Quantum Vortices and Ultracold Neutrons

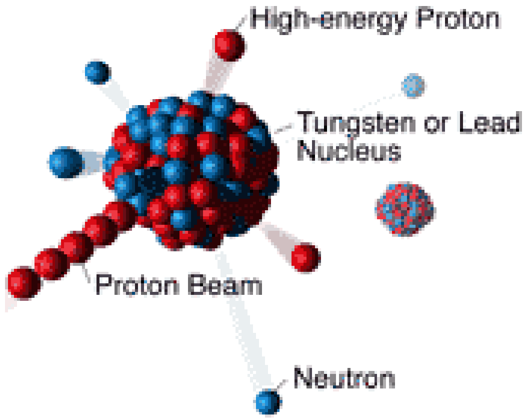
Jeff Martin

The University of Winnipeg

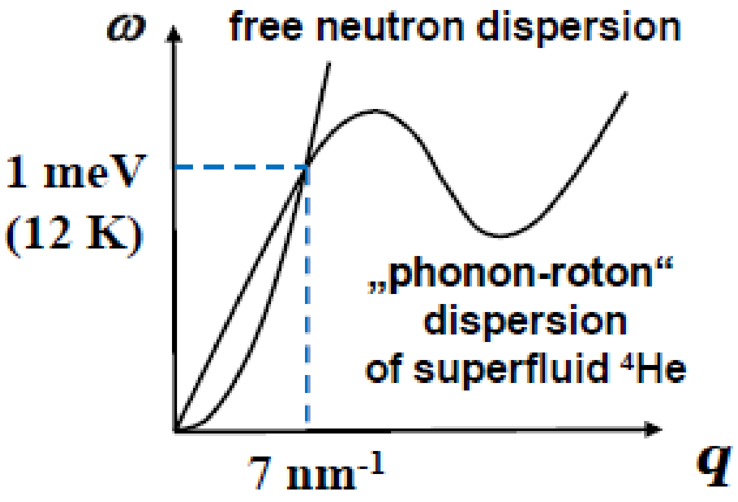
TUCAN Collaboration

Research supported by NSERC, CRC, CFI, JSPS

Spallation-driven superfluid helium UCN source

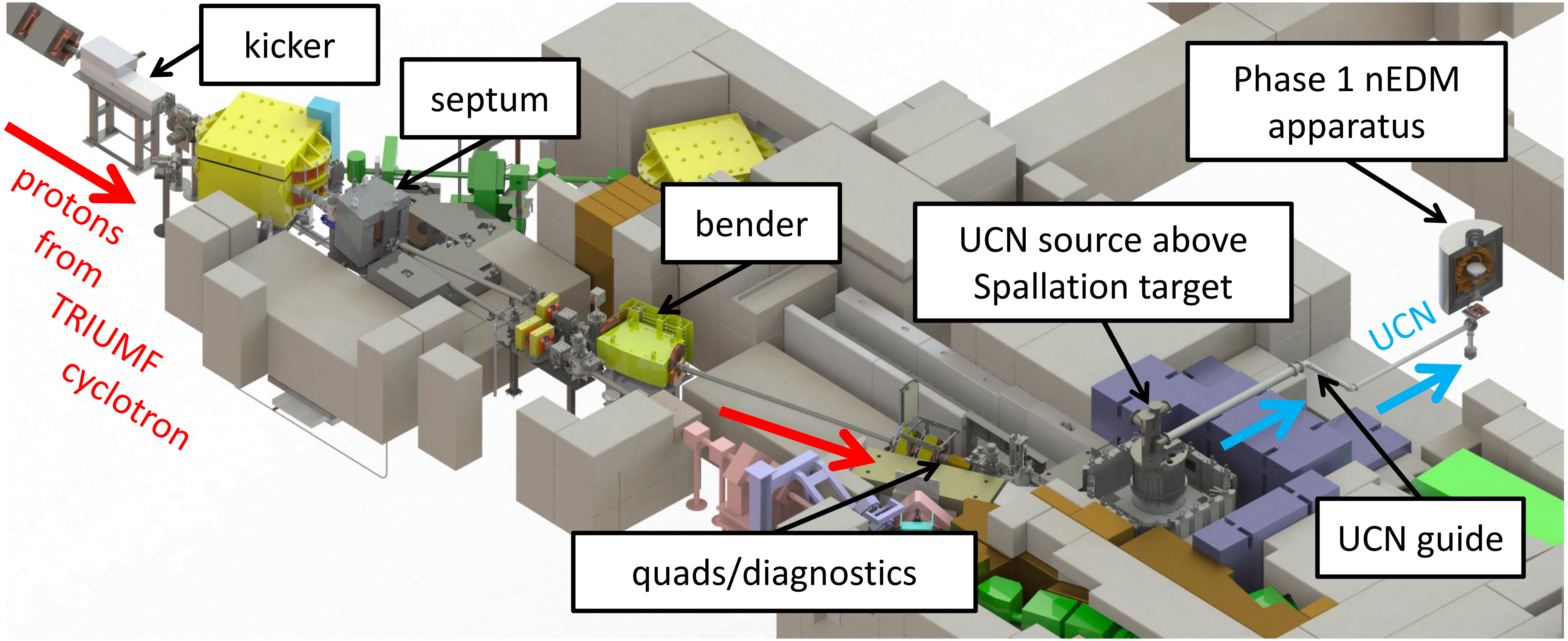


- Spallation produces free neutrons (hot) $T >\sim 1\ \text{MeV} = 10^9\ \text{K}$
- Moderation, reflection (thermal, cold) $T <\sim \frac{1}{40}\ \text{eV} = 300\ \text{K}$
- Downscattering (ultracold) $T < 300\ \text{neV} = 0.003\ \text{K}$
  - Cold neutrons produce phonons in the superfluid (1 K) and lose all their energy
- Transport by neutron guides out to room temperature experiments.



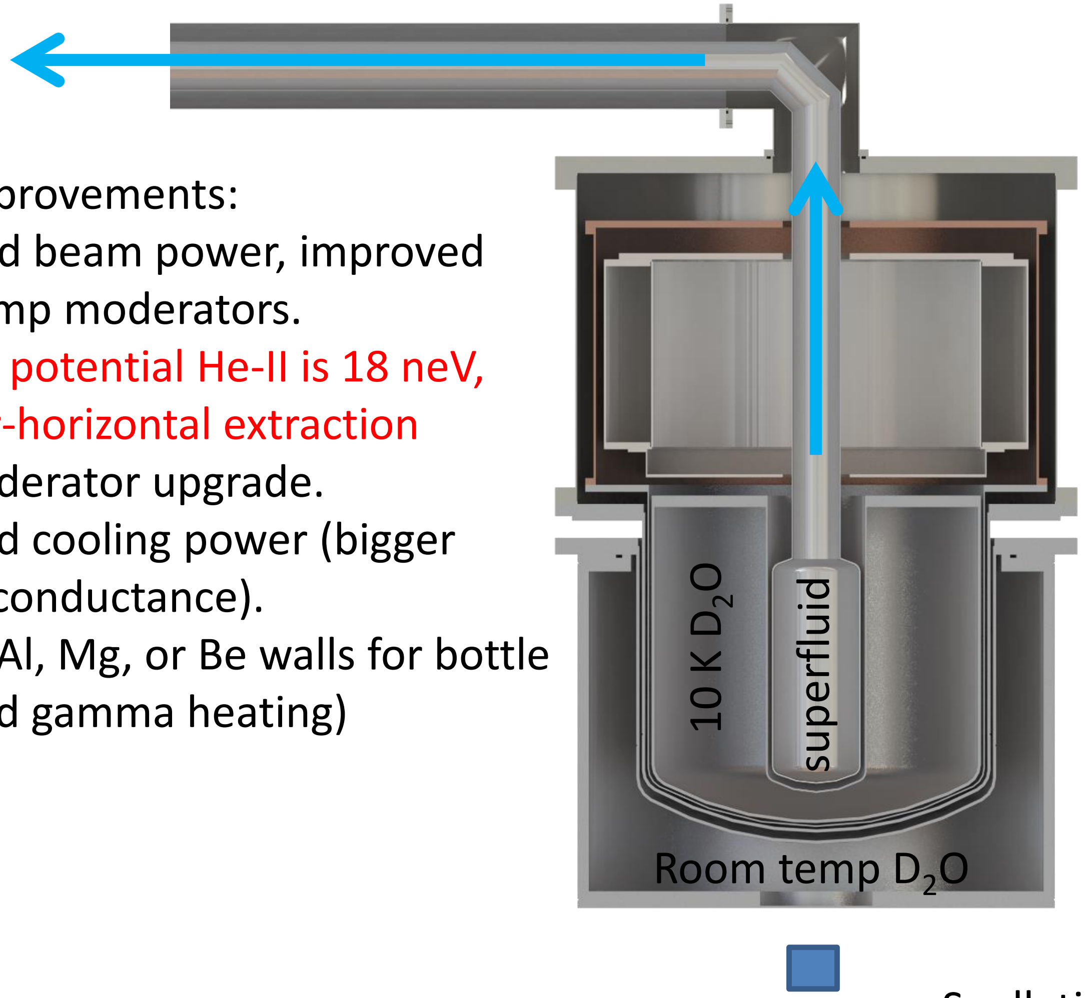
Courtesy O. Zimmer

UCN Facility at TRIUMF - Overview



Facility as of today – shielding blocks removed for clarity.

The UCN source we use today: Vertical He-II UCN source



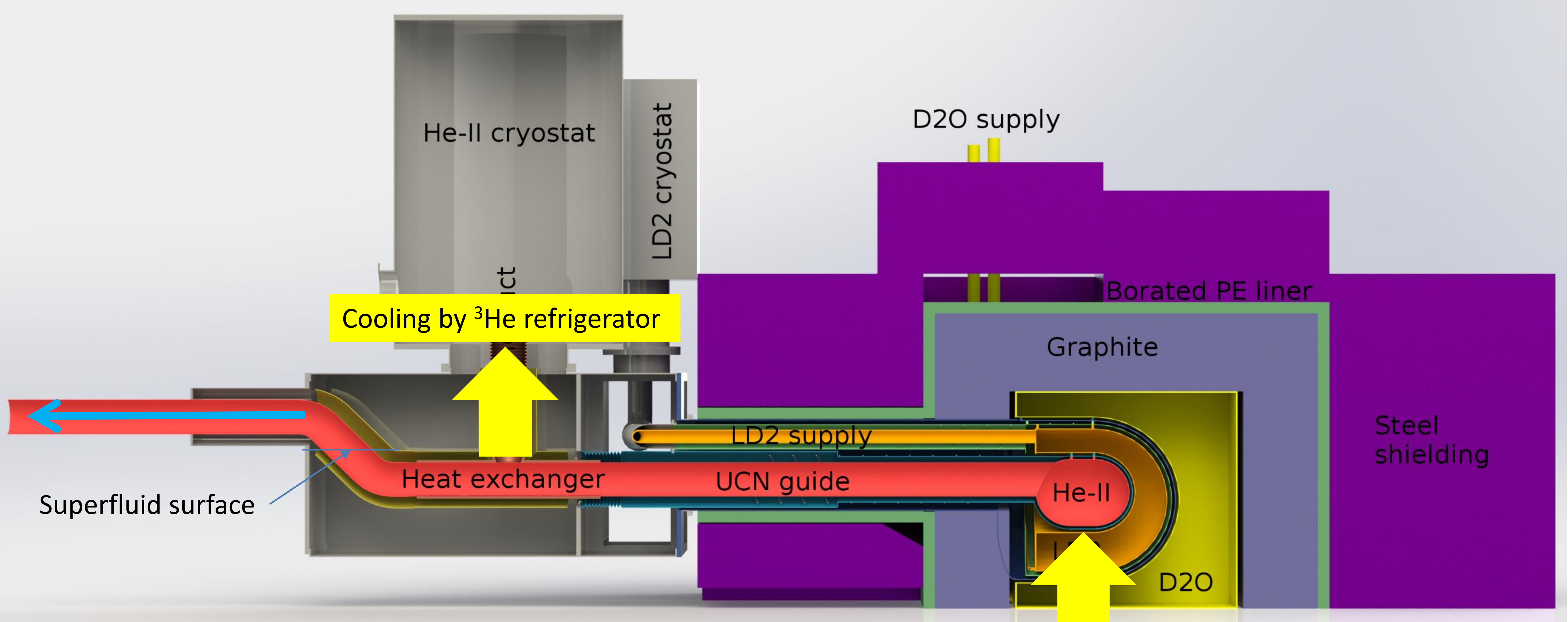
Surrounding graphite, steel not shown

Spallation target/neutron source

Planned improvements:

- Increased beam power, improved room temp moderators.
- Material potential He-II is 18 neV, use near-horizontal extraction
- Cold moderator upgrade.
- Improved cooling power (bigger pumps, conductance).
- Thinner Al, Mg, or Be walls for bottle (beta and gamma heating)

Plan for 2021: New 3rd generation He-II cryostat being built in Japan



Cooling by ^{3}He refrigerator

Superfluid surface

Channel of He-II transports heat.

Heat from spallation target

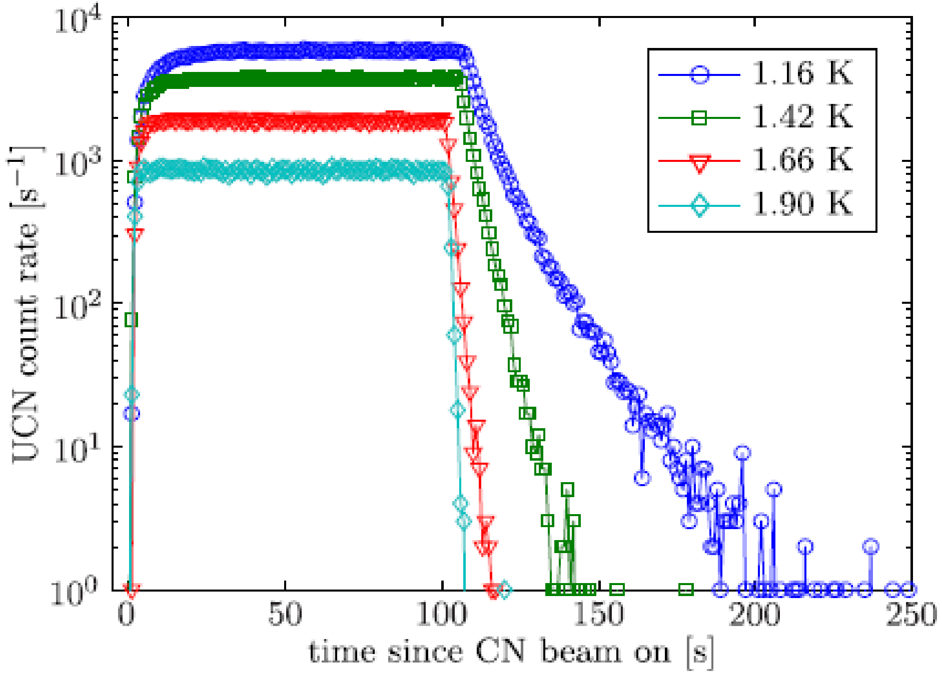
UCN Losses in Superfluid Helium (He-II)

- Key question for this project:
  - At design beam current 10 Watts of heat enter the He-II
  - Can we keep the He-II cold enough, at far end of long channel?

UCN are always far from thermal equilibrium:

$T_{neutron} < 0.003$ K

$T_{superfluid} \sim 1$ K



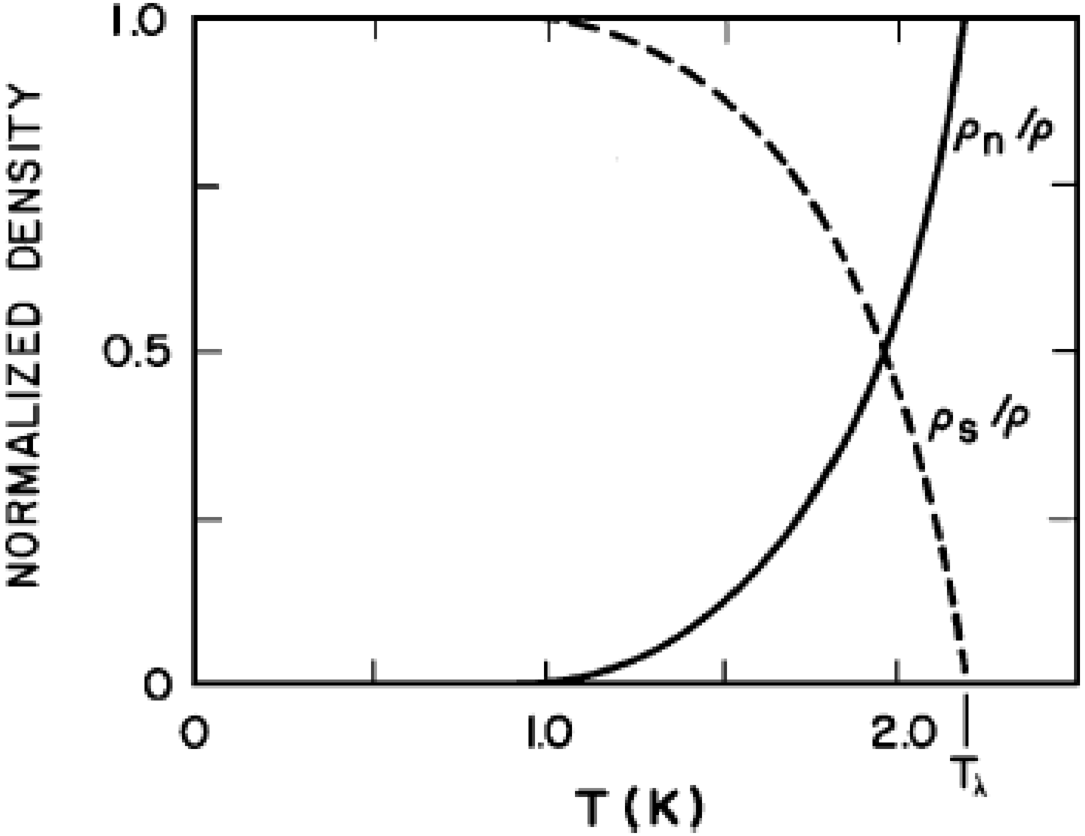
Leung et al., PRC **93**, 025501 (2016) measurements from ILL Grenoble

Losses dominated by 2-phonon UCN upscattering

loss rate $\sim T^7_{superfluid}$

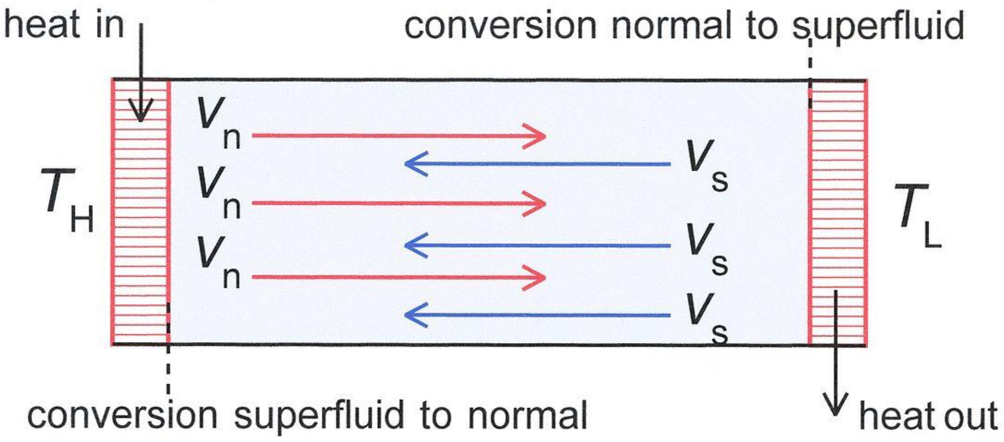
Two-fluid model of He-II

- He-II is made up of
  - Superfluid component ρ_s (entropy = 0, viscosity = 0)
  - Normal fluid component ρ_n
- Good at explaining viscosity contradictions, thermal transport properties, second sound, …

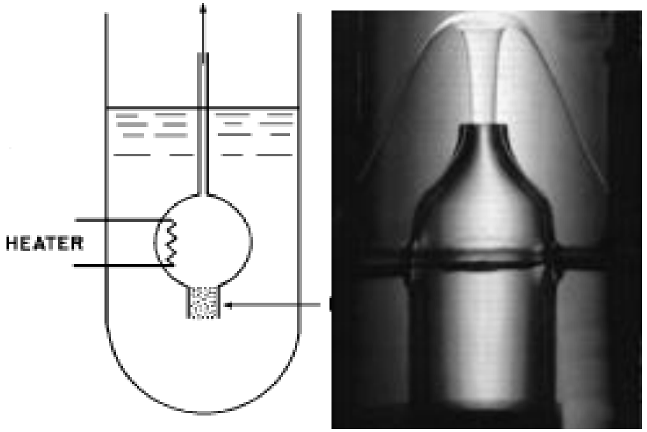


Thermal “Counterflow”

- Superfluid component flows towards heat source, normal component flows away.
- Normal component carries away entropy.
- Basis of heat transport is thermal counterflow of normal vs. superfluid components.

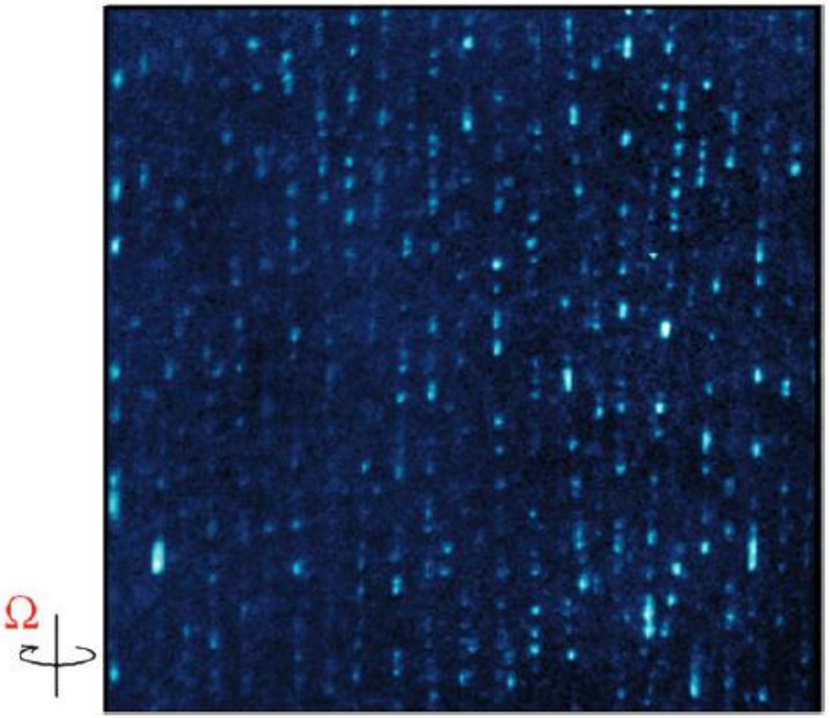


Nature **141,** 243-244 (1938)

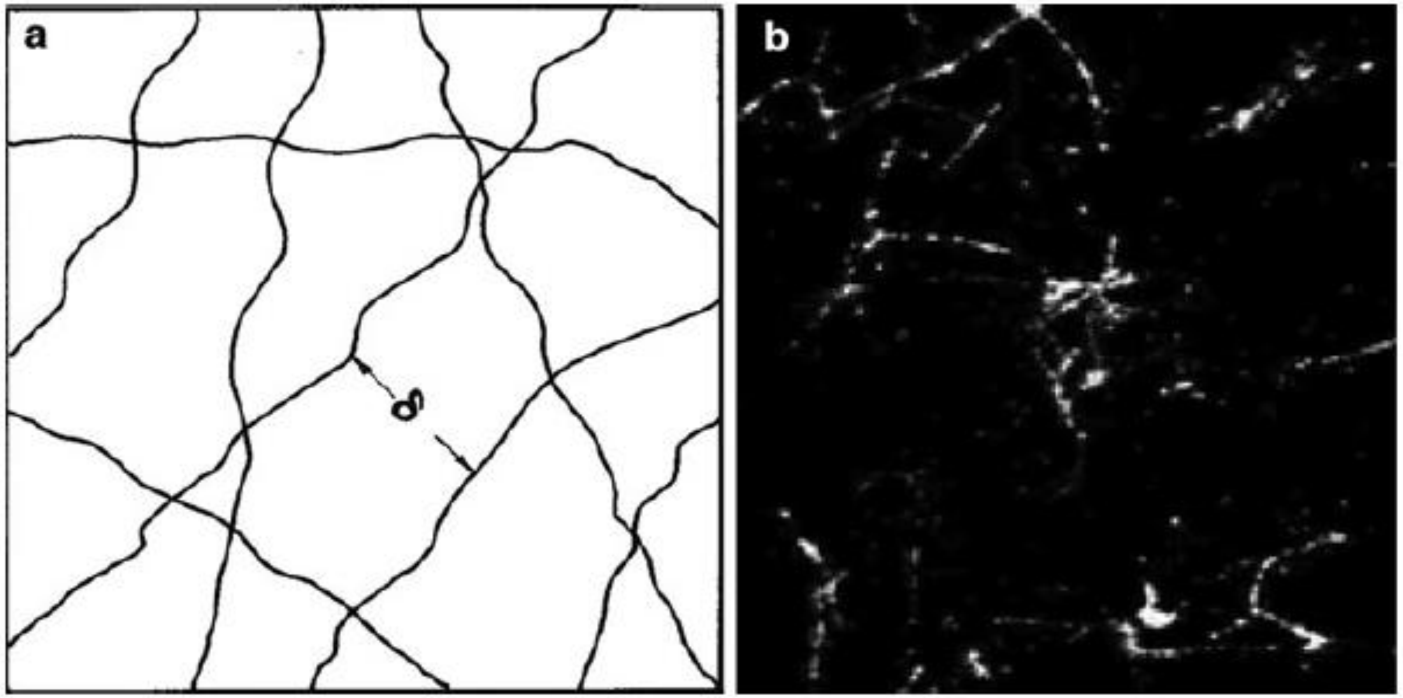


Fountain
Effect

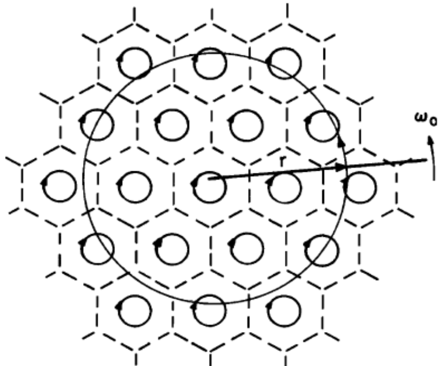
Turbulent He-II and Quantum Vortices



Vortices in rotating He-II



Vortices in thermal counterflow



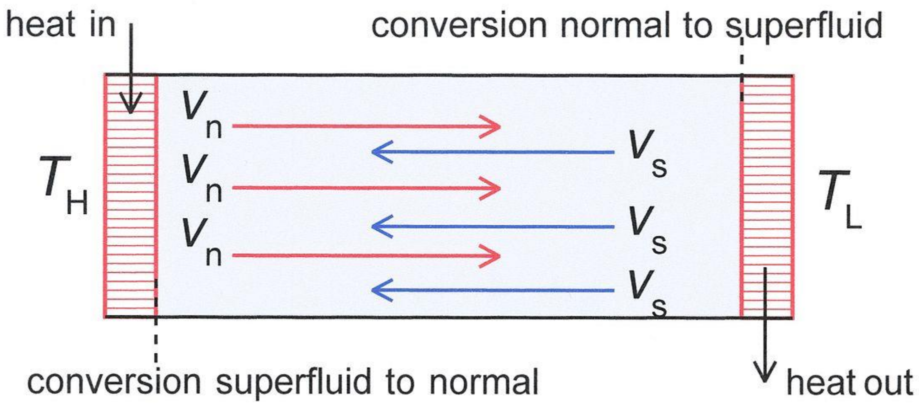
Circulation is quantized.

$$\oint \vec{p} \cdot d\vec{q} = nh$$

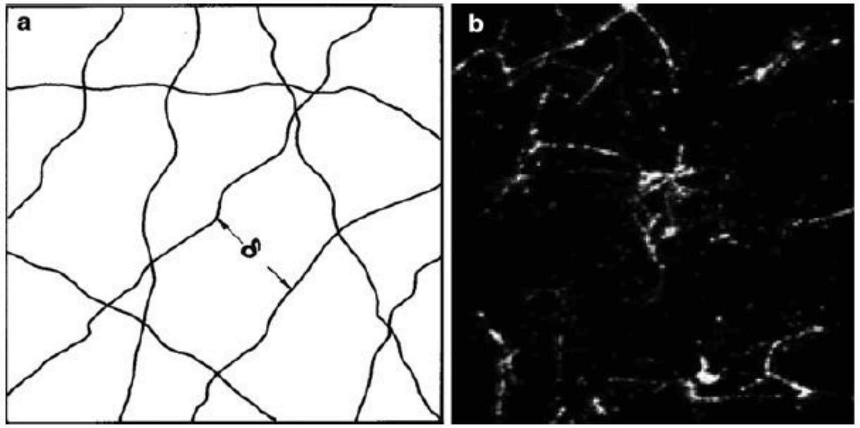
Images from van Sciver, *Helium Cryogenics*.
Hydrogen particles attached to vortices.

Turbulence in Thermal Counterflow

- For large heat flux, $|v_n - v_s|$ is large.
- Friction force between normal and superfluid creates vortex tangles.
- Normal component, which carries away heat, is impeded by mutual friction with vortices.



$$\frac{dT}{dx} = -\underbrace{\frac{\beta \mu_n q}{d^2 (\rho s)^2 T}}_{\text{viscous}} - \underbrace{\frac{A_{GM} \rho_n}{\rho_s^3 s^4 T^3} q^3}_{\text{turbulent}}$$



Conclusion: Turbulent He-II does not conduct heat like a usual material ~ q^3, indicates presence of vortices.

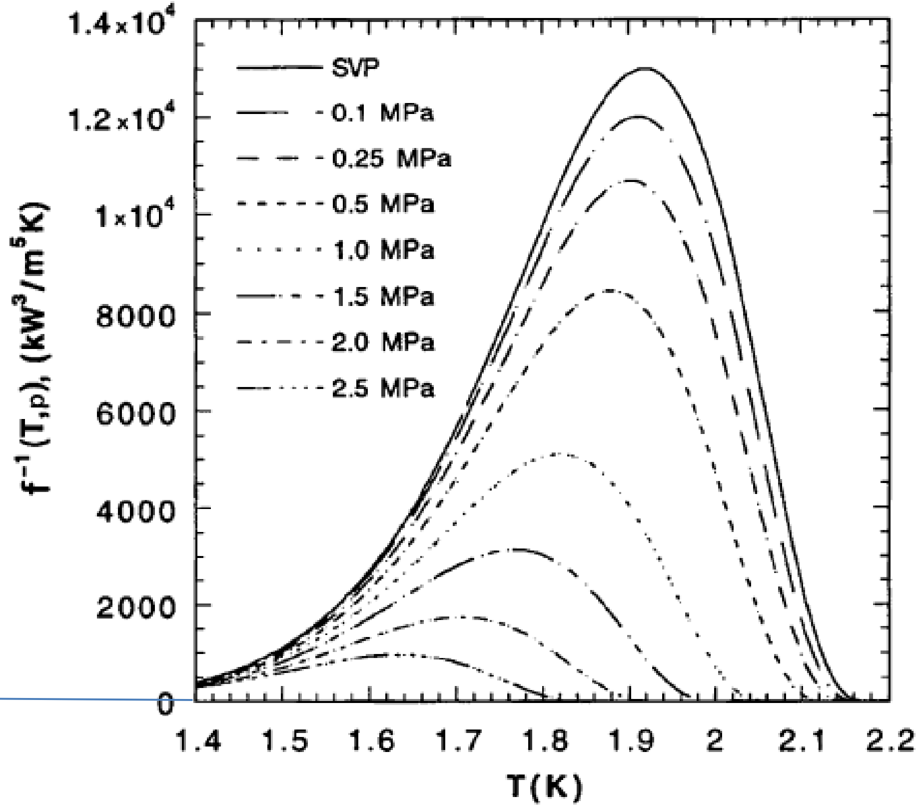
Heat conduction of turbulent He-II

- Empirical fits to data for "thermal conductivity function"

$$\frac{dT}{dx} = -f(T,p)q^{m}$$

m =~ 3
According to expt.

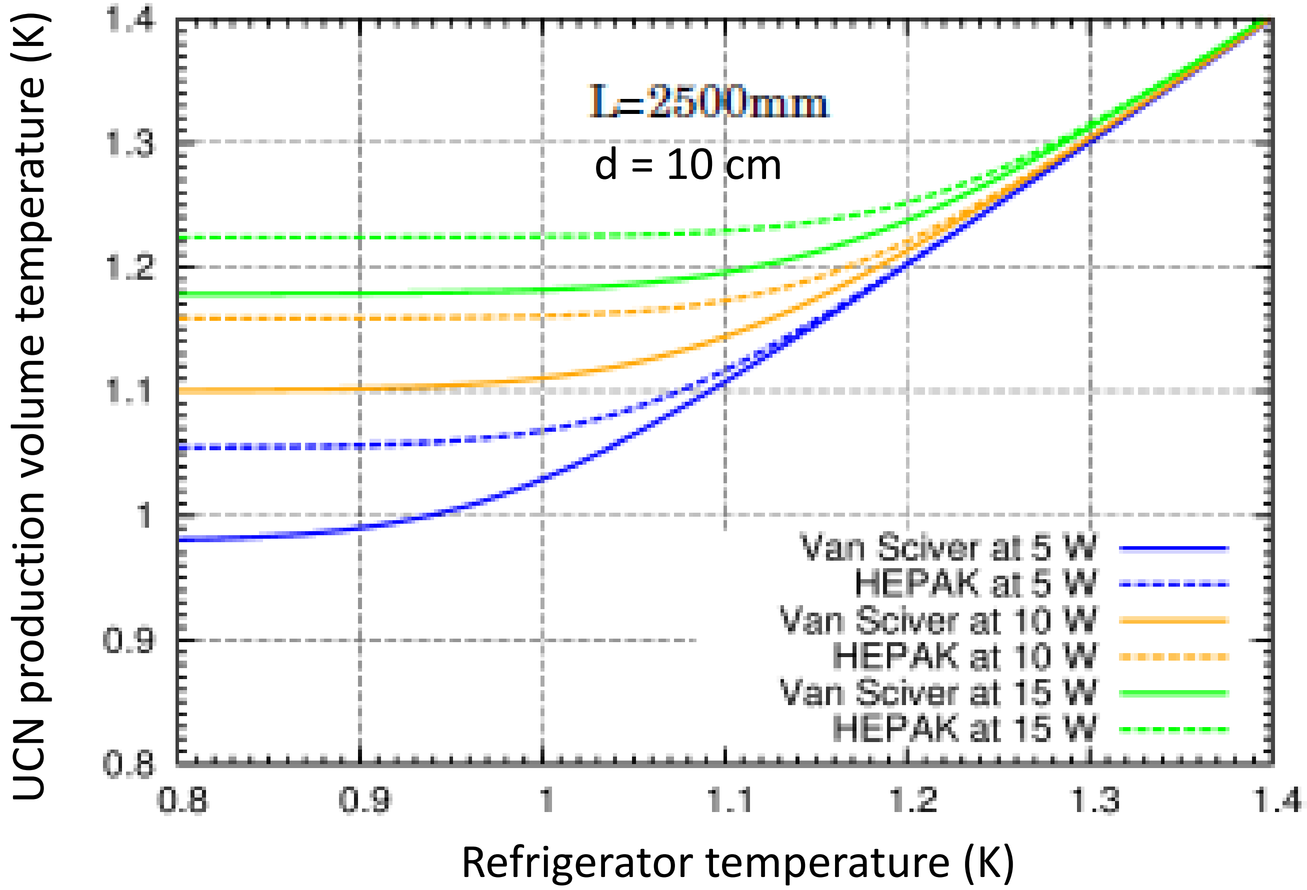
- Strong peak in f^{-1} at 1.9 K
  - Basis of e.g. LHC
- Small "conductivity" at lower temperatures.



Our experiment
0.8 – 1.0 K

Most measurements

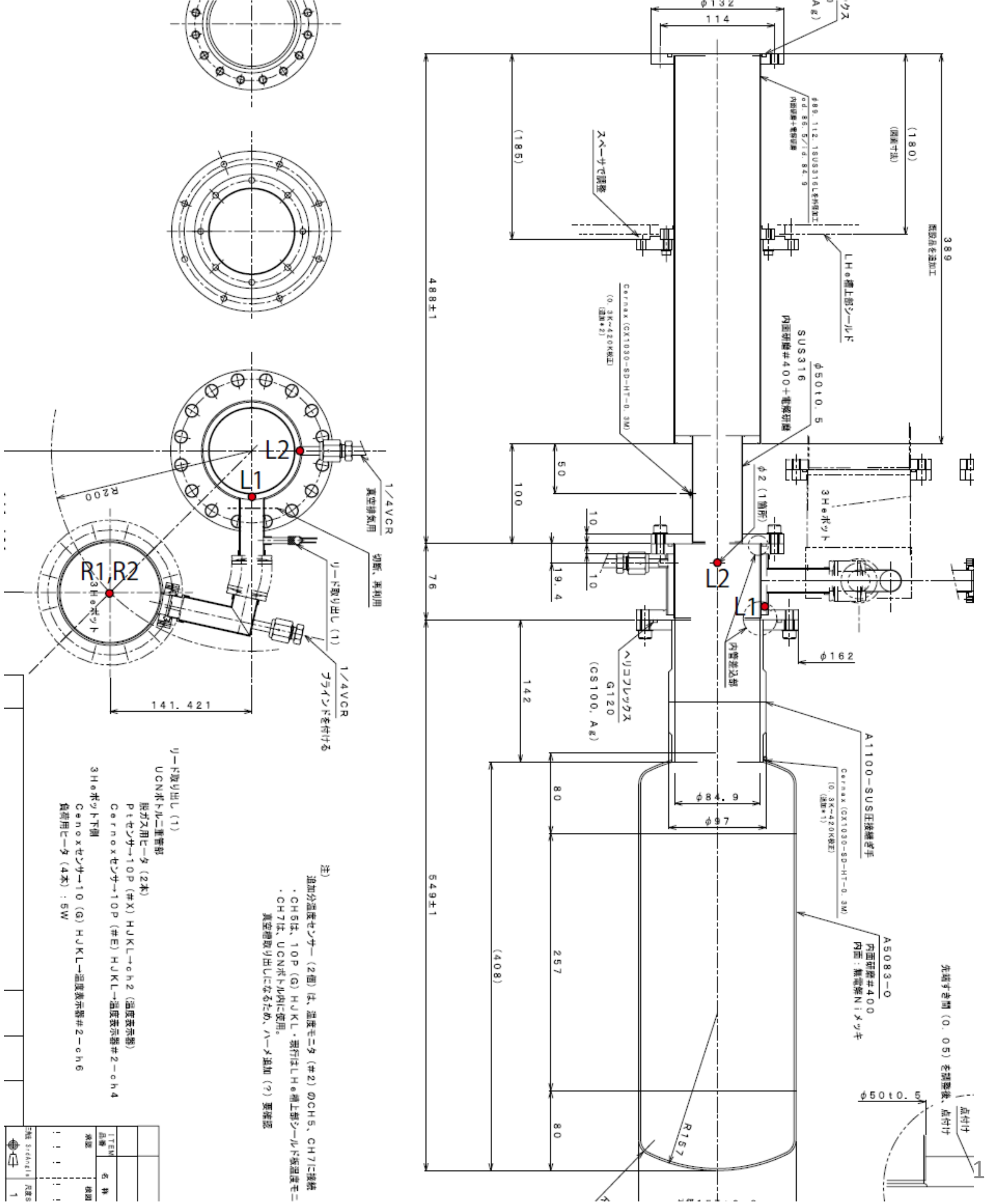
Calculation for our UCN Source based on Gorter-Mellink fits



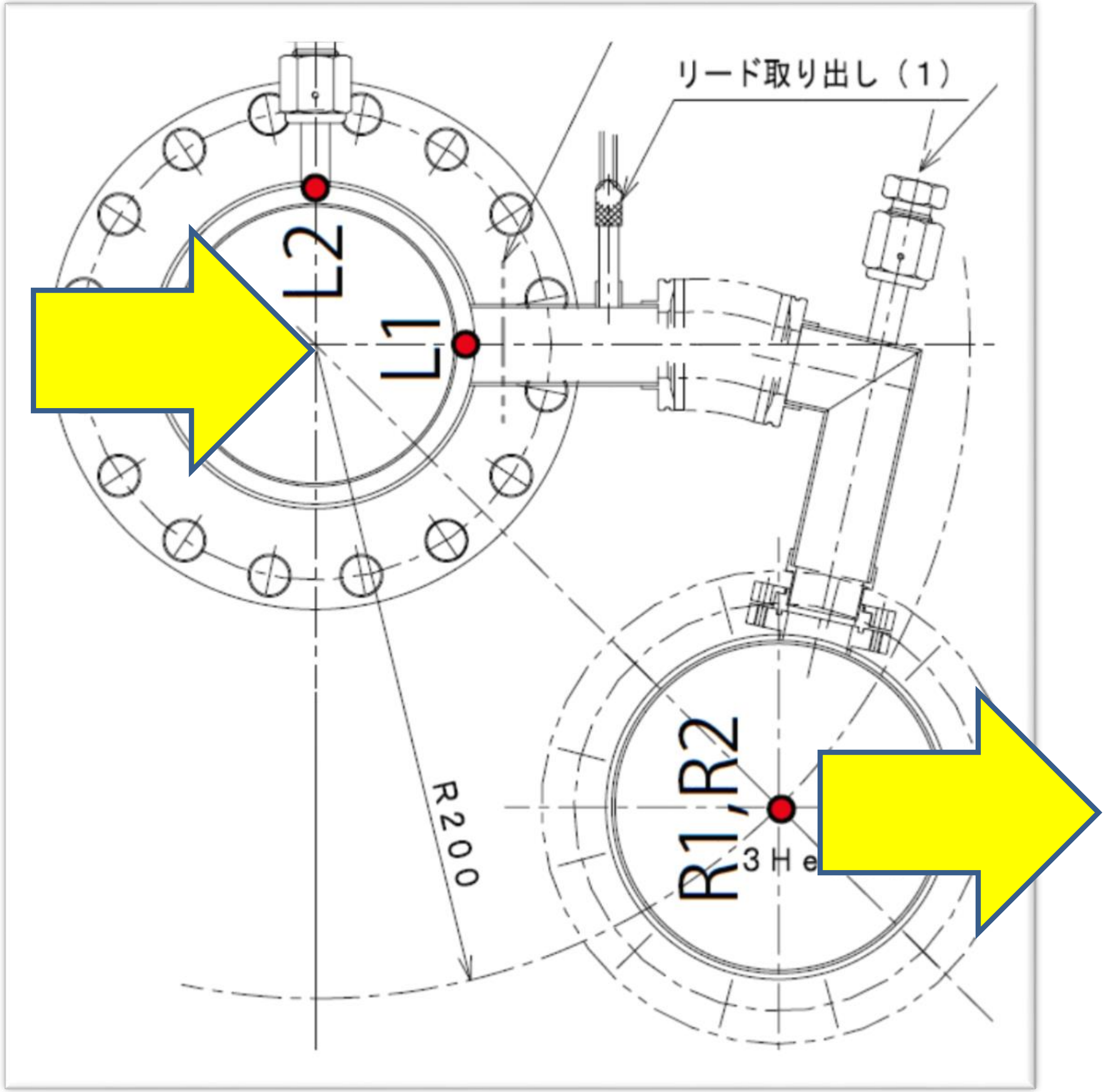
Example of calculations by T. Okamura, KEK

- For 10 W heat input, UCN production volume cannot be cooled below 1.1 K, no matter how much refrigeration power available.
- Strongly dependent on channel diameter ~ d^6

Can we use our present UCN source cryostat to measure the temperature gradient in He-II?



Top view of UCN bottle and ^{3}He pot

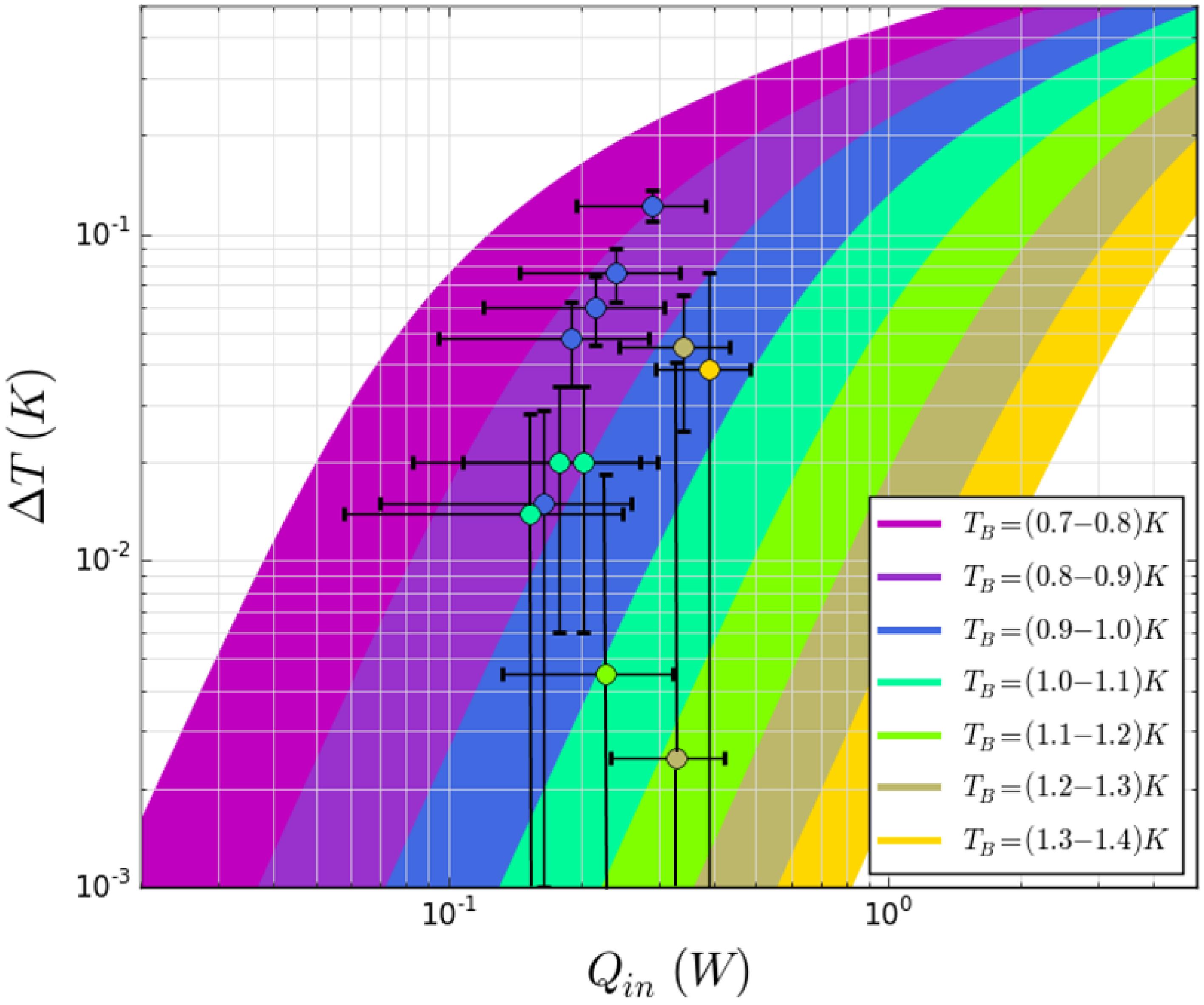


Heat applied by heater coil

Heat removed by Evaporation of 3He

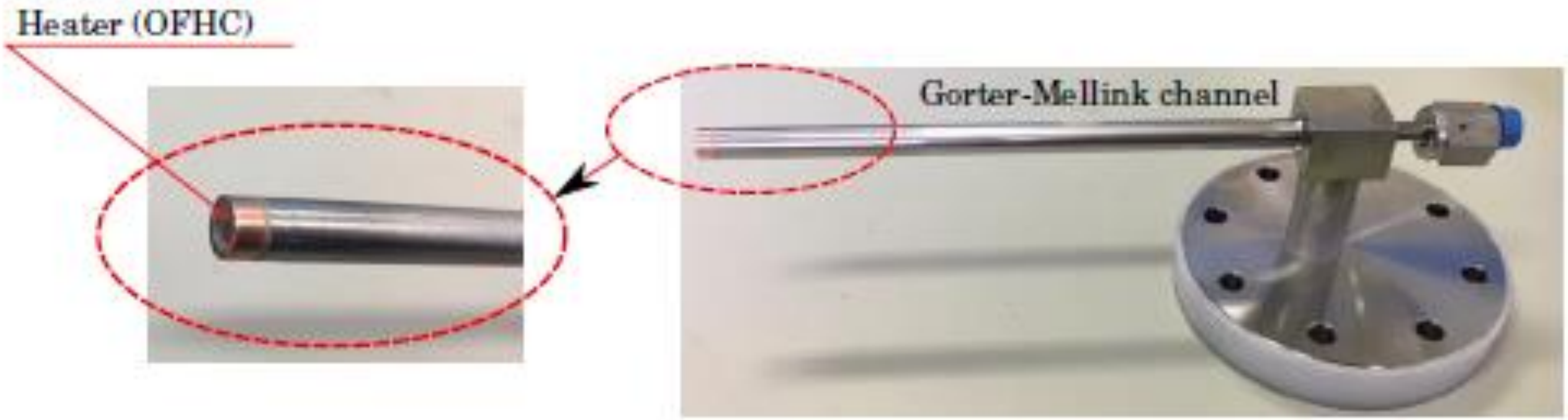
Results of Heat Test
Nov. 2017

- Colors: measurements and theory in different temperature ranges.
- Vertical Errors:
  - disagreement between sensors
  - sensor resolution
- Horizontal Errors:
  - uncertainty in background heat
  - correlated error
- Conclusion:
  - Errors are large, but data consistent with scale of expected temperature gradient.

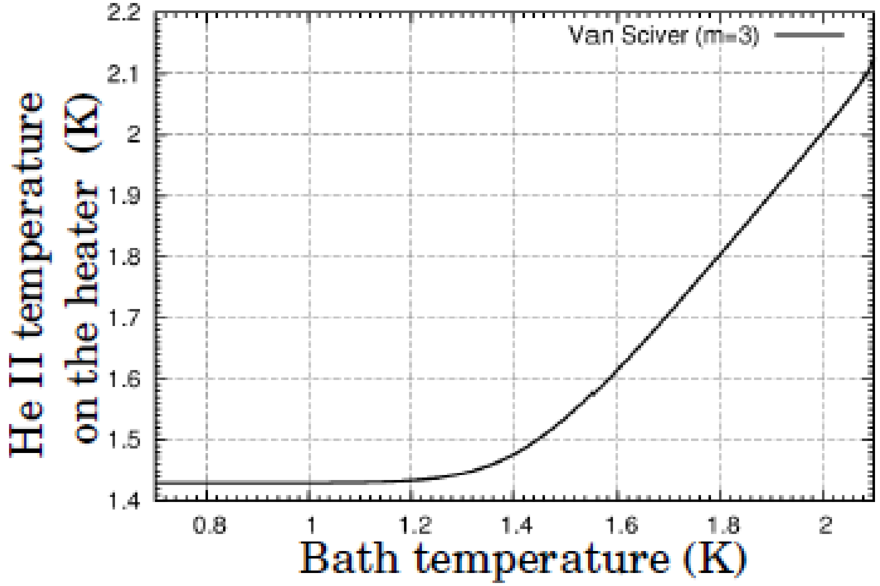


Florian Rehm - Heat Conductivity in Superfluid Helium & Ultracold Neutron Source Cryogenics
(Bachelor thesis, Coburg University of Applied Sciences and Arts, Jan. 2018)

Plan to measure in controlled experiment

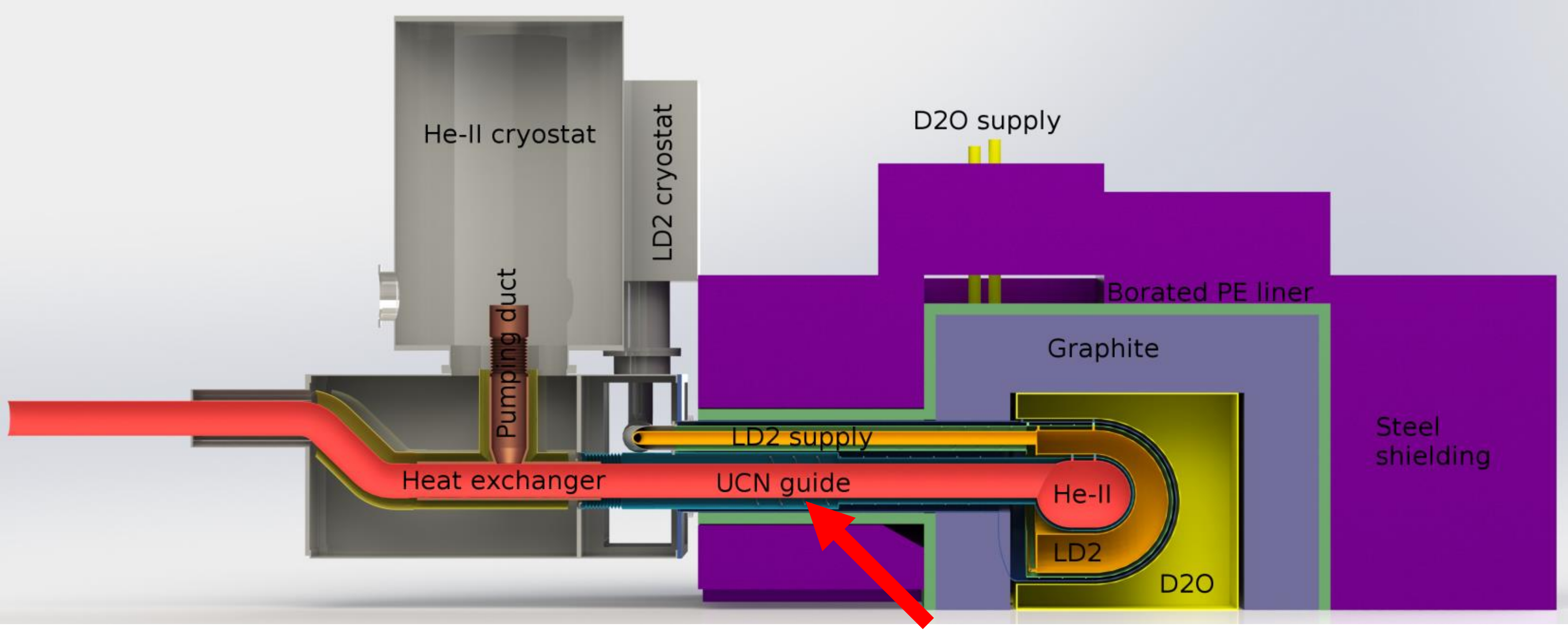


- Prediction for this channel.



T. Okamura, S. Kawasaki, Y. Makida, and K. Hosoyama (KEK)

Conclusion



- Superfluid He-II does not have infinite thermal conductivity!
- Quantum turbulence in He-II will limit this UCN source design
  - $T_{He\text{-}II}$ ~ 1.1-1.2 K (UCN lifetime in He-II ~ 60-35 s) (UCN source CDR 2018)
- New measurements of heat conduction in turbulent He-II are being conducted in order to finalize the design. More generally, our existing vertical UCN source can be used to learn about many design issues.
- Design goal of 10^{-27} e-cm measurement of nEDM is in reach.

The TUCAN Collaboration

Collaboration name: TUCAN
(**T**RIUMF **U**ltra**C**old **A**dvanced
Neutron source)

S. Ahmed[3,4], E. Altiere[2], T. Andalib[3,4], C. Bidinosti[3,8], J. Birchall[4], M. Das[3,4], C. Davis[5], B. Franke[5],
P. Giampa[5], M. Gericke[4], S. Hansen-Romu[3,4], K. Hatanaka[6], T. Hayamizu[2], B. Jamieson[3], D. Jones[2],
S. Kawasaki[1], T. Kikawa[5,6,1], M. Kitaguchi[10], W. Klassen[3,4], A. Konaka[5,8], E. Korkmaz[7], F. Kuchler[5],
M. Lang[3], T. Lindner[5,3], K. Madison[2], Y. Makida[1], J. Mammei[4], R. Mammei[3,5], J. Martin[3], R. Matsumiya[5],
E. Miller[2], K. Mishima[1], T. Momose[2], T. Okamura[1], S. Page[4], R. Picker[5,9], E. Pierre[6,5], W. Ramsay[5],
L. Rebenitsch[3,4], W. Schreyer[5], H. Shimizu[10], J. Sonier[9], I. Tanihata[6], S. Vanbergen[2],
W.T.H. van Oers[4,5], Y. Watanabe[1]

[1]KEK, Tsukuba, Ibaraki, Japan
[2]The University of British Columbia, Vancouver, BC, Canada
[3]The University of Winnipeg, Winnipeg, MB, Canada
[4]The University of Manitoba, Winnipeg, MB, Canada
[5]TRIUMF, Vancouver, BC, Canada
[6]RCNP, Osaka, Japan
[7]The University of Northern BC, Prince George, BC, Canada
[8]Osaka University, Osaka, Japan
[9]Simon Fraser University, Burnaby, BC, Canada
[10]Nagoya University, Nagoya, Japan

Spokespeople: J. Martin (Canada), K. Hatanaka (Japan)

Other superfluid helium UCN sources

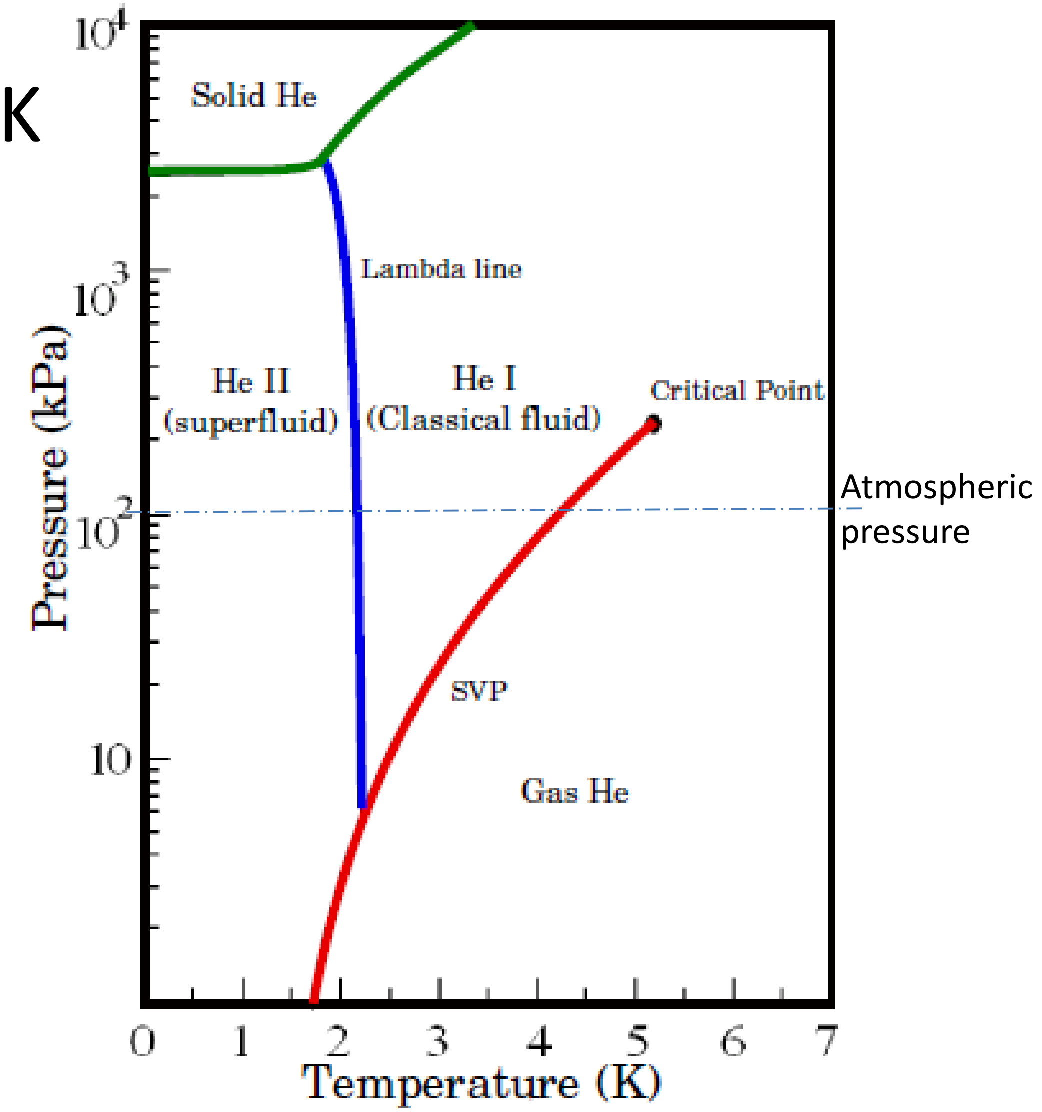
Ultracold Neutrons (UCN)

- Neutrons that are moving so slowly that they bounce off surfaces and can be held in room-temperature bottles.
  - $v < 8$ m/s = 30 km/h
  - $T < 4$ mK
  - K.E. < 300 neV

- Interactions:
  - Gravity: $V = mgh$ $mg = 100$ neV/m
  - Magnetic: $V = -\mu \bullet B$ $\mu = 60$ neV/T
  - Weak: $\tau_n = 886$ s = 15 mins.
  - Strong: $V = V_{\mathrm{eff}}$ $V_{\mathrm{eff}} < 335$ neV

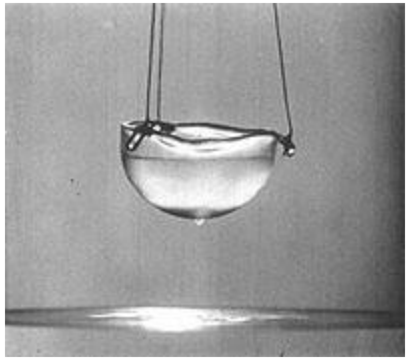
Phases of ^{4}He

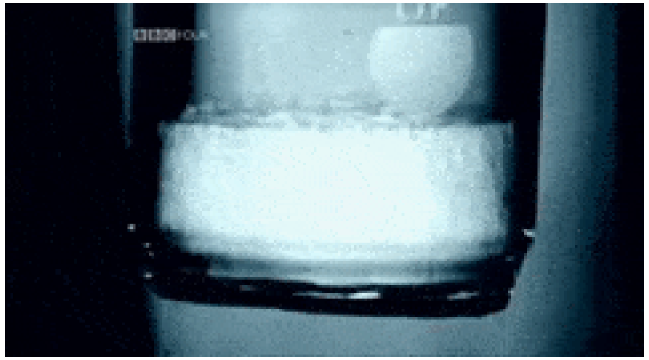
- He-I = normal liquid, 2.177 < T < 4.2 K
- He-II = superfluid, T < 2.177 K
- If all the particles are in the same quantum state:
  - Zero entropy
  - Zero viscosity
- These properties are seen experimentally in He-II



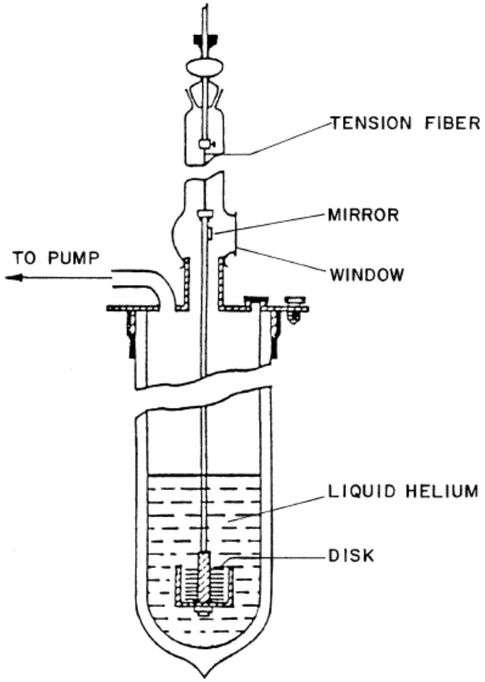
The superfluid phase of helium, He-II: Zero viscosity, … or not???

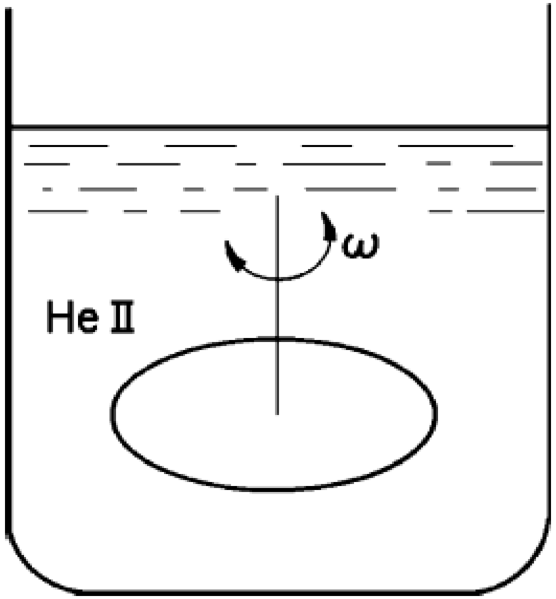
- Film flow (Rollin film)
- Superleak





- But… a contradiction?
  Rotating viscometer

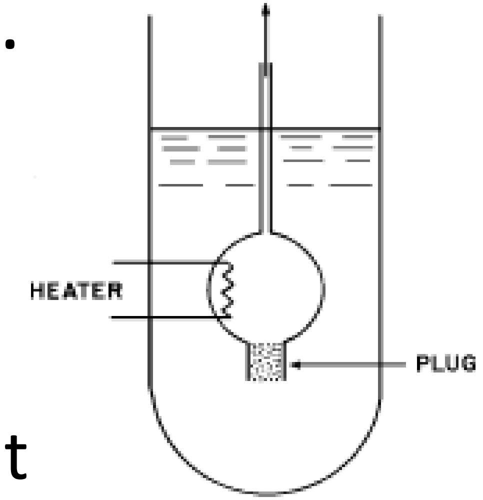


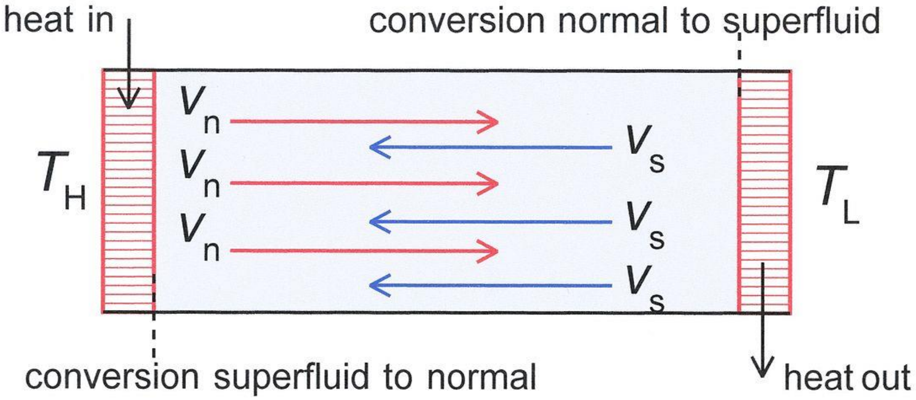


Fountain Effect and Thermal “Counterflow”

- Fountain of He-II when heater turned on.
- Easy to explain in two-fluid model.
  - Superfluid flows towards heat source, normal component flows away.
  - Normal component carries entropy and heat away.
- Basis of heat transport is thermal counterflow of normal vs. superfluid components.

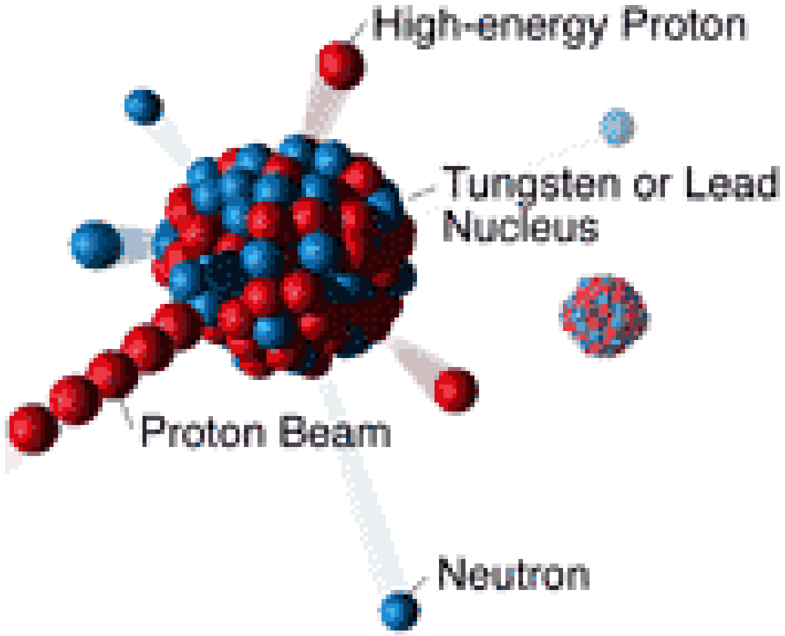
Nature **141,** 243-244 (1938)





Where we get our neutrons

- TRIUMF, Vancouver, Canada
- 500 MeV cyclotron delivers 40 uA current producing neutrons by spallation.



Survey of UCN Sources Worldwide

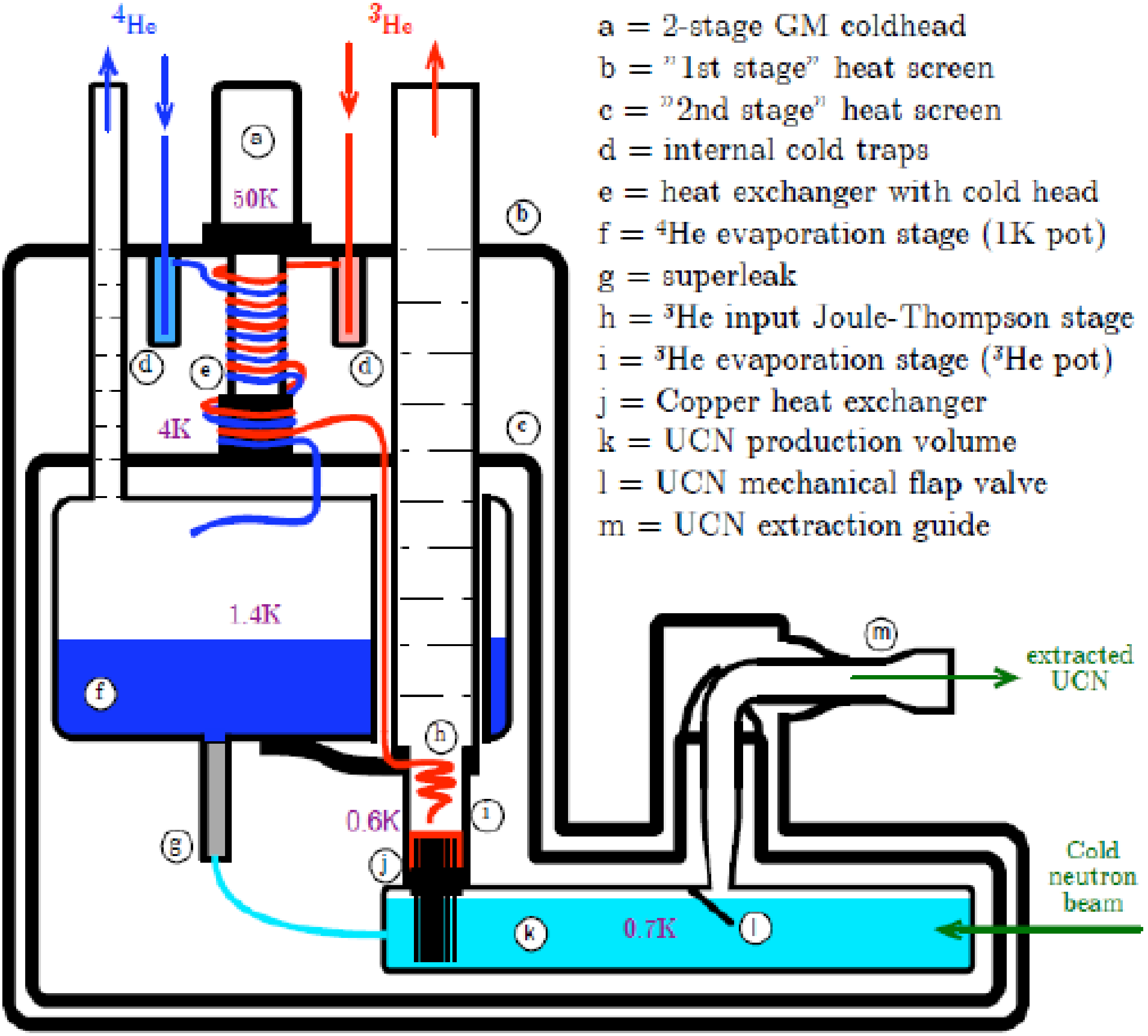
Place	Neutrons	UCN converter	Status
ILL	Reactor, CN	Turbine	Running
J-PARC	Spallation	Doppler shifter	Running
ILL SUN-2	Reactor, CN	Superfluid He	Running
ILL SuperSUN	Reactor, CN	Superfluid He	Future
RCNP/KEK/TRIUMF	Spallation	Superfluid He	Installing/Future
Gatchina WWR-M	Reactor	Superfluid He	Future
LANL	Spallation	Solid D2	Running/Upgrading
Mainz	Reactor	Solid D2	Running
PSI	Spallation	Solid D2	Running
NSCU Pulstar	Reactor	Solid D2	Installing
FRM-II	Reactor	Solid D2	Future

KEK-TRIUMF combination of spallation target and superfluid helium is unique.
Upgrade schedule is competitive with other leading sources of UCN.

Constructed second source prototype “SUN-2”

Development goals

- modularity: converter r&d
- shorter turnaround time
- more cooling power

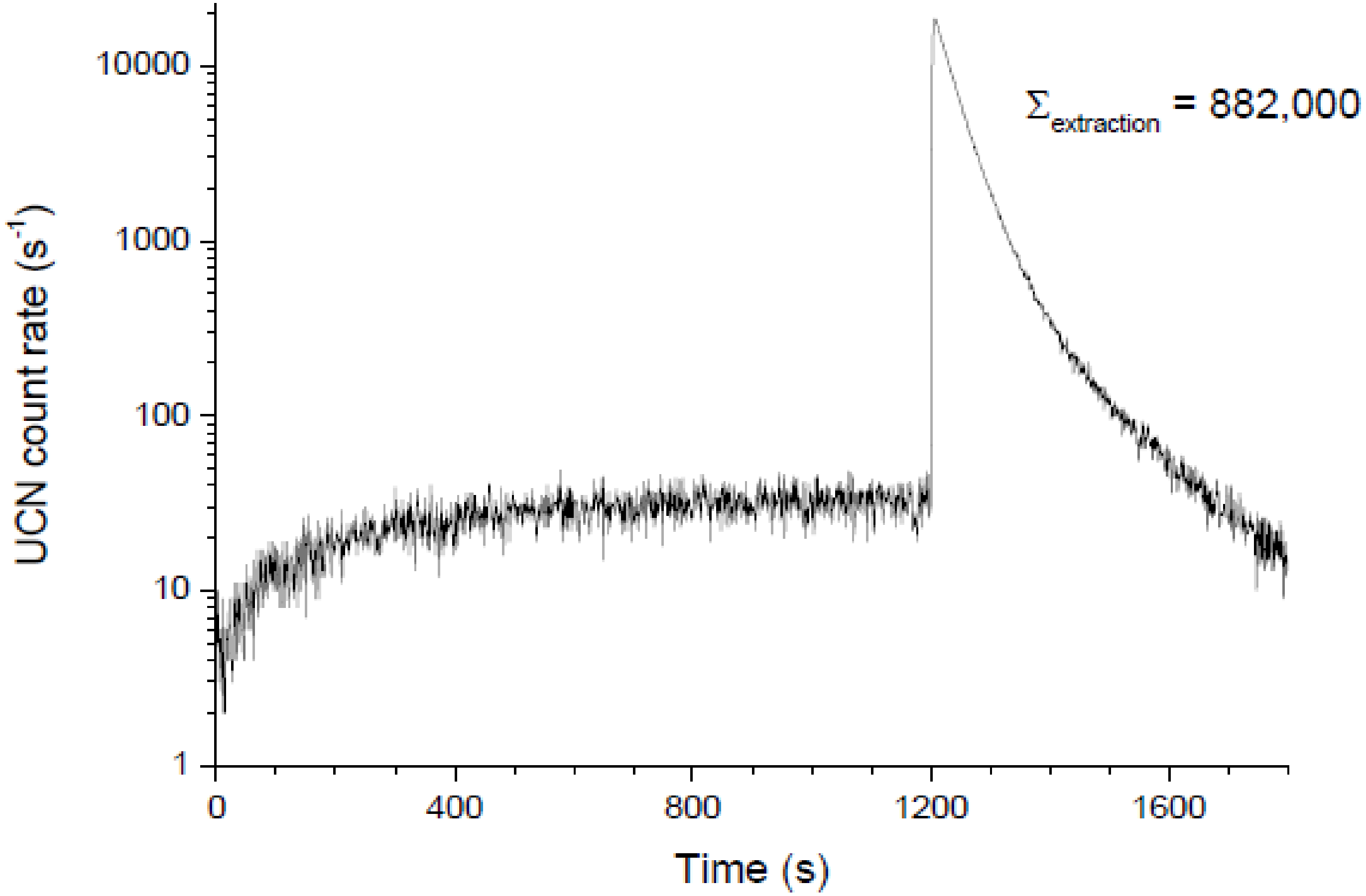


a = 2-stage GM coldhead
b = ”1st stage” heat screen
c = ”2nd stage” heat screen
d = internal cold traps
e = heat exchanger with cold head
f = ^{4}He evaporation stage (1K pot)
g = superleak
h = ^{3}He input Joule-Thompson stage
i = ^{3}He evaporation stage (^{3}He pot)
j = Copper heat exchanger
k = UCN production volume
l = UCN mechanical flap valve
m = UCN extraction guide

Slides courtesy of
O. Zimmer and P. Geltenbort

Recent achievement (16 July 2015, repeated since)

(fomblin grease on Be on Al converter vessel)



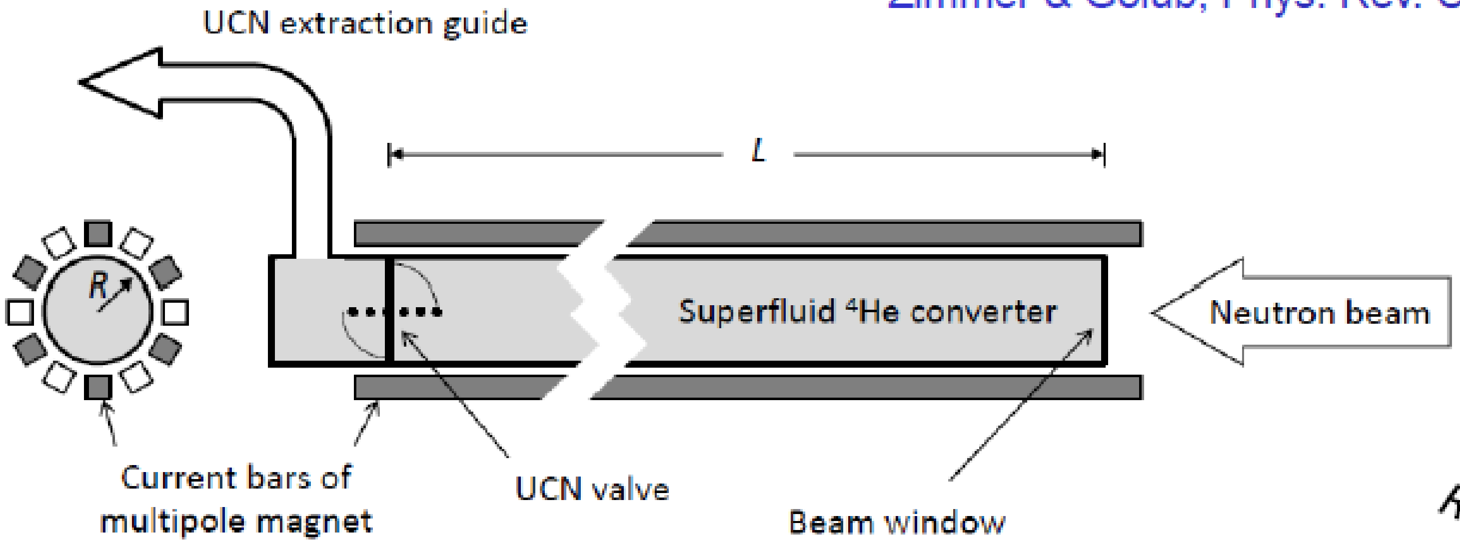
0.61 K: **882000** accumulated UCN from 4 litres He-II ~ **220/cm^3**

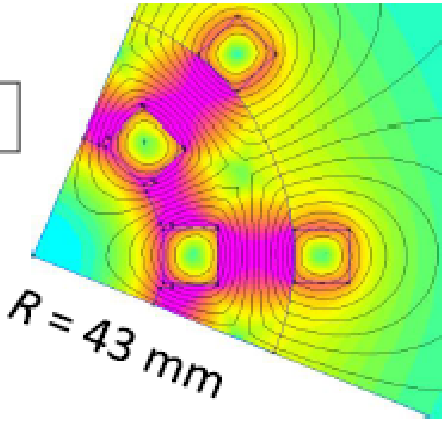
ILL project **SuperSUN** (3 m magnetic 12-pole UCN reflector)

Idea: magnetic confinement

For calculations of UCN storage see:

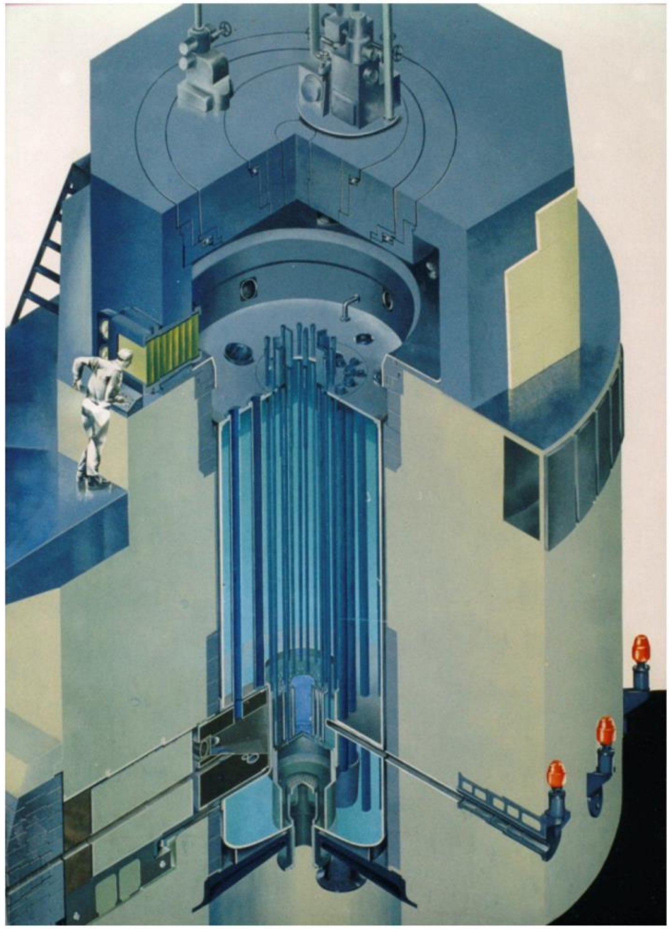
Zimmer & Golub, Phys. Rev. C **92** (2015) 015501



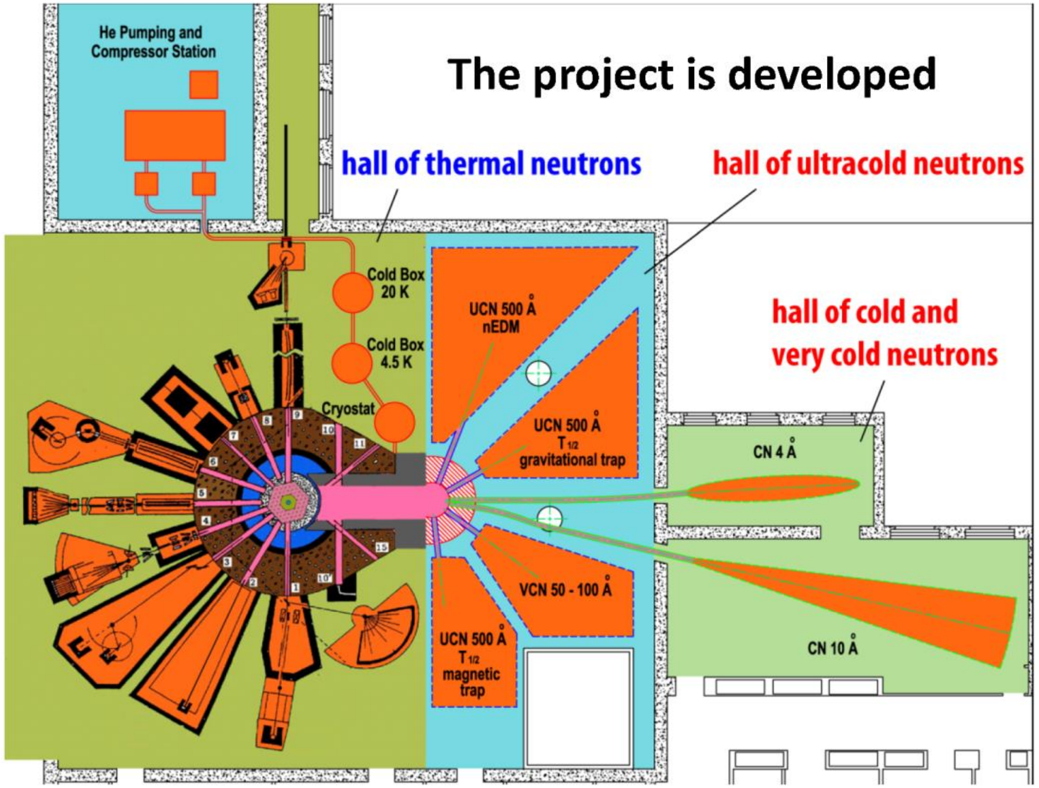


- Single-user facility
- Converter volume: 12 litres
- UCN production rate: 10^5 s^{-1} (E < 230 neV)
- UCN saturation number: 4×10^6 (2017, fomblin spectrum)
  2×10^7 (2019, polarised, E < 230 neV)

Prospects for UCN source at WWR-M reactor



The resource of basic elements of the reactor provides its further operation within 25 years.



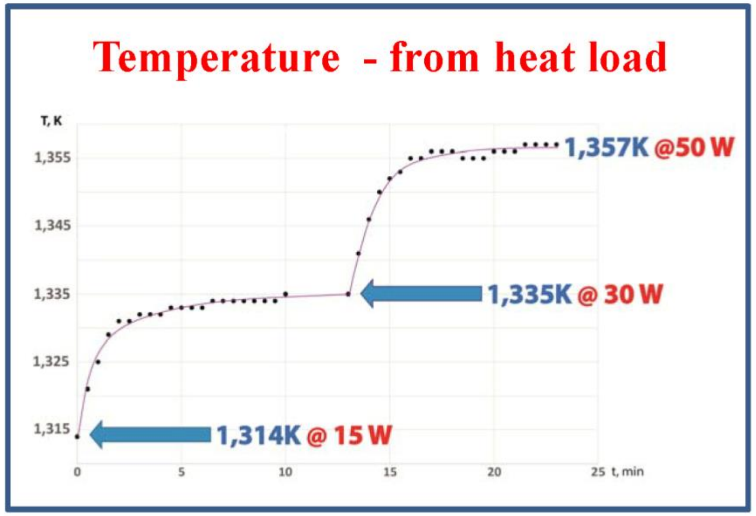
The scheme of experimental installations on the WWR-M reactor after installation in a thermal column of the reactor of UCN source with superfluid helium at a temperature of 1.2K.

Slides courtesy of A. Serebrov

The full-scale model of UCN source with superfluid helium is tested up to 50 W at 1.3 K

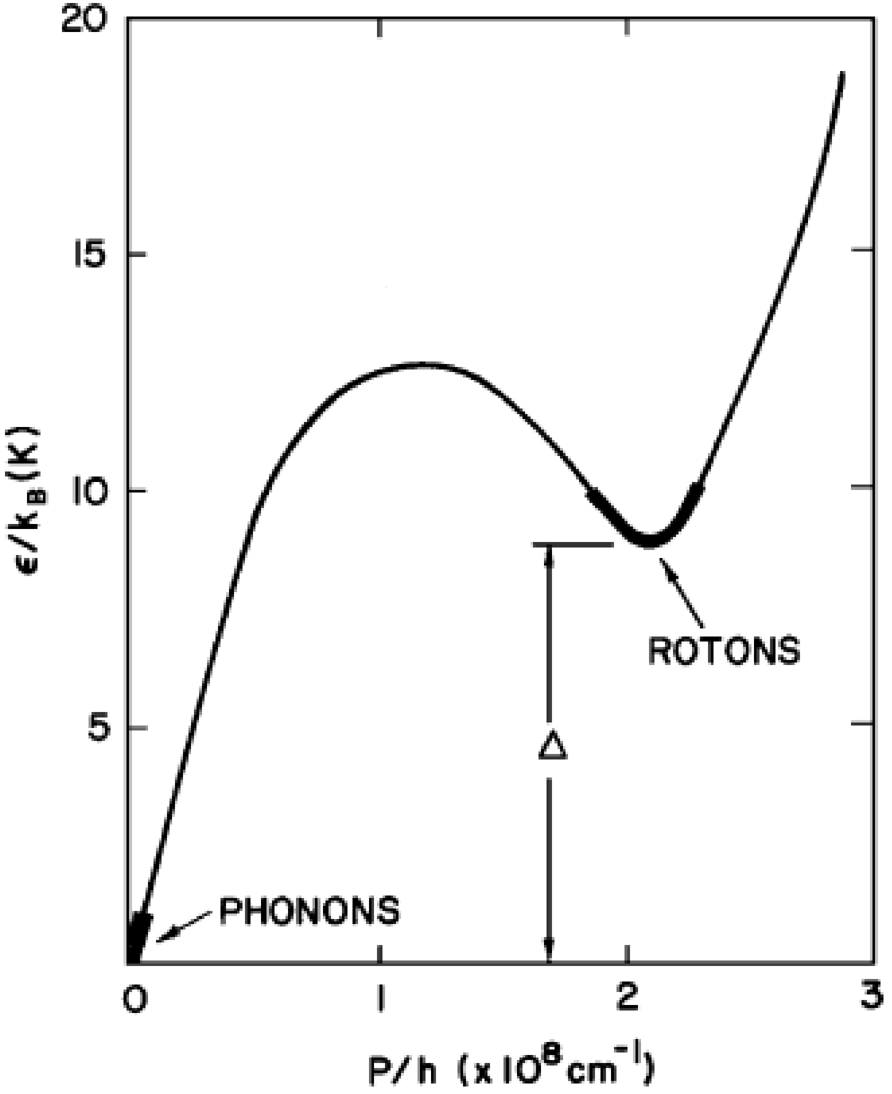
It means that project can be realized. *(Possible UCN density in EDM trap is about* $10^4 cm^{-3}$ *)*

November 2015

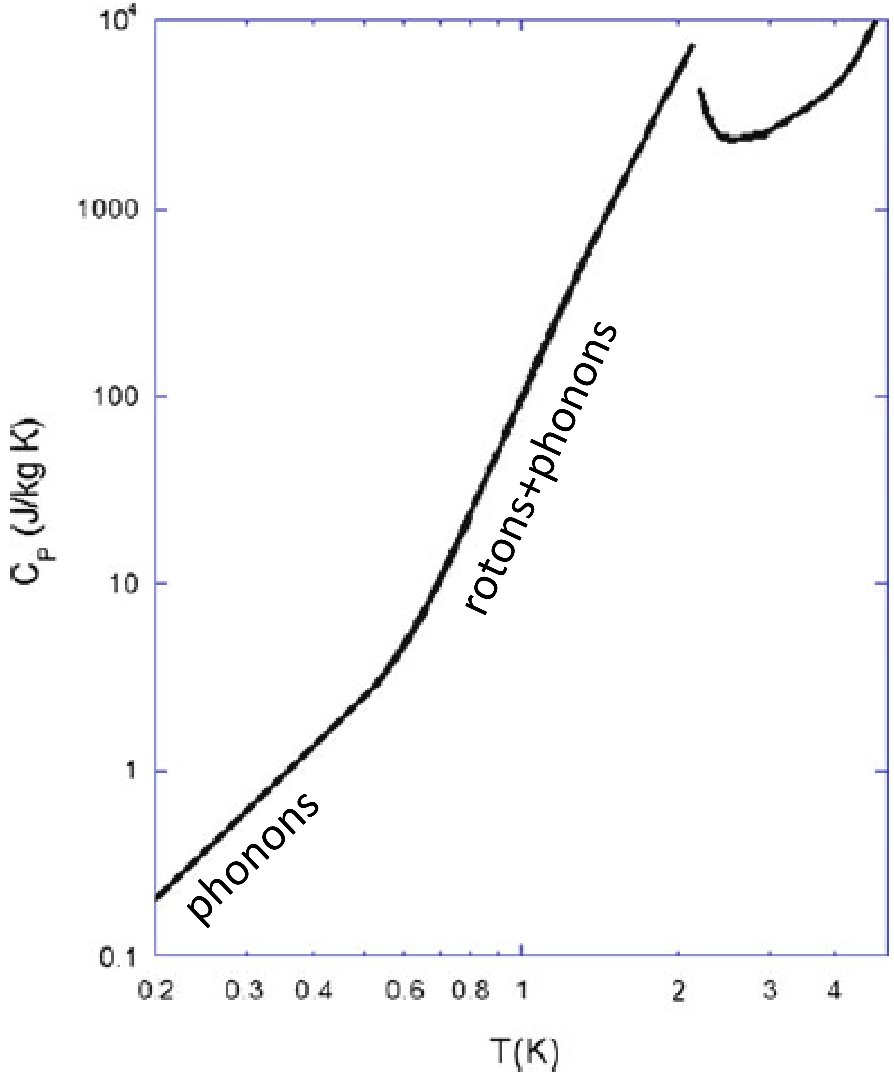

Temperature - from heat load

Refrigerator 20 K **Cryostat 1 K** **Liquefier 4 K**

Landau Theory



- Collective excitations of He-II: phonons and rotons
- Explains e.g. specific heat, entropy, correspondence with two-fluid model.
- Important for neutron scattering!



Helium as a quantum fluid

- Heisenberg uncertainty principle prevents solidification of He at T = 0 K:
  - Energy uncertainty >> Interatomic potential energy
  - Quantum mechanics will be important for this material at low temperature.
- ^{4}He forms a (kind of) Bose condensate at low temperature, but with some interactions, a “superfluid”.