Cryogenic Design Studies for UCN Project

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KEK/IPNS/Cryo

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Introduction

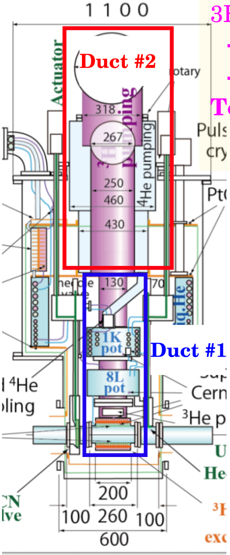
- Cryogenic system for UCN is interesting apparatus from the cryogenic view point.
  - He II and some properties under the sub-K and around 1 K have several unique characteristics. And some phenomena have never fully clarified until now.
- To clarify them through the designing is also worthwhile from a low temperature engineering viewpoint.
- Design studies have been continuously done by means of calculation, simulation and (experiments)
- Actually, some cryogenic element experiments for more reliable cryogenic design will be done from next month.

Some simulation results and cryogenic element experiments will be introduced.

Contents

1. Flow Conductance in the vacuum line
2. Heat Exchanger and brief specification
3. Thermo Fluid behaviour and ΔT of Superfluid Helium
4. Essential Experiments for designing
    - Kapitza Conductance
    - Heat Transfer function measurement of He II
5. Schedule
6. Summary
7. (Digression: cryogenic safety estimation)
    - Thermo fluid simulation for coolant spill into air

1. Flow Conductance through the exhaust pipe

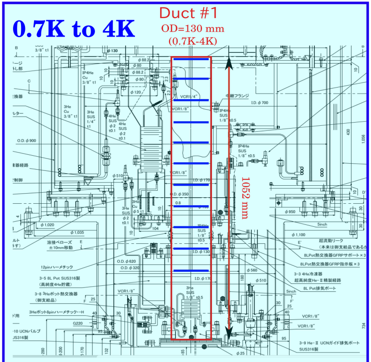


3He exhaust pipe is divided into following two section.

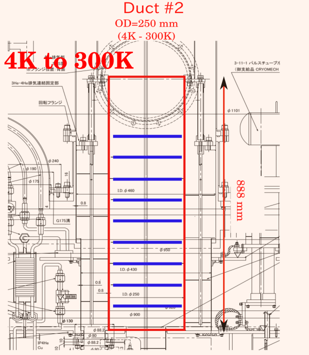
- sub-K to 4 K stage
- 4 K to 300 K stage

To reduce radiation heat load, 20 buffle plates are inserted .

→ Conductance calculation is needed.

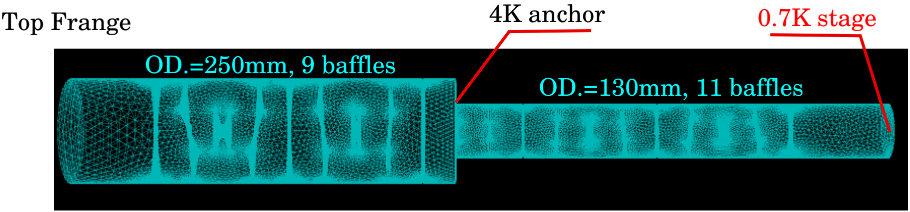


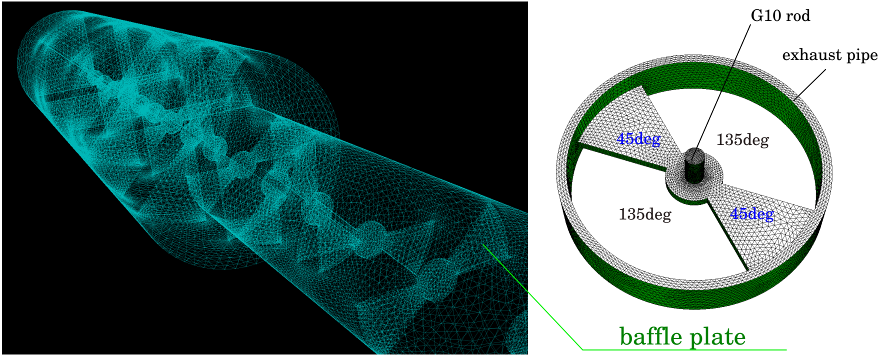
11 baffle plates, (75mm interval)



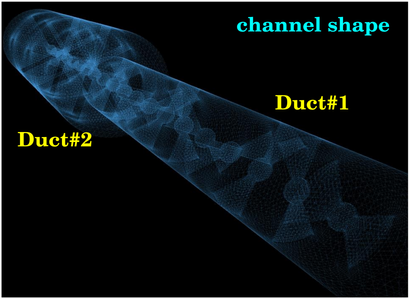
9 baffle plates (75mm interval)

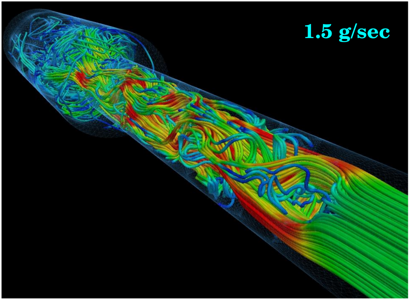
1. Flow Conductance through the exhaust pipe

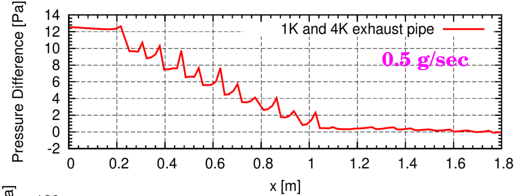


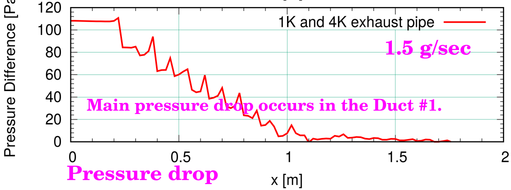


Pressure drop Results









Main pressure drop occurs in the Duct #1.

Pressure drop

- **w/o baffle dP = 1 Pa @ 0.5 g/sec**
- **w/ baffle dP = 12.5 Pa @ 0.5 g/sec**
- **w/ baffle dP = 110 Pa @ 1.5 g/sec**

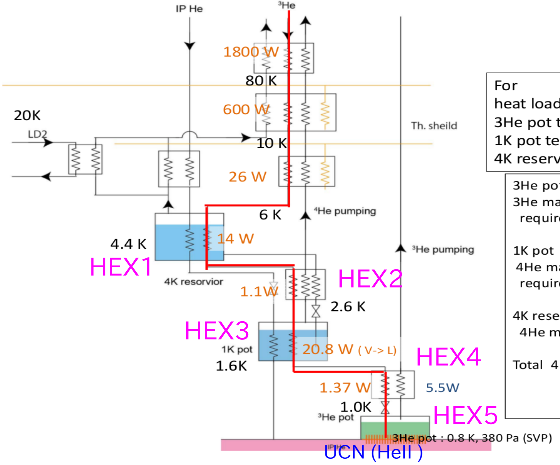
Present design has no problem.

Following relation was confirmed from simulation

$$\Delta p = \lambda \frac{L}{D} \frac{\dot{m}^2}{\rho A^2}$$

2. Heat exchanger Flow Diagram

There are 10 heat exchanger (HEXs) in the UCN cryostat.
Especially, HEX 1 to 5 is quite important and pay special attention to
heat transfer coef by considering convection, conduction and Kapitza condutance.

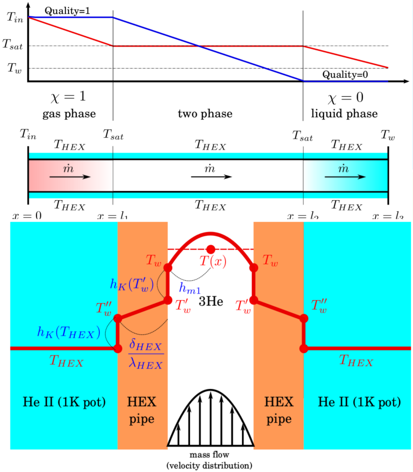


For
heat load: 10W
3He pot temp.: 0.8 K
1K pot temp. : 1.6 K
4K reservoir temp. : 4.4 K

3He pot
3He mass flow : 1.22 g/sec
required pumping speed
8,900 m^3/hour
1K pot
4He mass flow : 1.24 g/sec
required pumping speed
3,000 m^3/hour
4K reservoir
4He mass flow: 0.69 g/sec

Total 4He usage
55.5 L/hour
(100%duty)

2. Heat exchanger
How to evaluate required length of HEX ?



Heat Exchanger model for "HEX1" and "HEX3"

- Local heat flux, $q_1(x)$ at $x \in [0, l_1]$ is described using effective heat transfer coef. h_1.

$$q_1(x) = h_1(T(x) - T_{HEX})$$

$$h_1 = \left(\frac{1}{h_{m1}} + \frac{\delta_{HEX}}{\lambda_{HEX}} + \frac{1}{h_K(T'_w)} + \frac{1}{h_K(T_{HEX})} \right)^{-1}$$

  - h_{m1}: convective heat transfer coef., [W/m^{2}K].
  - h_K: Kapitza conductance. [W/m^{2}K].
  - $(\delta_{HEX}/\lambda_{HEX})^{-1}$ conductive heat transfer coef [W/m^{2}K]. (due to pipe thickness made of OFHC.)

Convection Term

In case of single phase flow

h_{m1} is estimated following non-dimensional Dittus-Boelter correlation.

$$Nu_{d1} = 0.023 \times Re_d^{0.8} Pr^{1/3}$$

$$Re_d = \frac{Ud}{\nu}, \quad Pr = \frac{\nu}{D_T}, \quad Nu_{d1} = \frac{h_{m1} d}{\lambda_g}$$

In case of gas-liquid two phase flow

- $h_{m2}(x)$ is averaged convective heat transfer coef which is based on Dittus-Boelter correlation. This correlation is applied in the case of $\chi \neq 1$. [3].

$$Nu_{d2}(x) = 0.023 Re_l(x)^{0.8} Pr_l^{0.4} \left[(1 - \chi(x))^{0.8} + \frac{3.8\chi(x)^{0.76}(1 - \chi(x))^{0.04}}{(p/p_{cr})^{0.38}} \right]$$

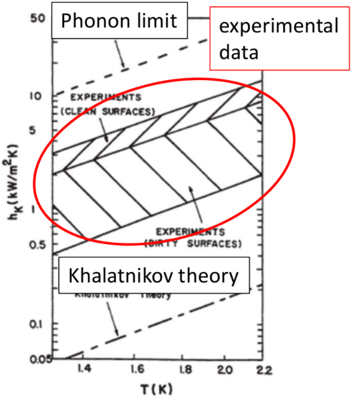
$$Nu_{d2}(x) = \frac{h_{m2}(x) d}{\lambda_l}, \quad Re_l(x) = \frac{G(1 - \chi(x))d}{\eta_l}, \quad Pr_l = \frac{\nu_l}{D_{Tl}}, \quad D_{Tl} = \frac{\lambda_l}{\rho_l c_{pl}}$$

$$G = \dot{m}/A, \quad A = \frac{1}{4}\pi d^2, \quad \text{[kg/m}^2\text{/sec]}$$

2. Heat exchanger
Kapitza conductance and surface condition of HEX

- Kapitza conductance is Conductance at the surface between liquid and solid is small at low temperature
- Kapitza conductance, $h_K(T)$ is a function of temperature.
- There are several theory on Kapitza conductance.
  - Phonon limit
    - $h_K(T)$ ~4500 T^3 [W/m^{2}K]
      - 2 - 10 times larger than measured
  - Khalatnikov theory
    - $h_K(T)$ ~ 20 T^3 [W/m^{2}K]
      - 10 - 100 times smaller than measured

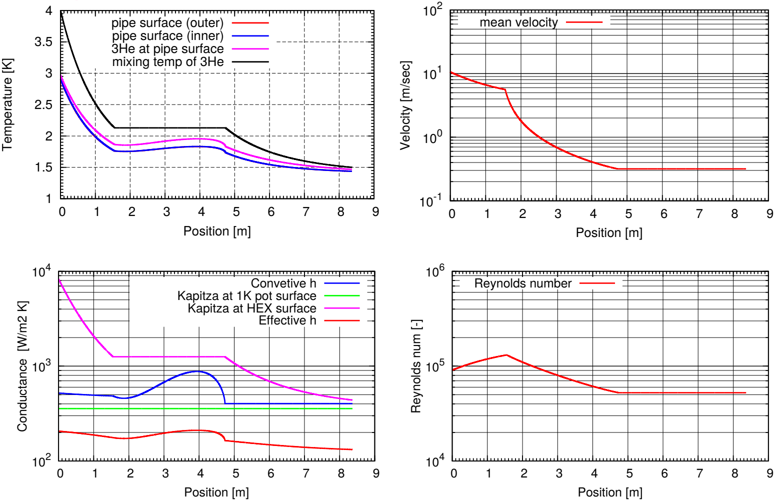
Kapitza conductance strongly depends on surface condition and inpurity in the Cu.
Kapitza of materials acutually used will be measured directly.



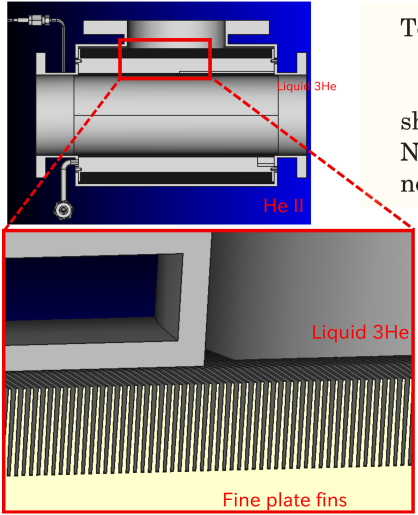
Kapitza conductance
between Copper and He-II
Helium cryogenics, Steven W. Van Sciver

3. Thermo-fluid behaviour of He II around 1 K
Results Examples

1K pot temp, $T_{HEX} = 1.4$ K



3. Thermo-fluid behaviour of He II around 1 K HEX5 (HEX bet. 3He and He II)



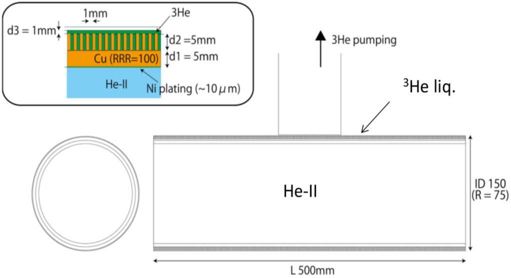
To determine the fine shape and span,

Kapitza conductance and

Buoyant convection behaviour

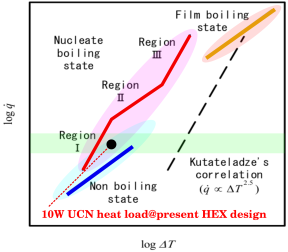
should be considered.

Now to obtain optimal design, simulation is now on going including both effects.



3. Thermo-fluid behaviour of He II around 1 K HEX5 (HEX bet. 3He and He II)

Katagiri et. al. Teion Kogaku vol 40, No7 (2005)



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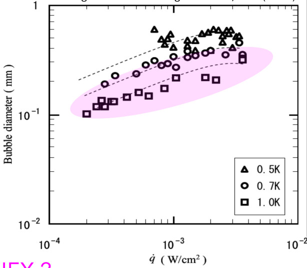
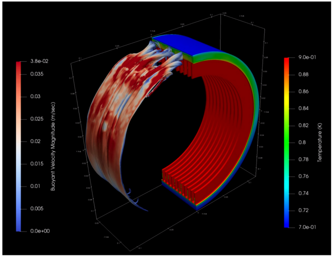




How to optimize the 3He-HeII HEX ?

HEX specifications such as fin shape and span should be chosen by considering free-convection and nucleate boiling of saturated 3He.

A few data of 3He boiling curves gives us good information to optimize the HEX. Simultaneously, simulation studies are now on going for closs checking.

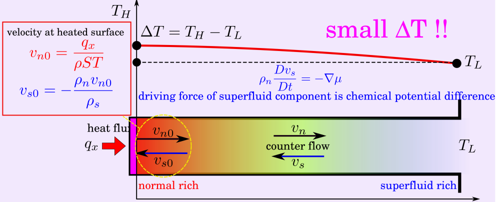
Estimation of Present Design.

gap distance between adjacent fins is 1mm which is several times larger than averaged bubble dia.

Heat transfer enhancement due to nucleate boiling can be expected.

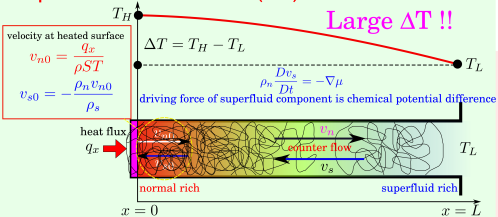
3. Thermo-fluid behaviour of He II around 1 K
Heat transfer of ST. What is $f(T)^{-1}$

Laminar Flow

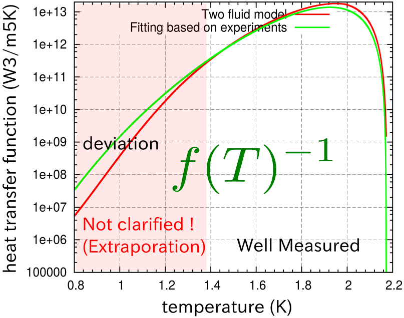


No Friction !!

Superfluid Turbulent (ST)



Mutual Friction!!

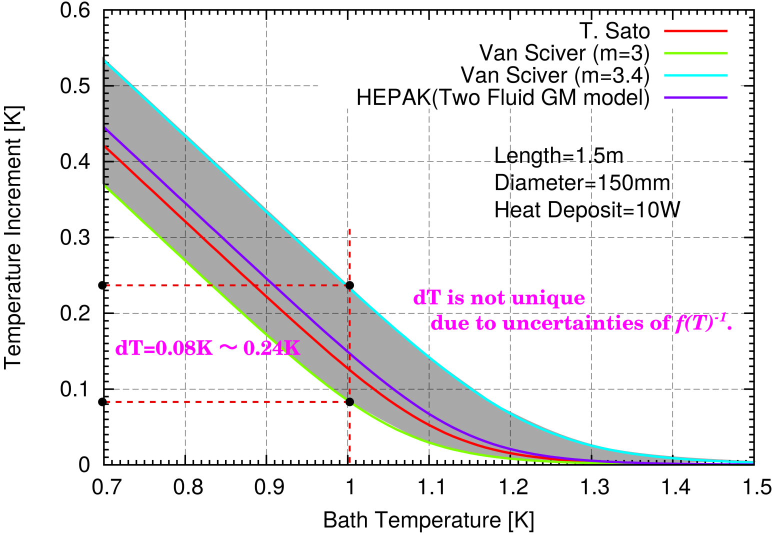


Gorter-Mellink Equation at ST

$$q_x^3 = -f(T)^{-1}\frac{dT}{dx}$$

Heat transfer function, f(T)-inv, at sub K to 1K is not sufficiently clarified.

3. Thermo-fluid behaviour of He II around 1 K
Calculation results



dT is not unique due to uncertainties of $f(T)^{-1}$.

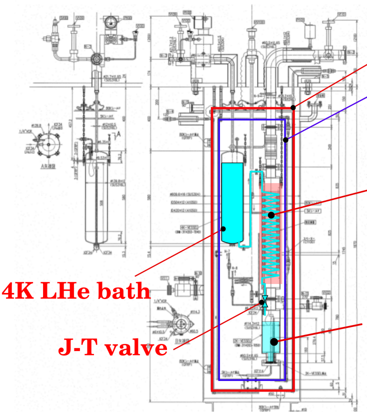
dT=0.08K ∼ 0.24K

5. Experiments purpose and cryostat overview

Two Key Issues

Simulation studies introduced above have following two uncertainties.

1. **Kapitza conductance of Cu with Ni coating**
2. **Heat transfer function, $f(T)^{-1}$**



1K cryogenic system

70 K shield
5K shield
2.2 K HEX
are installed in the cryostat.

2.2 K HEX with spiral coil structure

heat exchange
between 2K return gas and 2.2K LHE

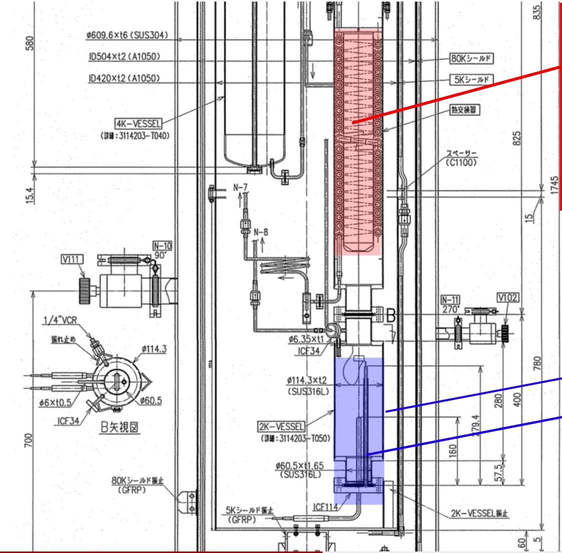
4K LHe bath

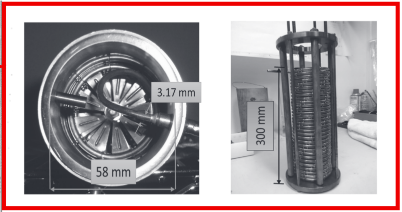
J-T valve

1K He II bath

We will measure Kapitza and FT with TNSC.

5. Experiments
superfluid bath in the cryostat





2.2K Heat exchanger

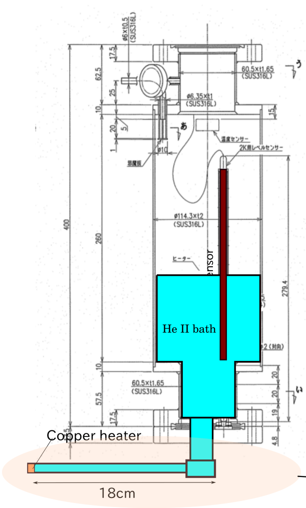
- total length of 2.2K He supply line = 7m
- supply temp reaches 2.4K at 16 W heat load

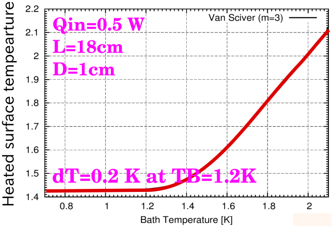
He II bath

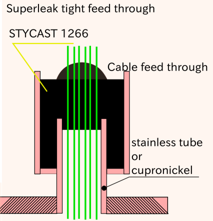
Level sensor for He II bath

5. Experiments

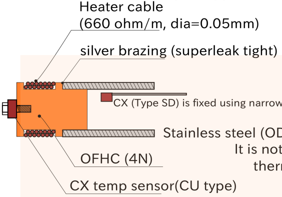
$f(T)^{-1}$ measurement system



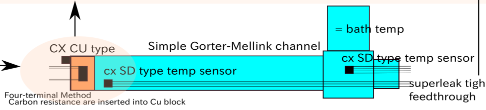




Thermal contruction of STYCAST is larger than Stainless etc.
Stainless tube etc should be covered with STYCAST (see above)
Thermal contruction of STYCAST2850 is similer to metal.
Therefore, STYCAST 1266 is better than 2850.



Stainless steel (OD=10mm, Length=18cm)
It is not good from the view point of thermal conductivity.



Test channel to measure the fT inverse and Kapitza conductance

6. Schedule

- FY2017/Dec: Design and machining of test sample and channel
- FY2018/Feb: installation into the cryostat and begin to measure
- FY2018/Mar: Measurement of $f(T)^{-1}$ and Kapitza and summarize the data.
- FY2018/Apr∼ : continue to measure and feedback experimental results into the simulation. Performance test of the realistic HEX will be measured using the cryostat introduced in the previous page.

7. Summary

- Cryogenic design studies have been continuously done. Some expert says that obtained values are consistent.
- We will build an optimum design by making use of experiments and some kinds of simulations.
- UCN pipe design is quite important. To obtain optimal design, Kapitza conductance and heat transfer function, $f(T)^{-1}$ is quite important. These characteristics will be clarified from experiments which will be done from next month.
- Concerning the $f(T)^{-1}$, existing UCN experimental apparatus in TRIUMF does not have direct measurement system about it, however some important sensors, such as temperature and pressure sensor and flow meter, are installed in the cryo system. So we can get several good information about $f(T)^{-1}$ etc. from this existing UCN apparatus.

  We will clarify $f(T)^{-1}$ and heat transfer characteristics of He II under sub-K from the dedicated experiments and existing UCN apparatus.

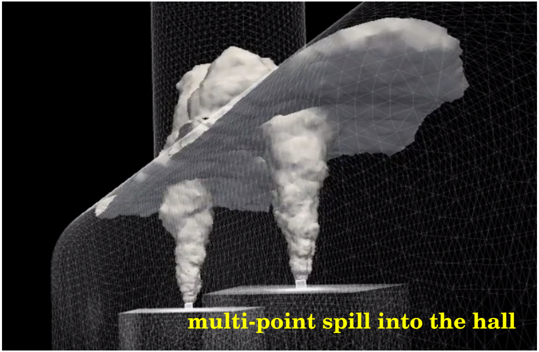
Back Data

Safety Estimation for the Cryogenic System

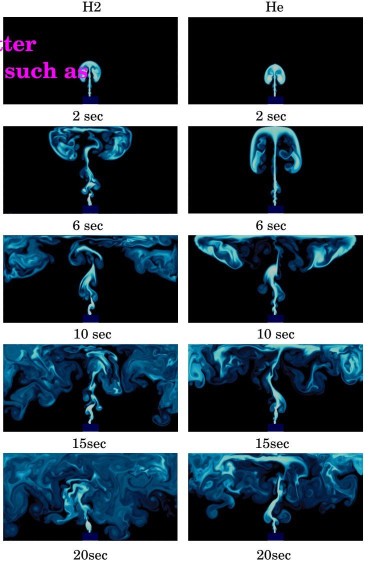
To clarify oxygen dificiency or H2 concentration distribution during some kind of incident had better be clarified to prevent serious secondary damage such as detonation and human damege.

If necessary, dynamic simulation on the oxygen deficiency and H2 concentration will be done.

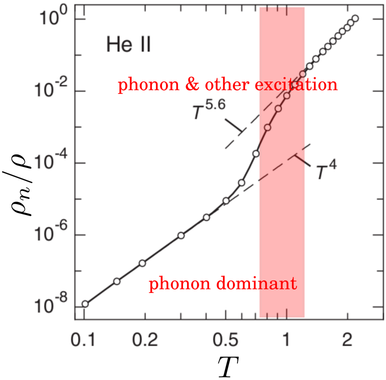
Simulation exaple of He and H2 spill into the hall



multi-point spill into the hall

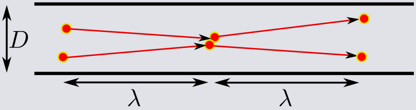


3. Thermo-fluid behaviour of He II around 1 K
Another model around sub-K



power of 4 : phonon dominant
power of 5.6 : phonon + other excitation
(roton)
(Quantized Vortex,QV)

Ballistic Heat Transfer w/o QV
(Phonon Dominant region)



phonon-phonon interaction is dominant

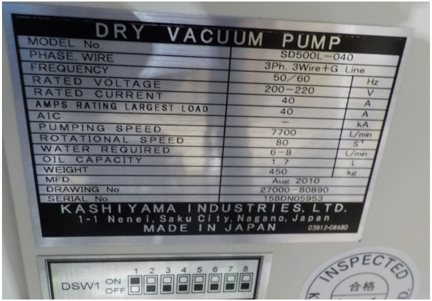
$$Kn = \frac{\lambda}{D} > 1$$

Kinetic motion of phonon w/ QV

phonon-QV (remnant vortex) interaction is dominant
→ Mean free path is much smaller than that
in case of w/o QV

$$Kn = \frac{\lambda}{D} < 1$$

5. Experiments
Kapitza conductance measurement system



DRY VACUUM PUMP

MODEL No.	SD500L−040	
PHASE. WIRE	3Ph. 3Wire+G Line	
FREQUENCY	50/60	Hz
RATED VOLTAGE	200−220	V
RATED CURRENT	40	A
AMPS RATING LARGEST LOAD	40	A
AIC	−	kA
PUMPING SPEED	7700	L/min
ROTATIONAL SPEED	80	S^{-1}
WATER REQUIRED	6−8	L/min
OIL CAPACITY	1.7	L
WEIGHT	450	kg
MFD	Aug. 2010	
DRAWING No	27000−80890	
SERIAL No	158DN05953	

KASHIYAMA INDUSTRIES, LTD.
1-1 Nenei, Saku City, Nagano, Japan
MADE IN JAPAN 03912-08680

manufacturer	KASHIYAMA IND. LTD
Type	Dry Vacuum Pump
P/No	SD500L-040
Capacity	7700 L/min
Input Power	3P 200V / 40A max
Cooling water	8 L/min
Weight	450 kg

5. Brief HEX Specification

- Effective pipe length of HEX for supply line is 5 m $\sim$ 8 m.
- To overcome the Kapitza conductance, HEX of surface with sintered silvered is sometimes employed below 1 K, however it is not necessary to employ the sintered silver coating around sub-K to 1 K. (Siltered silver is required below 0.1 K.)
- Brief design of HEX for counter flow type is as follows. Conceptual desing of this type HEX is done by Prof. Hosoyama.
- We will fabricate with Prof. Hosoyama. We will measure the heat transfer characteristics of this type HEX using the apparatus introduced before.