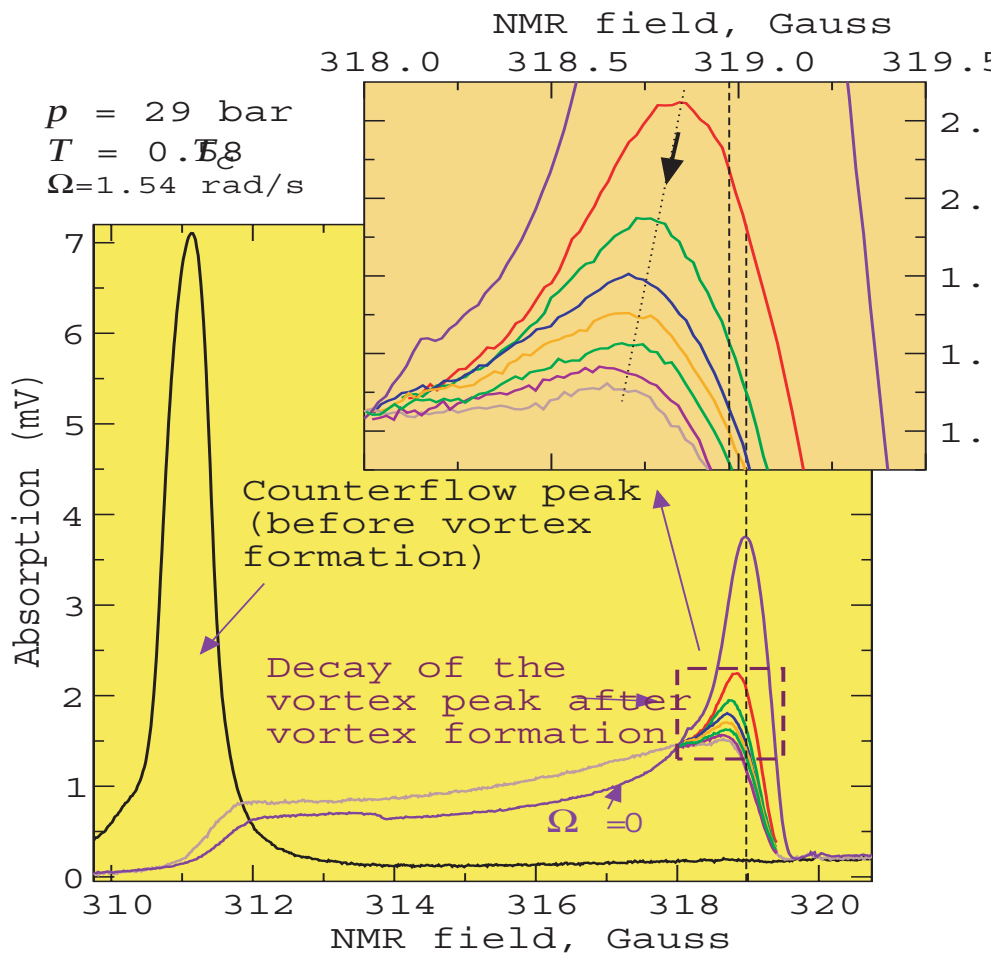
- Two independent NMR spectrometers
- Magnetically stabilized AB phase boundary for vortex line injection



NMR on ^{3}He-B

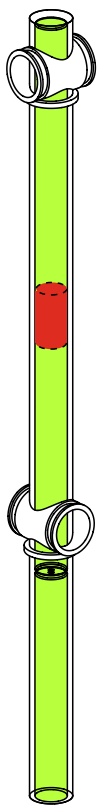

Ω = 1.61 rad/s
T = 0.532 T_C
P = 29.0 bar
f = 681. 8 kHz
N=0
Ω = 1.6 rad/s
N<N eq
Ω = 0
Equil state
Ω = 1.6 rad/s
Absorption (bottom spectrometer) [mV]
Magnetic field sweep (bottom spectrometer) [mT]
0
1
2
3
4
5
6
19
19.5
20
20.5
21

Spectra of turbulent events

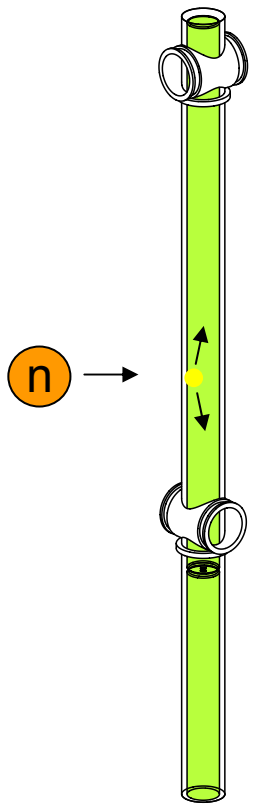


Mechanisms for vortex injection

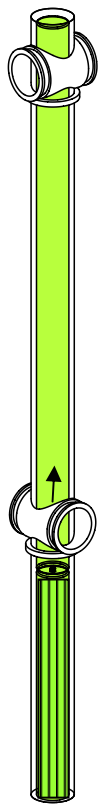
Shear-flow instability of AB interface



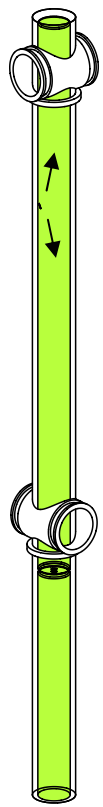
Kibble-Zurek after neutron capture



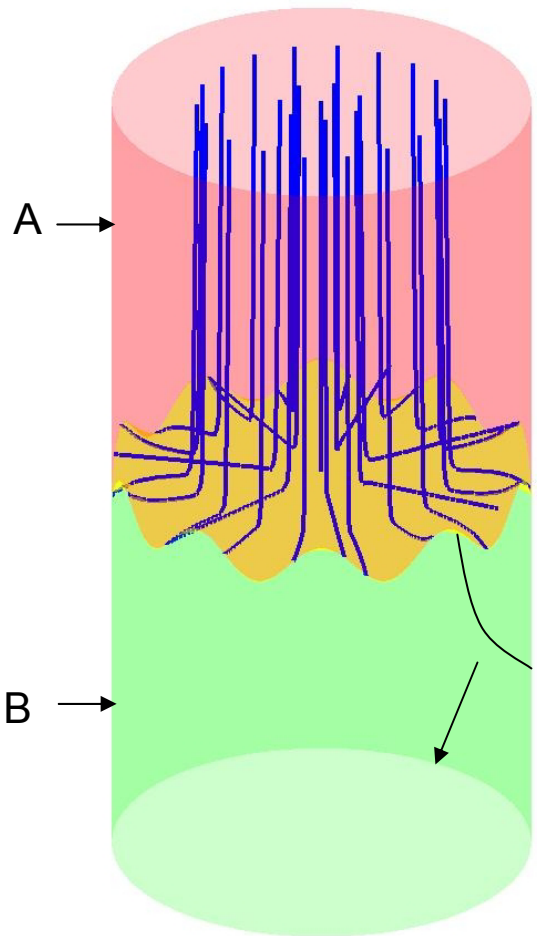
Flow through orifice



Wall defect



Shear-flow instability of the AB phase boundary

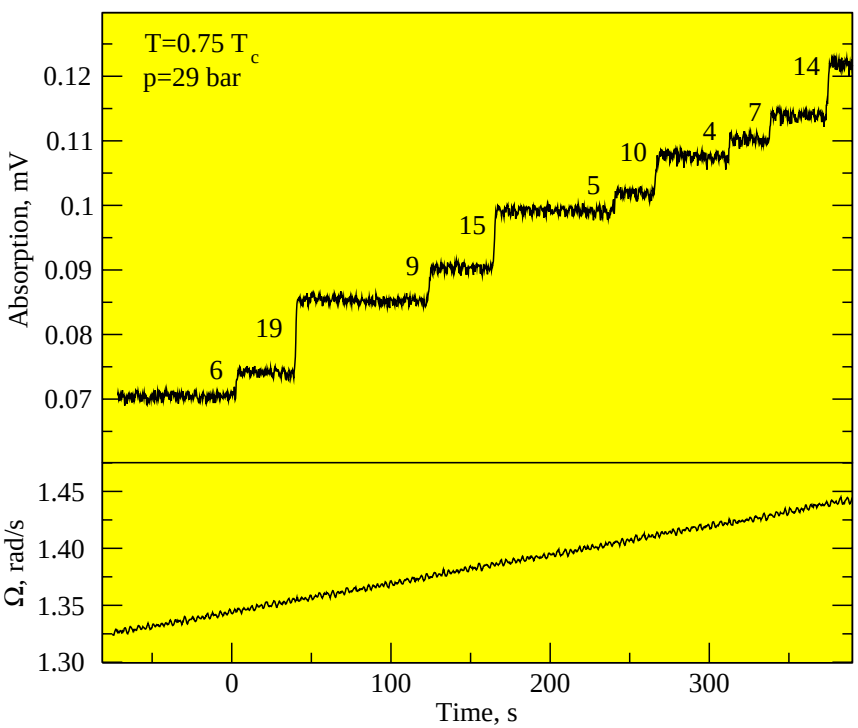


- A phase has low Ω_c and B phase high Ω_c
  - A mimics solid body rotation
  - B does not move
- Under rotation a velocity difference between the superfluids forms, ”wind”
- Phase boundary becomes unstable and vortex lines are injected in the B phase
- Number of vortex lines injected N~10
- Velocity where vortex lines are injected can be tuned with magnetic field

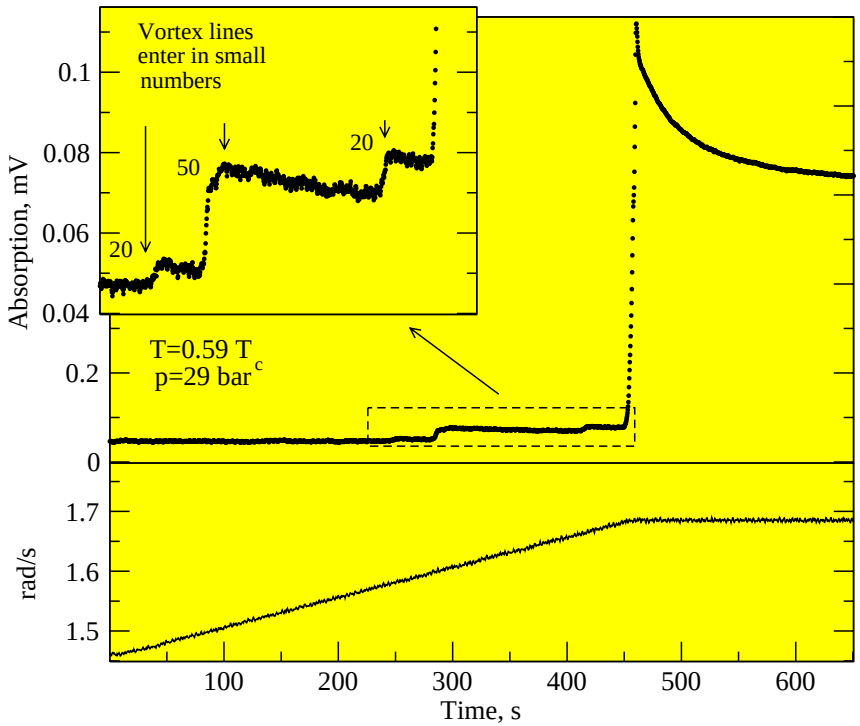
On thursday:
Vladimir Eltsov,
Instability of interface between two sliding superfluids and vortex formation

Vortex formation at high T

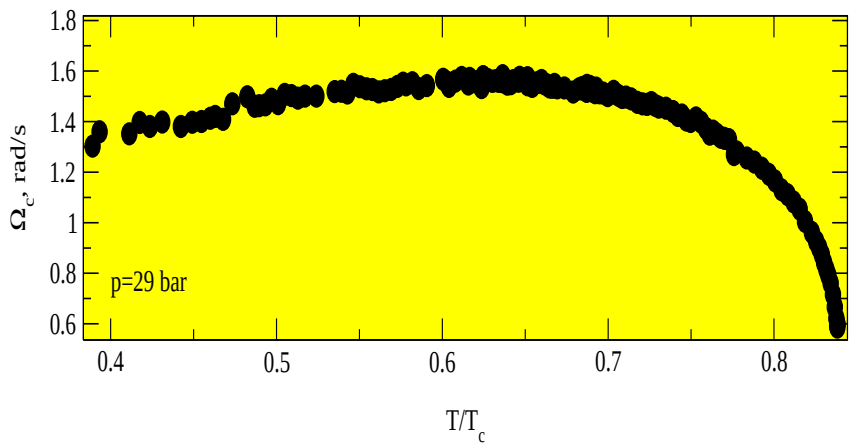
High T



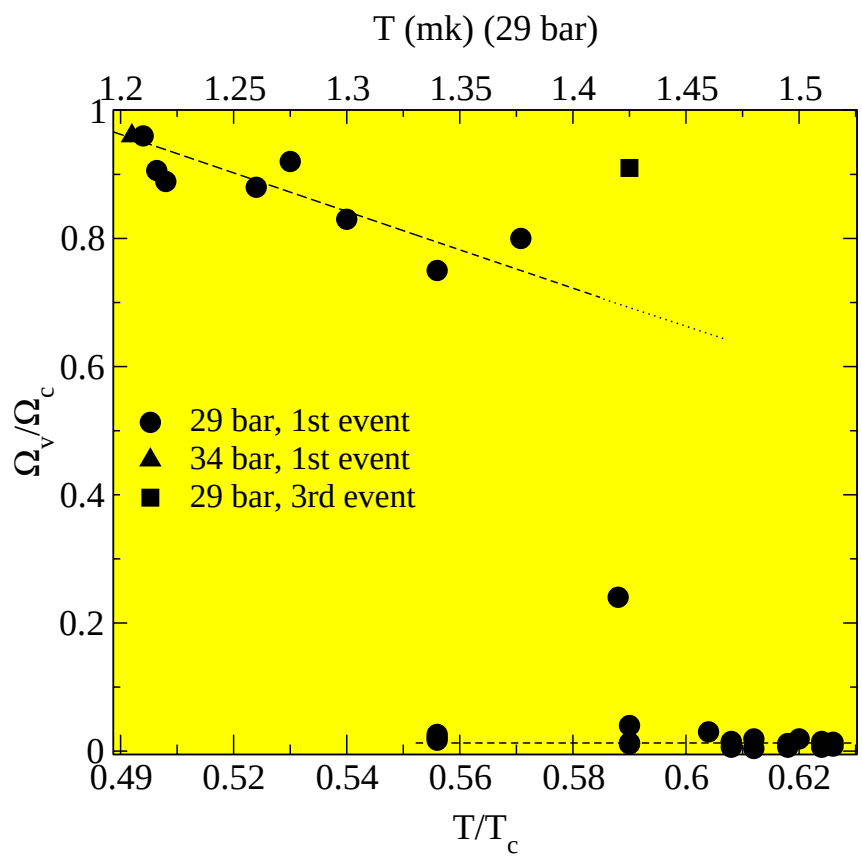
Transition regime



Number of vortex lines per event as a function of T



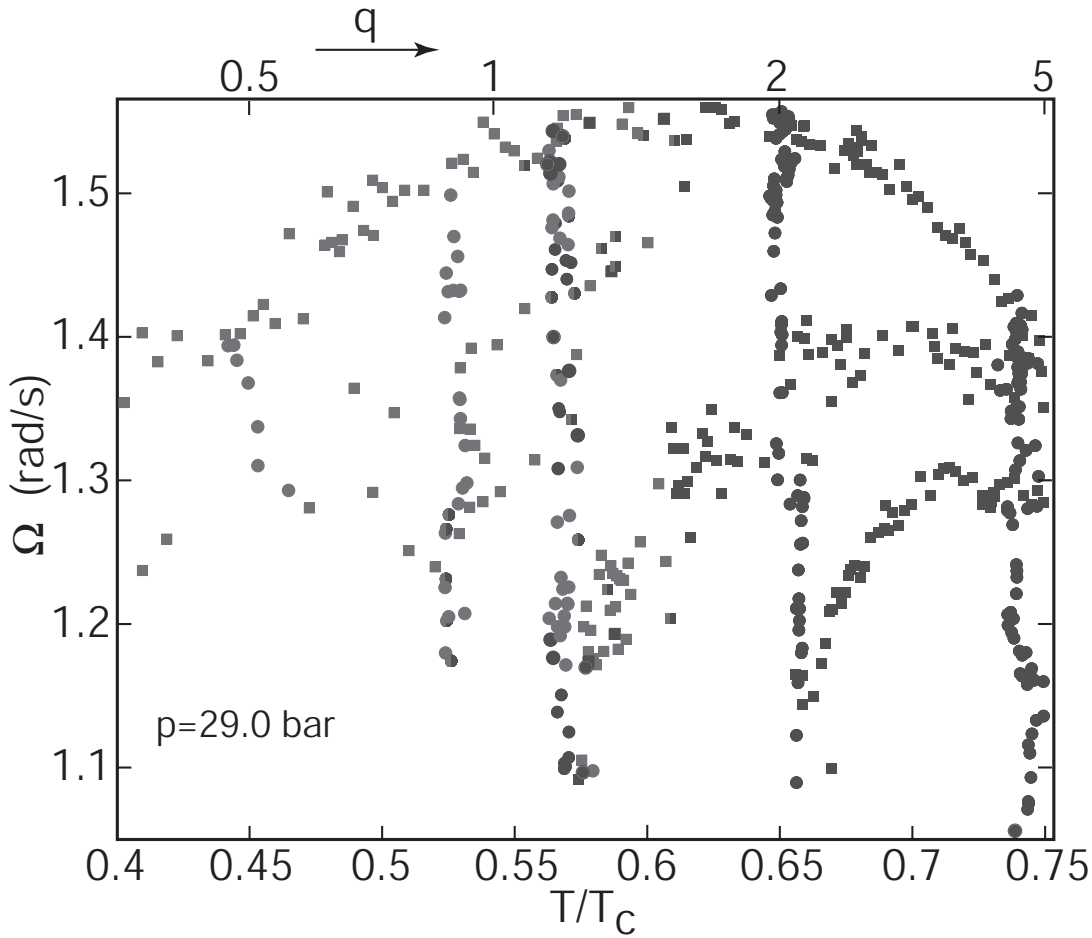
Rotation velocity of Kelvin-Helmholz instablity $I_{barrier}$=8 A



Calibrated number vortex lines as a function of temperature after injection using K-H instability

Transition to turbulence

- Start with vortex-free rotation
- Inject vortex lines using K-H instability of AB boundary at varying rotation velocities and temperatures
- Categorize results according to the final number of vortex lines:
  - A small number
  - Almost equilibrium amount



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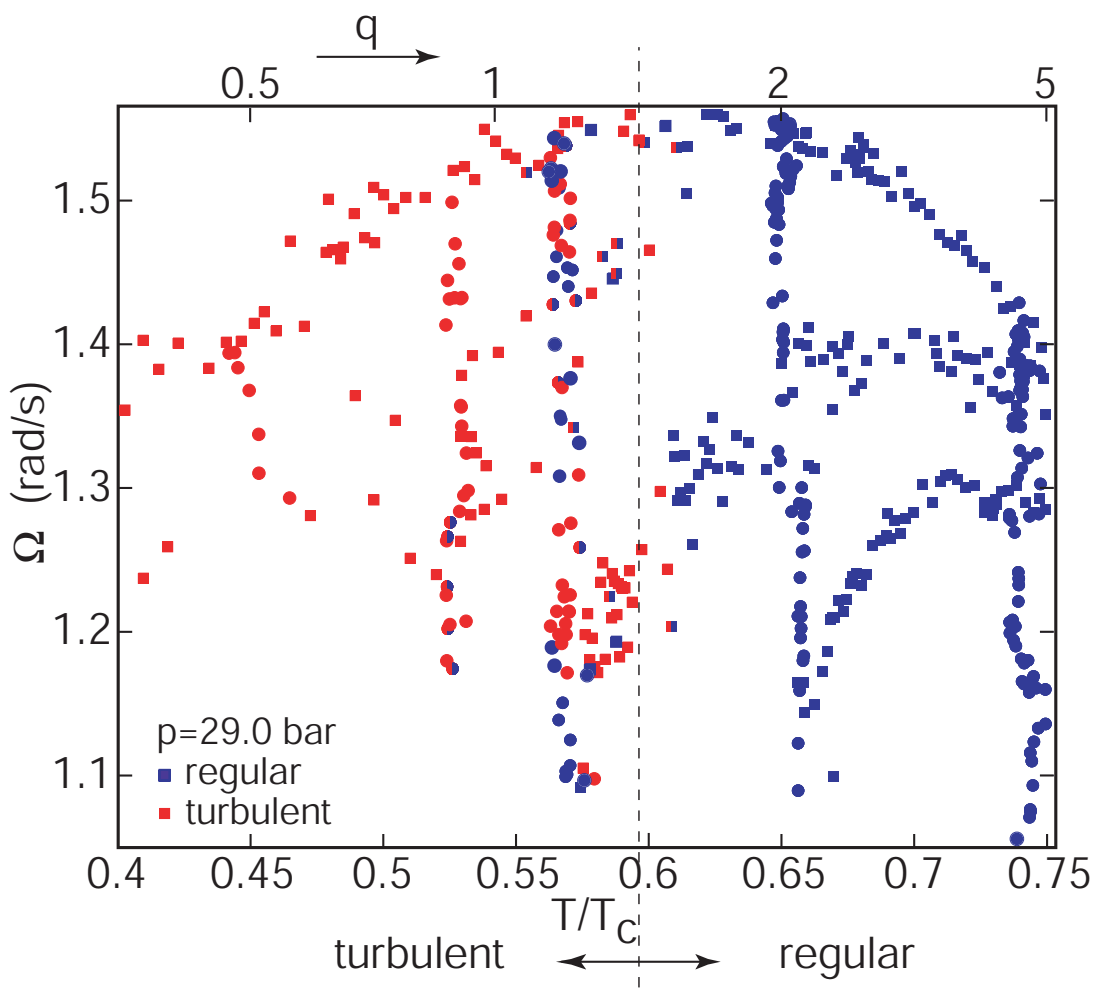


Velocity independent?

For classical liquids, taking $\omega = \nabla \times v$

$$\frac{\partial \omega}{\partial t} = \nabla \times [v \times \omega] + v \nabla \omega$$

inertial ~ Uω/R

viscous~vω/R^2

$$\frac{\text{inertial}}{\text{viscous}} = Re = UR/v > 1 \longrightarrow \text{turbulence}$$

For superfluids with v_n=0, Re_s=UR/κ >1 and $\omega_s = \langle \nabla \times v_s \rangle$ averaged over vortex lines

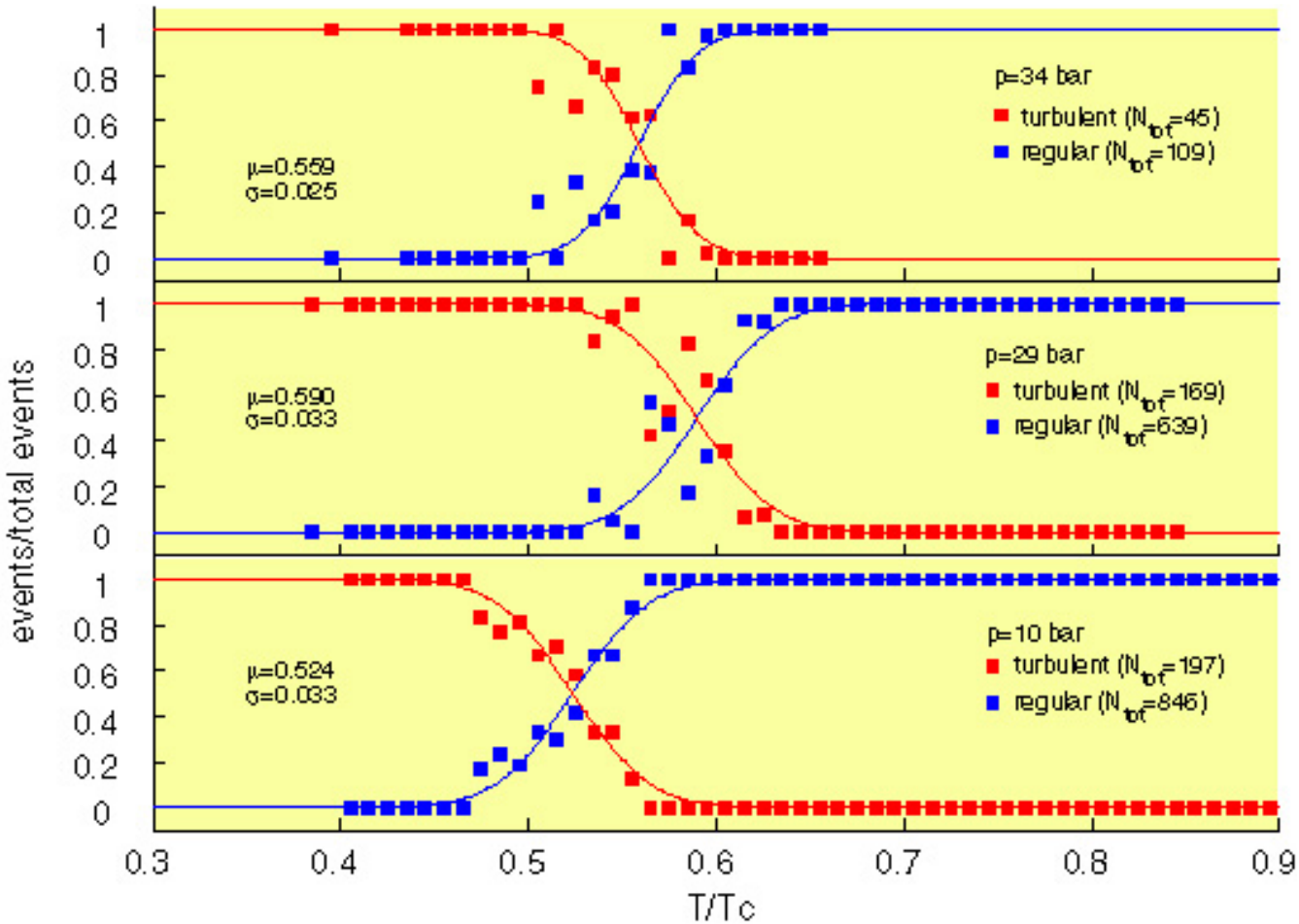
$$\frac{\partial \omega_s}{\partial t} = (1-\alpha')\nabla \times [v_s \times \omega_s] + \alpha \nabla \times [\hat{\omega}_s \times (\omega_s \times v_s)]$$

inertial ~ (1-α')Uω/R

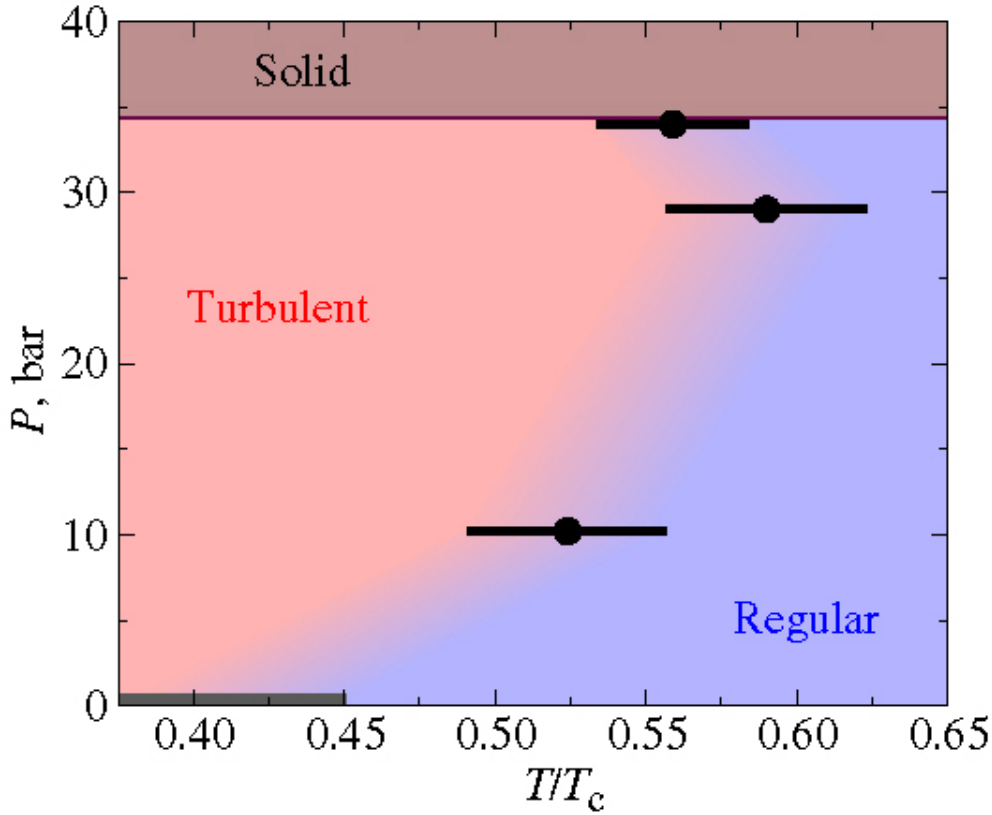
viscous~αUω/R

$$\frac{\text{inertial}}{\text{viscous}} = \frac{1-\alpha'}{\alpha}$$

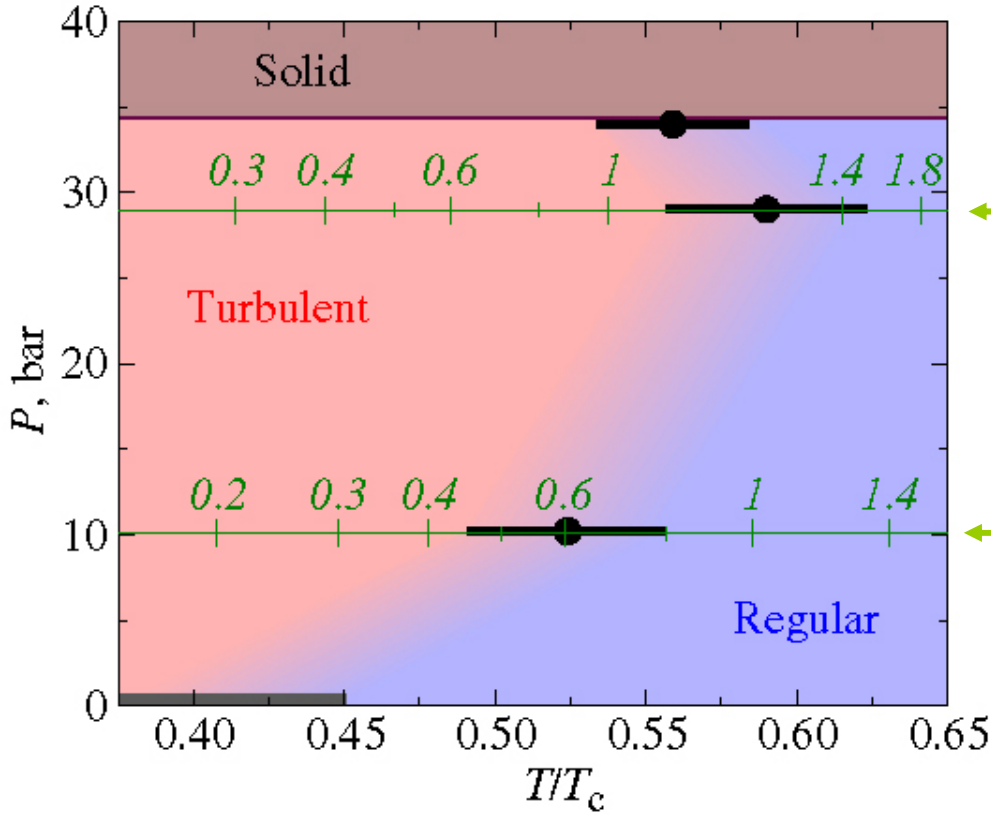
Pressure dependence



Turbulence at high flow



Turbulence at high flow

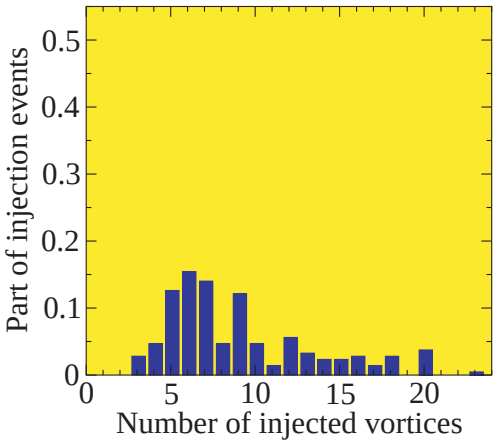


$\frac{\alpha}{1-\alpha'}$

from Bevan *et al.*

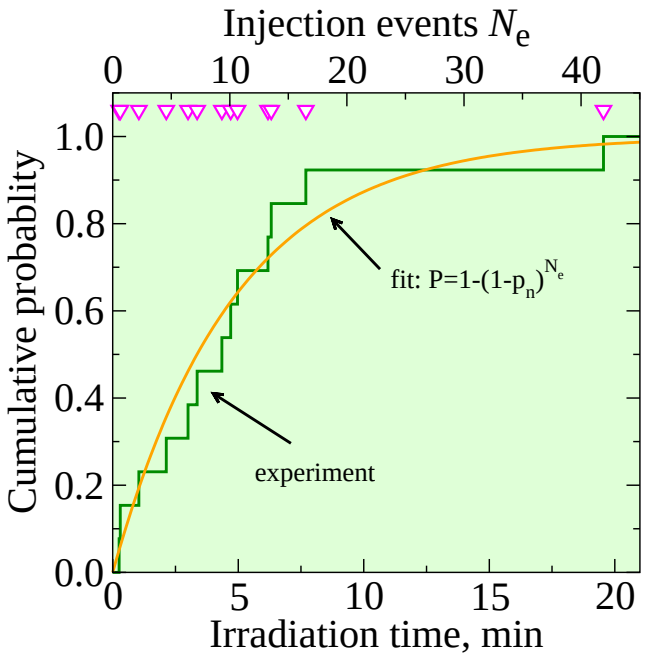
Initial configuration

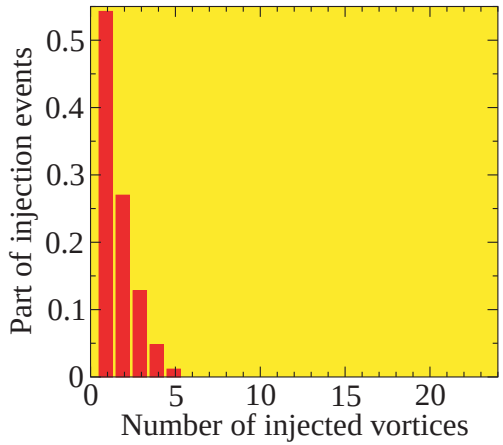
AB



Propability of turbulence after injection through AB boundary at T=0.53 T_c P_{AB}=0.96 (0.8<Ω<1.6 rad/s)

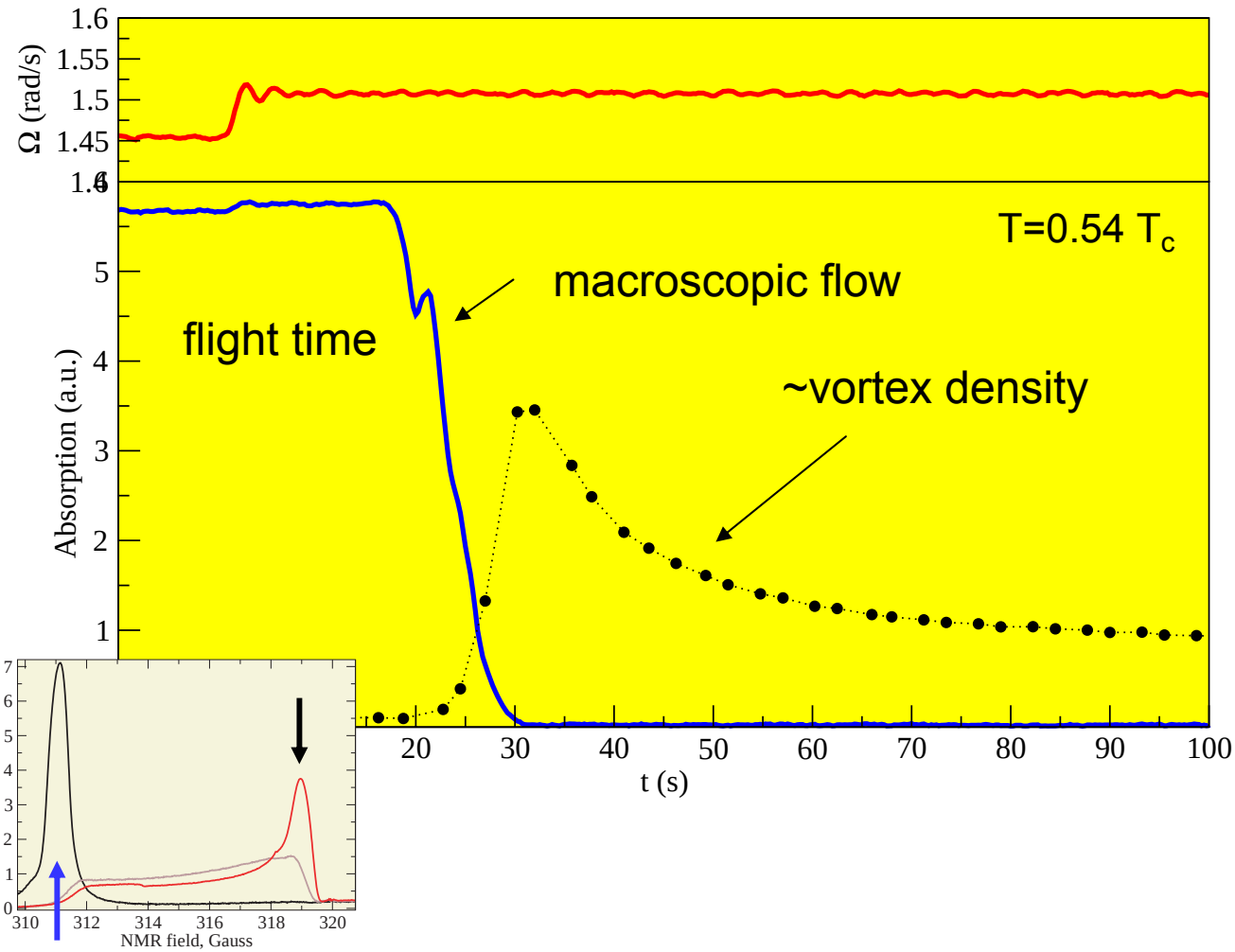
Neutron

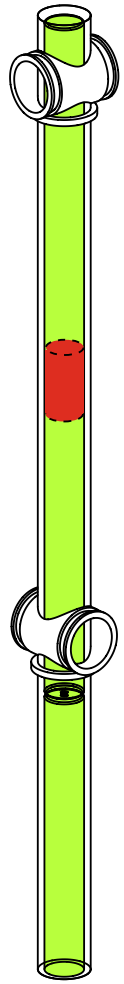




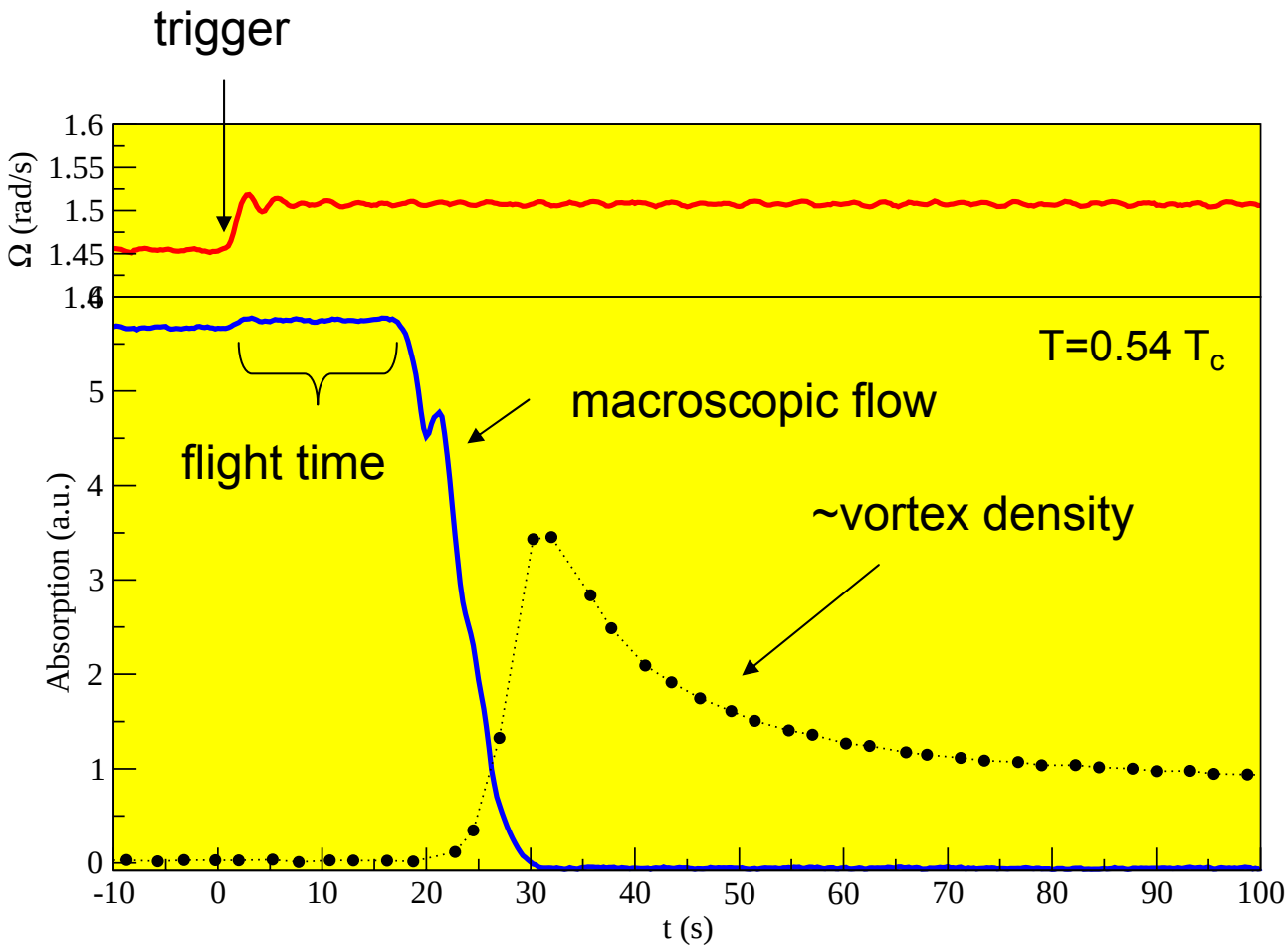
Propability of turbulence after injection through AB boundary at T=0.53 T_c P_n=0.09 (Ω=3.32 rad/s)

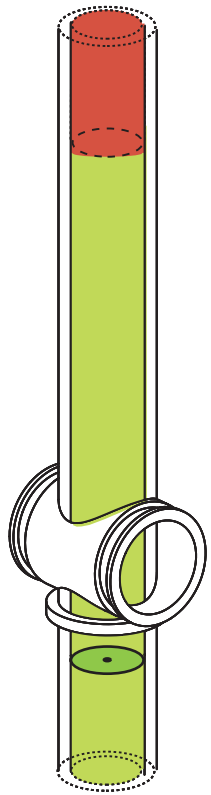
Experiment


Ω (rad/s)
1.6
1.55
1.5
1.45
1.4
Absorption (a.u.)
5
4
3
2
1
T=0.54 T$_c$
macroscopic flow
flight time
~vortex density
20
30
40
50
60
70
80
90
100
t (s)
Absorption (mV)
7
6
5
4
3
2
1
0
310
312
314
316
318
320
NMR field, Gauss

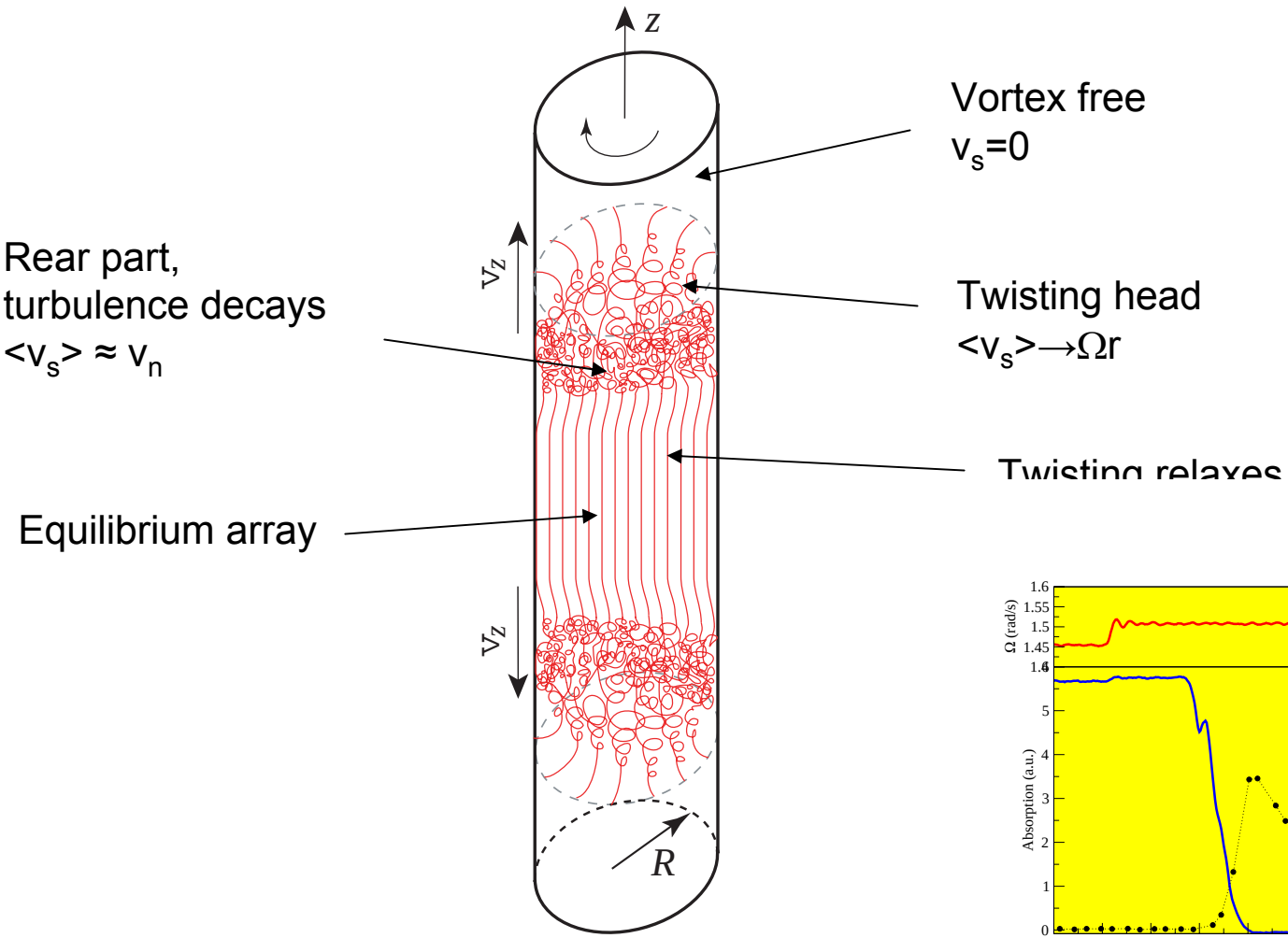


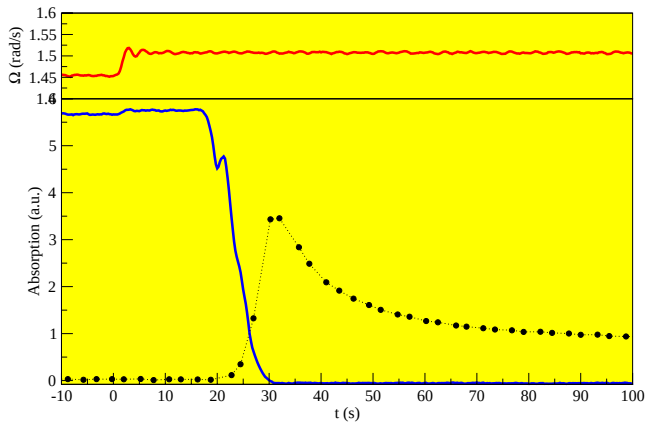
Experiment


trigger
Ω (rad/s)
1.6
1.55
1.5
1.45
1.4
T=0.54 T_c
macroscopic flow
flight time
~vortex density
Absorption (a.u.)
6
5
4
3
2
1
0
-10
0
10
20
30
40
50
60
70
80
90
100
t (s)

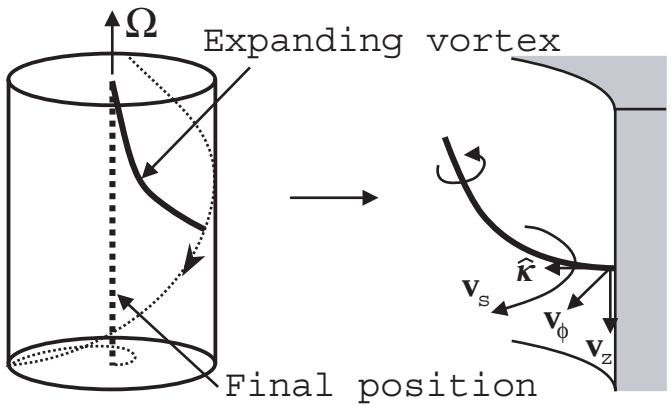


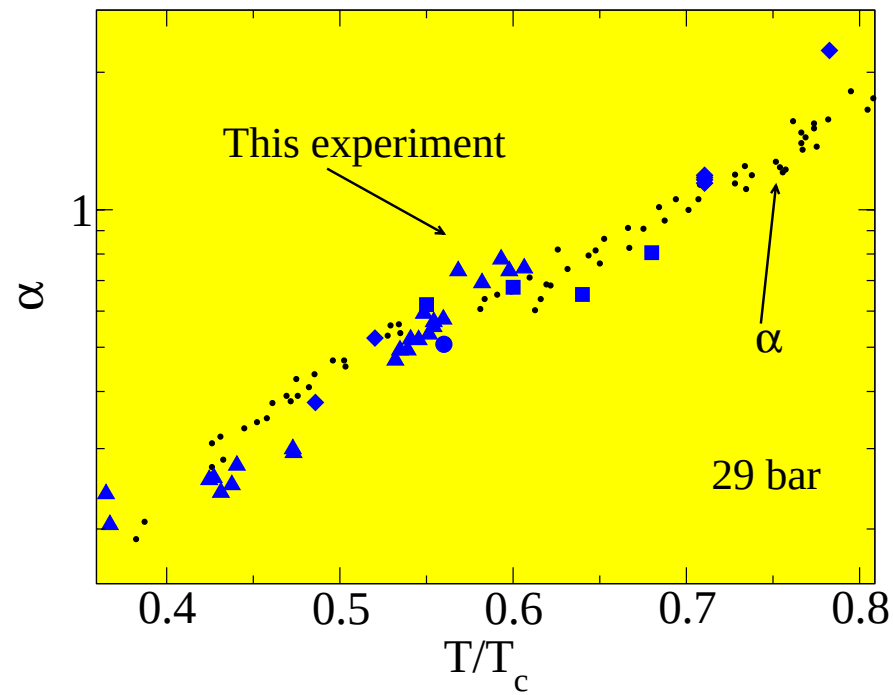
Structure of advancing vortex configuration





Movement of the turbulent front

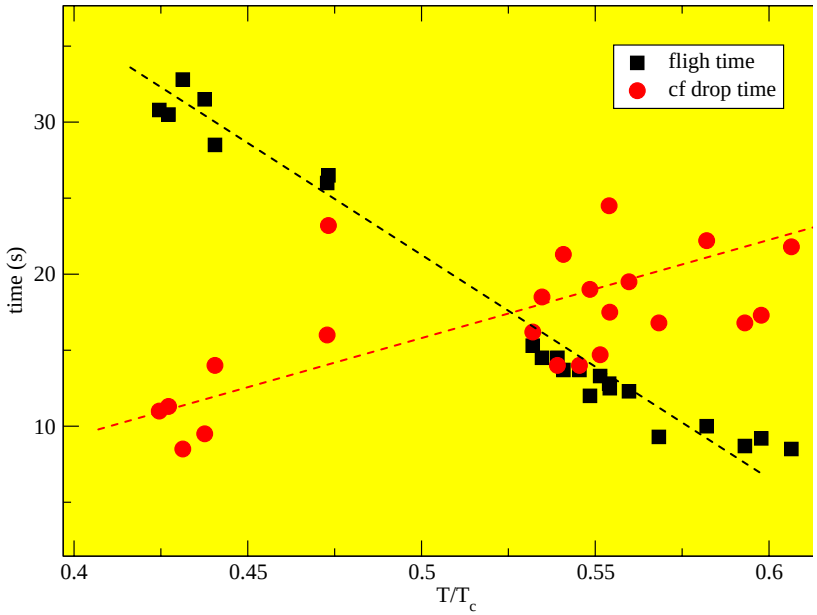




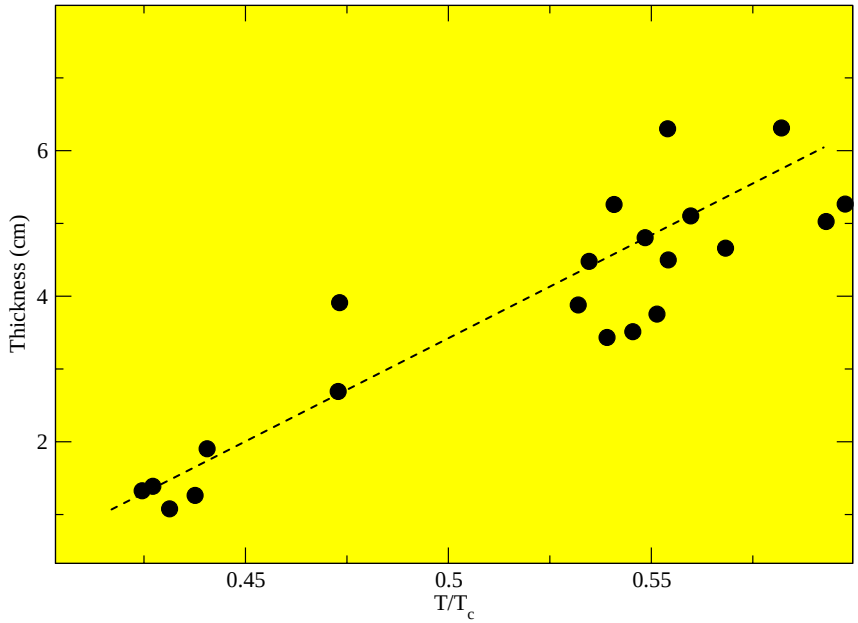
- The speed at which the turbulence expands to the vortex free counterflow

$$v_z = \Omega R \alpha$$

Twisting head

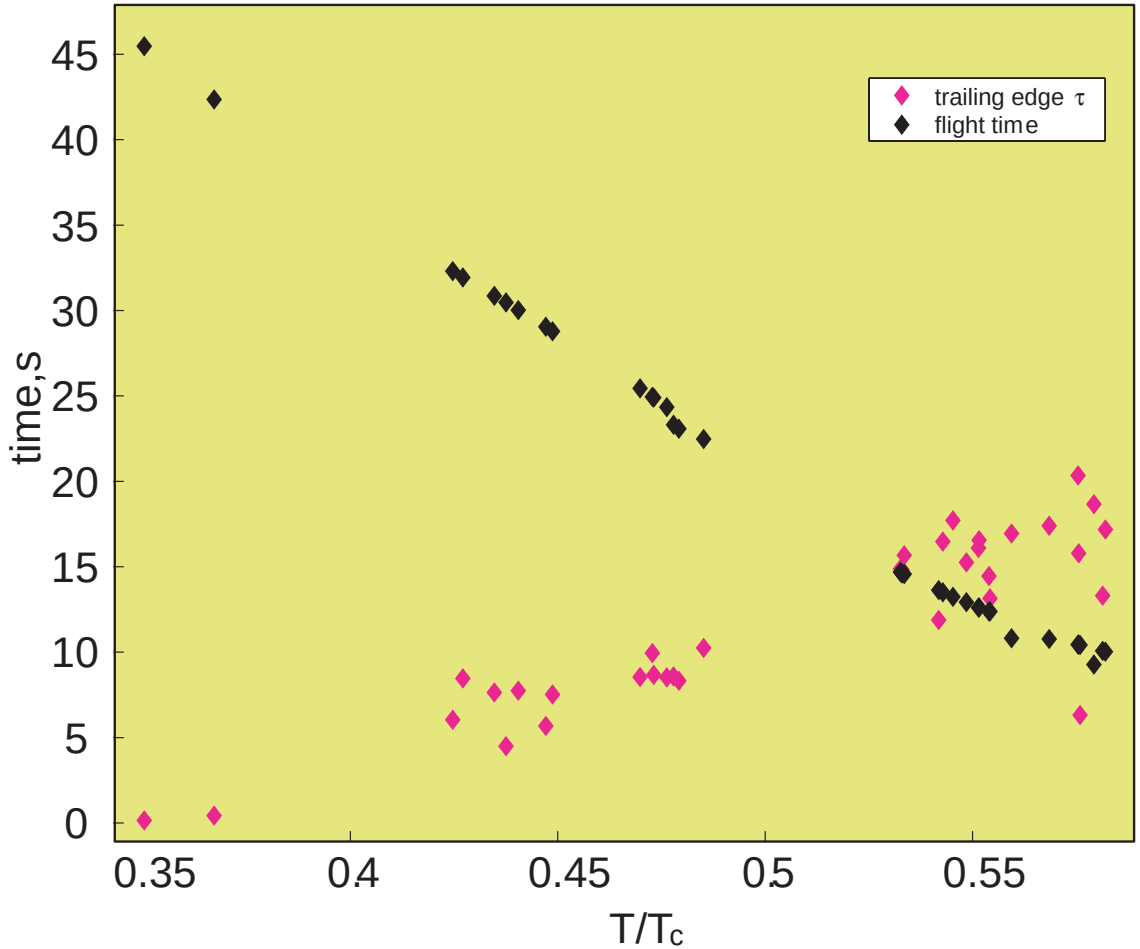


Time of flight and time it takes for the counter flow to disappear as a function of temperture.

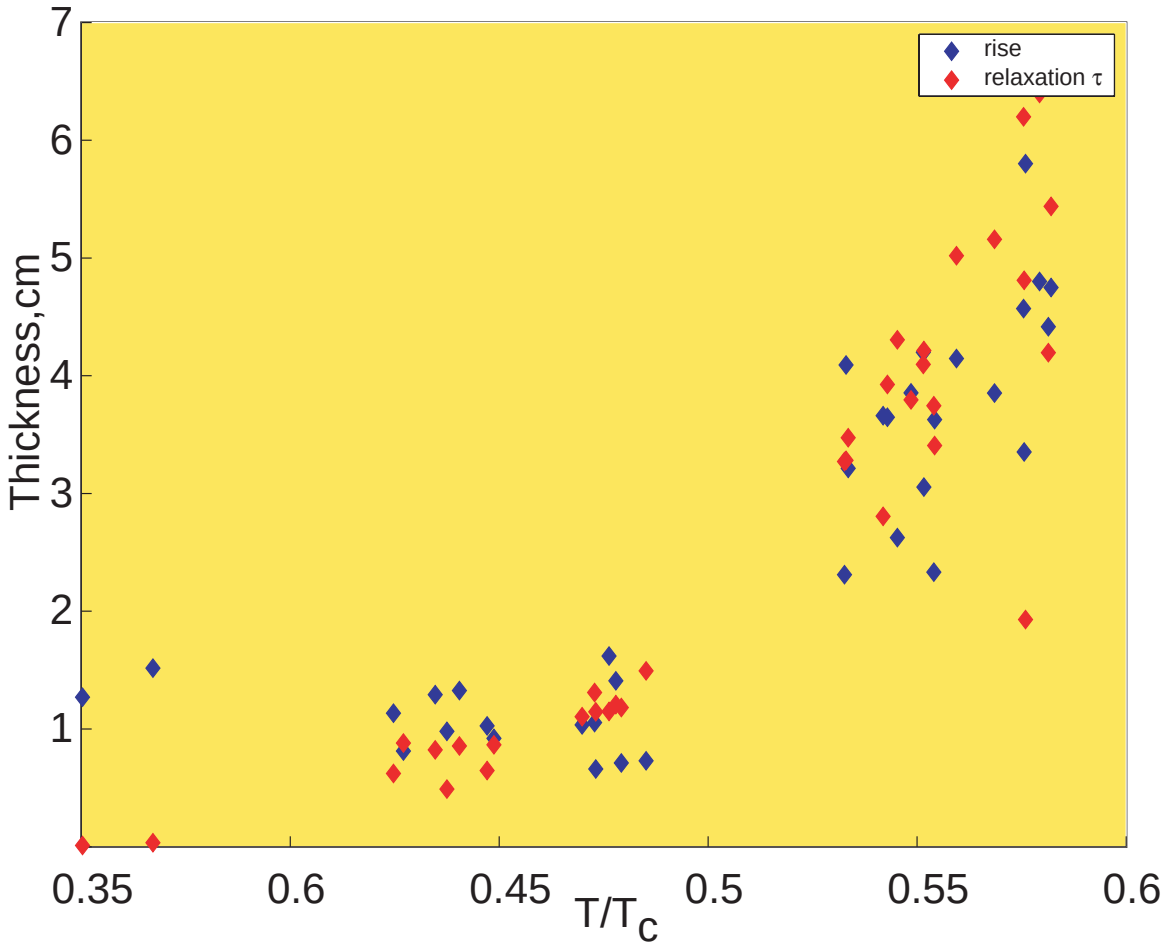


Thickness assuming velocity $v_z=\alpha\Omega R$

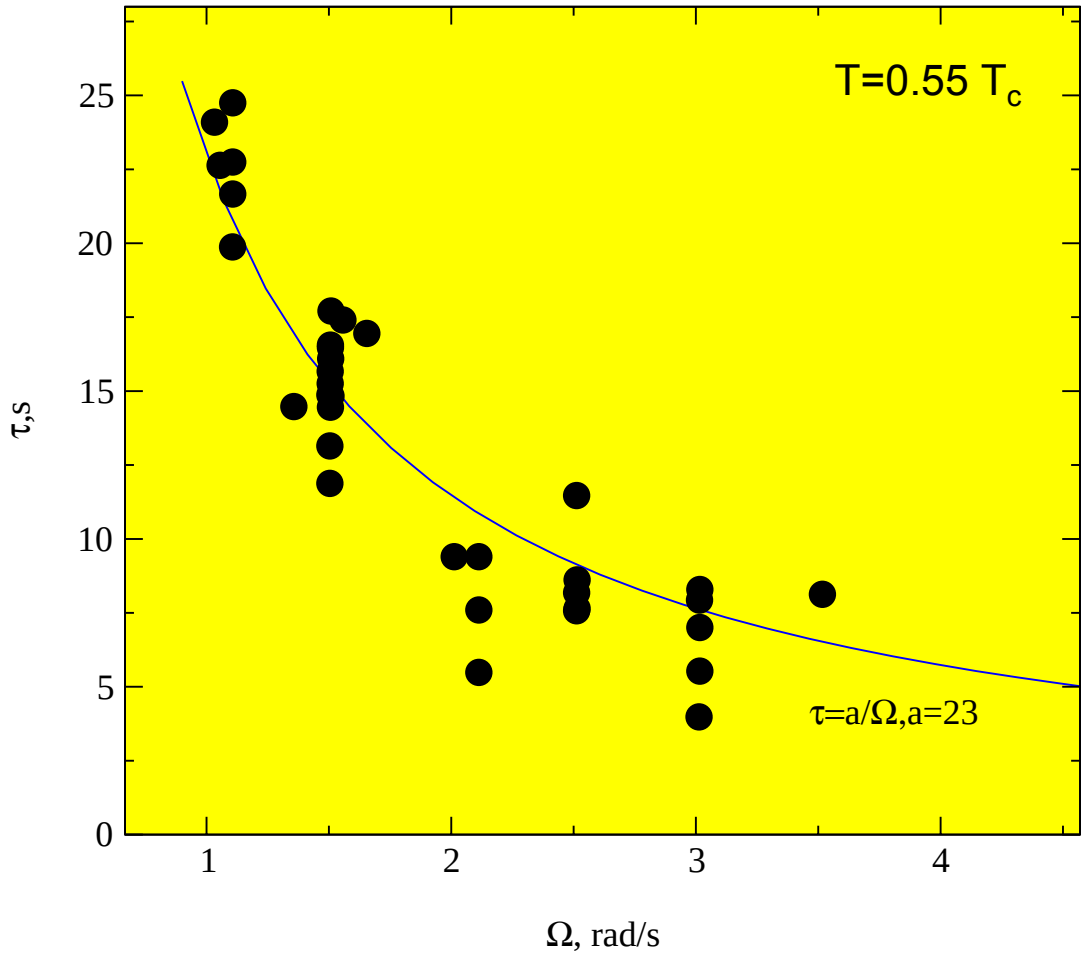
Trailing edge τ as a function of T



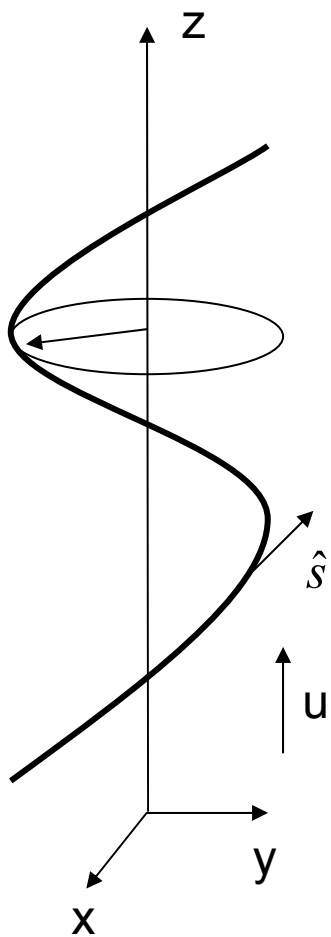
Layer thickness



Trailing edge τ as a function of Ω



Kelvin waves



The motion of vortex lines is described by the equation

$$v_L = v_s + \alpha \hat{s} \times (v_n - v_s) - \alpha' \hat{s} \times [\hat{s} \times (v_n - v_s)]$$

Consider a displacement from the undisturberd line

$$l(z) = \xi(z)\hat{x} + \eta(z)\hat{y} + z\hat{z}$$

for wavelike solutions the dispersion relation will be

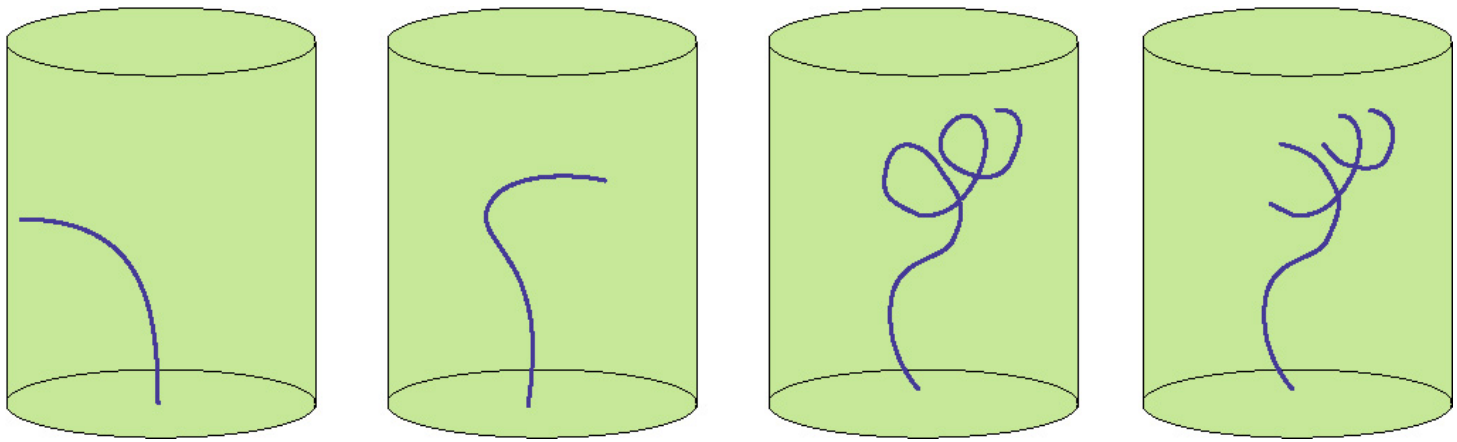
$$\omega = \nu k^2 - \alpha'(\nu k^2 - ku) + i\alpha(\nu k^2 - ku)$$

Modes that are excited exponentially:

$$k < k_{\max} = \frac{u}{\nu}$$

$$\nu = \frac{\kappa}{4\pi} \ln \frac{r}{a}$$

Kelvin wave instability of curved vortex lines



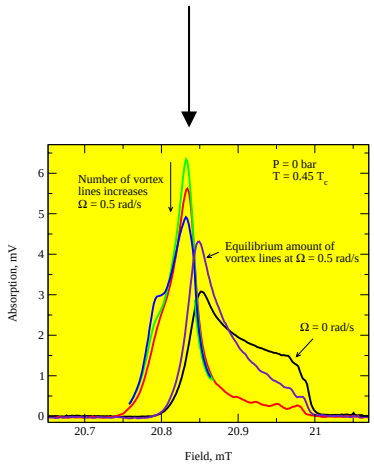
1. Injection and expansion

2. Orientation along the flow

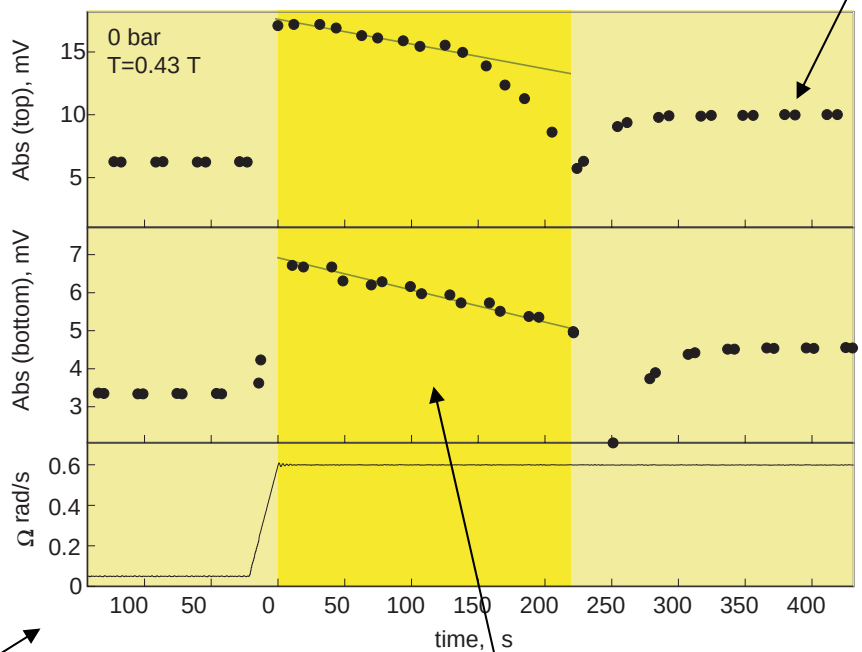
3. Kelvin-wave instability excited

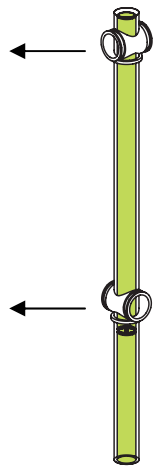
4. Growth of Kelvin waves and reconections

Slow vortex formation from Kelvin waves



Equilibrium number of vortex lines

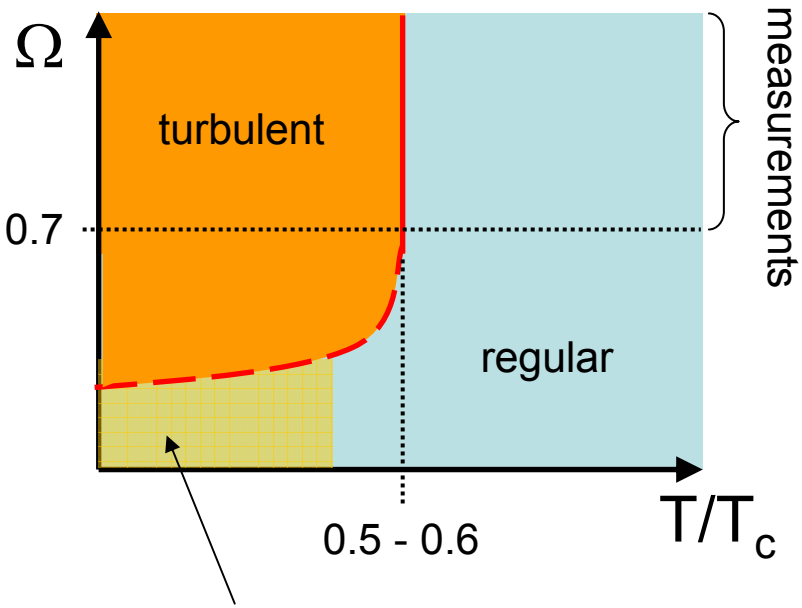




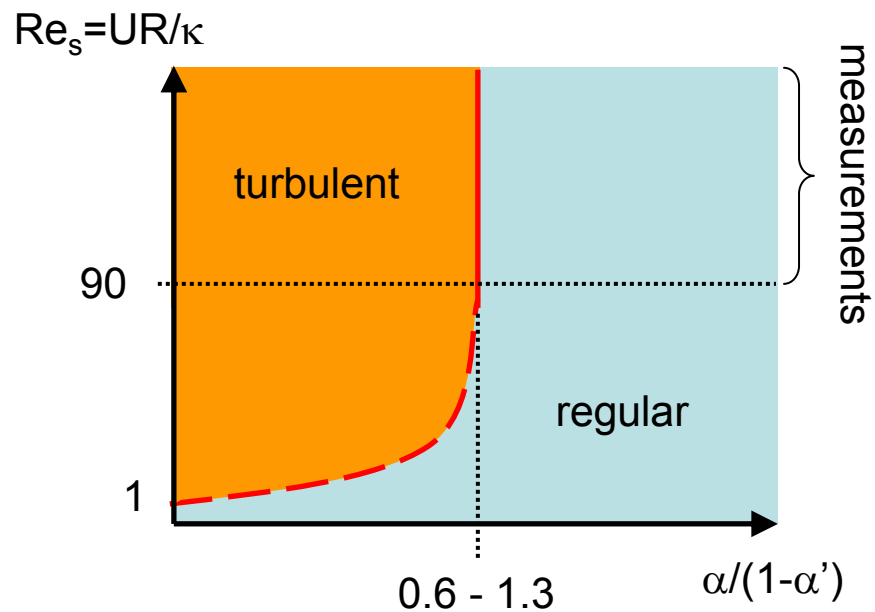
Initially 0.05 rad/s of vortex lines

Slow increase in the number of vortex lines

Conclusions I
transition to turbulence in ^{3}He-B



Curved vortex lines
in flow unstable



Conclusions II

- Two clear regimes in ^{3}He-B: laminar when $\alpha/(1-\alpha')>1$ and turbulent when $\alpha/(1-\alpha')<1$.
- In a long column of rotating ^{3}He-B a turbulent layer sweeps away vortex free flow and replaces it with an array of vortex lines.
- The layer moves slower and becomes thinner with decreasing temperature.