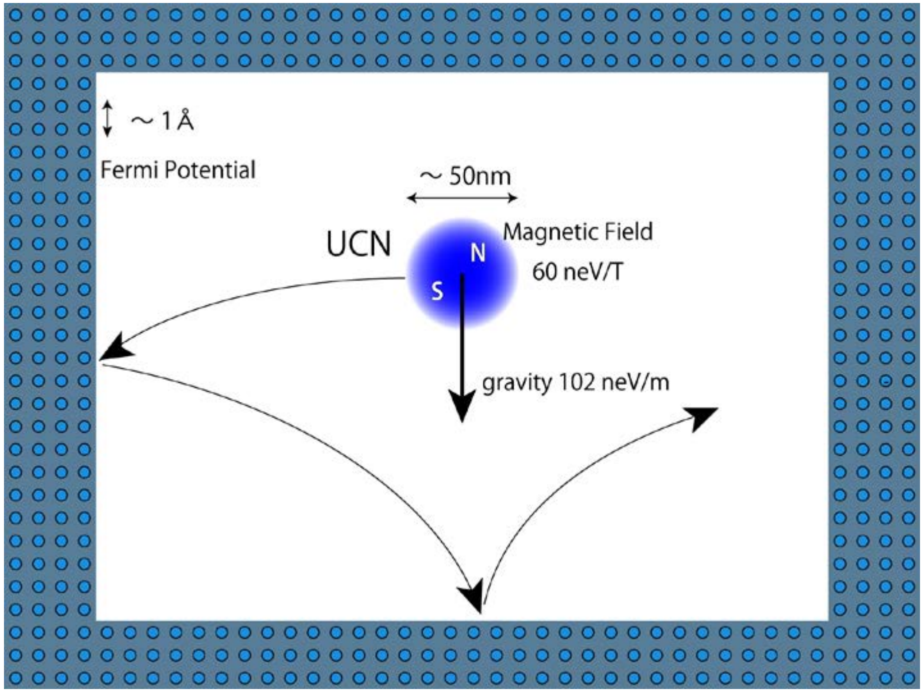
Development a High Intensity Ultra-Cold Neutron Source using Superfluid Helium at TRIUMF

Shinsuke Kawasaki (KEK)
for the TRIUMF Japanese-Canadian UCN Collaboration

outline

- Ultra-Cold Neutron (UCN)
- UCN production by super thermal method
  - storage time
- ^{3}He cryostat
- UCN source at TRIUMF
  - Vertical source <- was discussed by R. Matsumiya yesterday
  - new UCN source
    - with high cooling power
    - cooling scheme
      - temperature distribution
    - UCN production figure of merit as a function temperature
- Summary

Ultra Cold Neutron (UCN)



Ultra Cold Neutron

Energy	~ 100 neV
Velocity	~ 5 m/s
Wave length	~ 50 nm

Interaction

Gravity	100 neV/m
Magnetic field	60 neV/T

Weak interaction

β-decay n → p + e

Strong interaction

Fermi potential 335 neV (^{58}Ni)

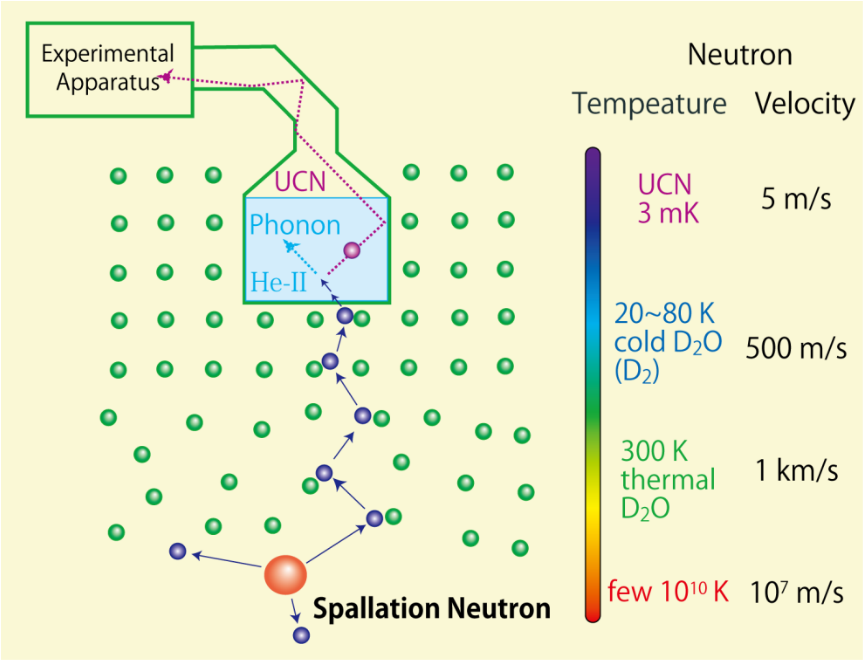
atom distance : ~ Å

UCN feels average nuclear potential

UCN can be confine material bottle

→Use various experiments

UCN production by super fluid Helium



UCN procution

spallation neutron
↓ D_2O, LD2 Moderator (300K, 20K)
cold neutron ～meV
↓ Phonon scattering in He-II
Ultra cold neutron ～100neV

Feature of our source

- spallation neutron
  - High neutron flux
    - small distance between target and UCN production volume
- Super-fluid Helium converter
  - long storage lifetime
    - up-scattering by phonon
      - τ_s = 600 s at T_{HeII} = 0.8 K
      - τ_s = 36 s at T_{HeII} = 1.2 K
      - $1/\tau_s \propto T^7$

UCN Storage Life Time

UCN density

= Pτ (1 – exp(-t/τ))

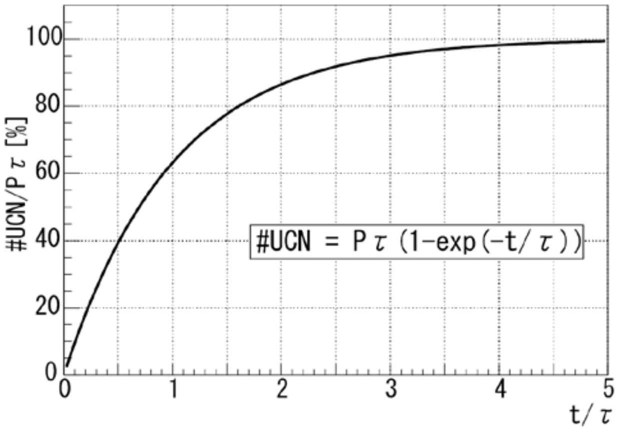
P : UCN production rate ∝ cold neutron flux

τ : Storage time

t : proton irradiation time

- large cold neutron flux
- long τ

are important



UCN density during proton irradiation

UCN Storage Life Time

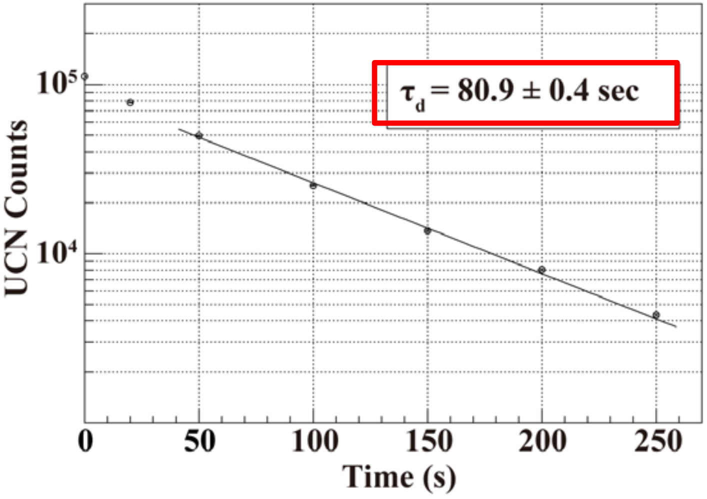
$$1/\tau = 1/\tau_{up-scat} + 1/\tau_{abs} + 1/\tau_{wall} + 1/\tau_{\beta}$$

τ_{abs} : absorption by ^{3}He ^{3}He/^{4}He <10^{-11}

$\tau_{up\text{-}scat}$: phonon up-scattering ∝T^{-7}

τ_{wall} : wall loss clean surface

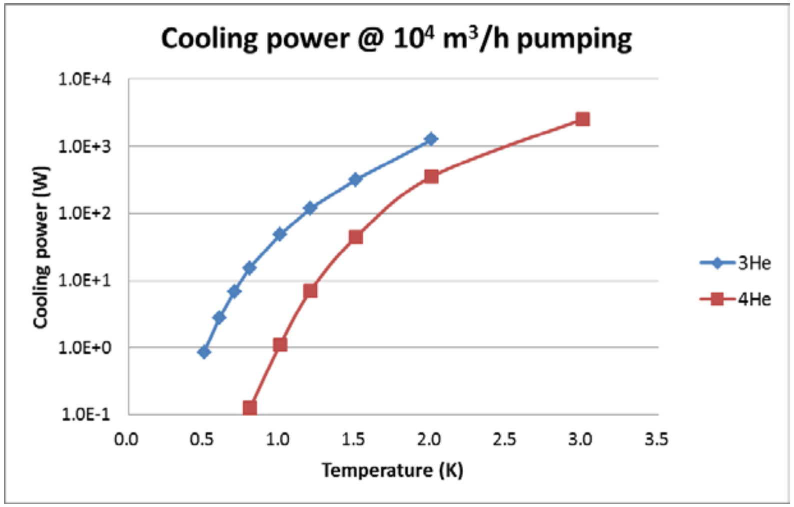
τ_{β} : β decay (886s)

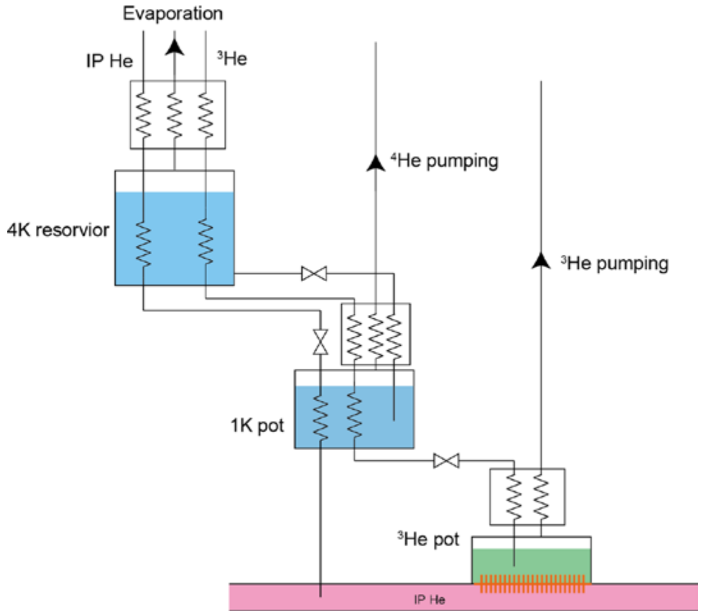


UCN Storage Time measurement at RCNP

^{3}He cryostat

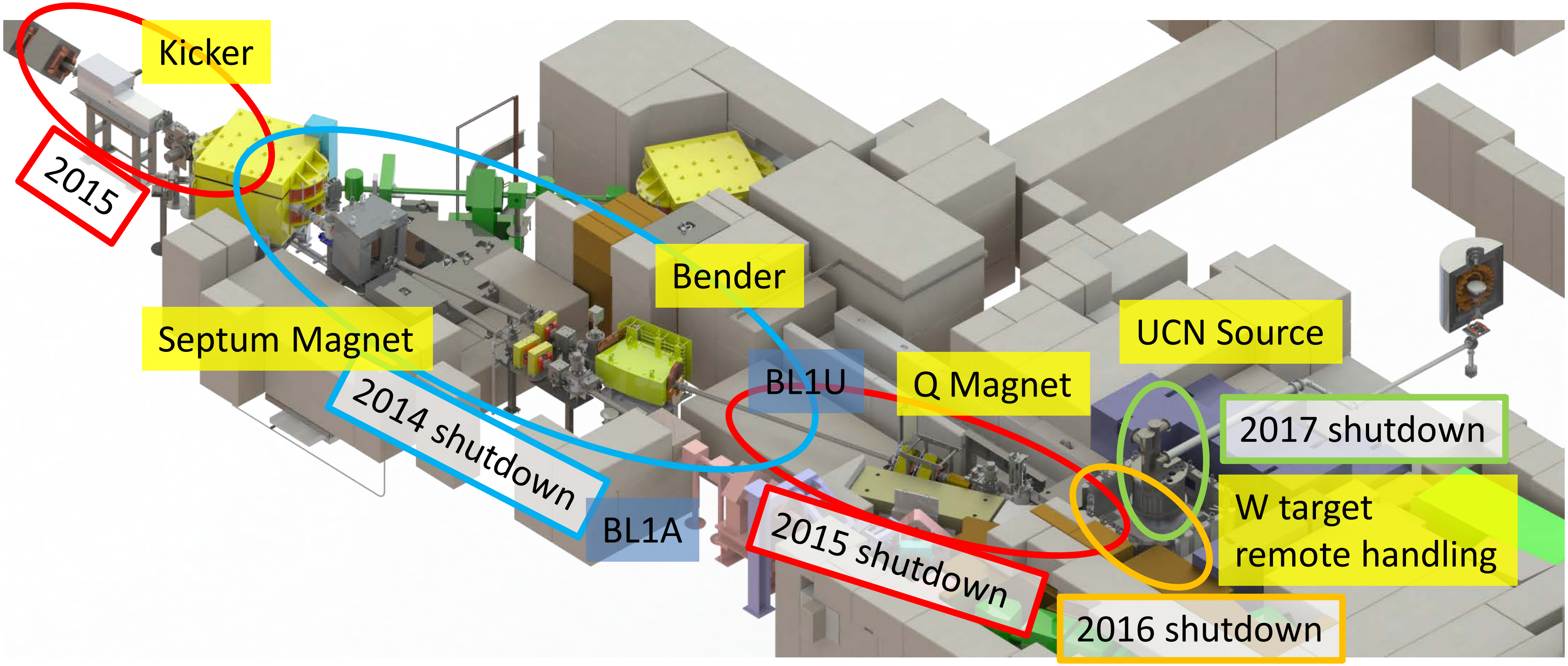
- to keep He-II temp. 1.0K
- decompressed Helium 3
- ^{3}He vs ^{4}He
  - vapor pressure @ 0.8K
    - ^{3}He: 9 Torr
    - ^{4}He: 0.1 Torr
  - cooling power
    @ 1.0 K with 10, 000 m^3/hour pumping
    - ^{3}He: 48 W
    - ^{4}He: 1.1 W
  - Cooling power depend on temperature
    - larger vapor pressure in higher temperature
- ^{3}He cooling
  - evaporated ^{4}He gas
  - liquid He bath 4.2K
  - 1K pot (^{4}He pumping) 1.4K
  - ^{3}He pumping < 1.0K





Helium flow diagram

UCN Source @ TRIUMF



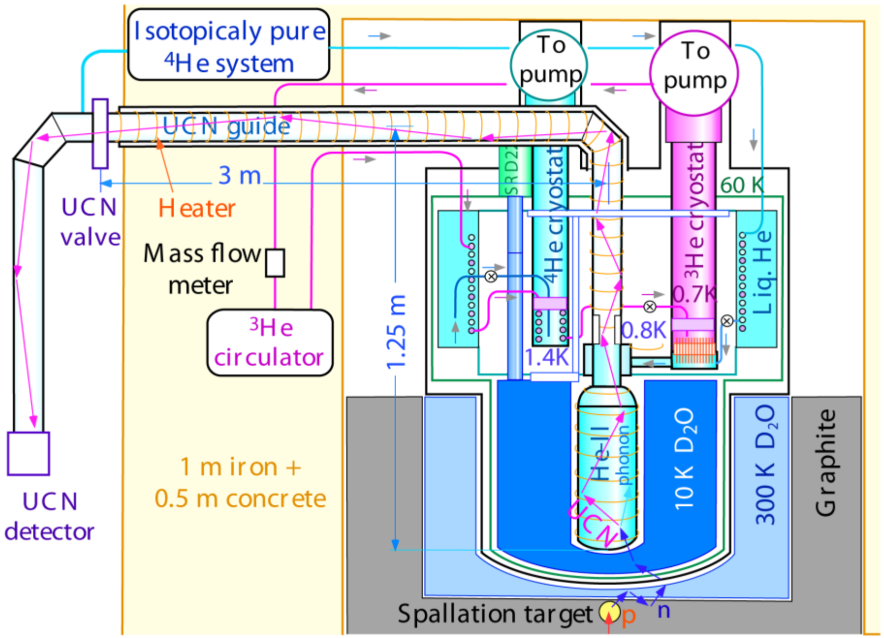
Major Milestone

✓ - 2016	proton beam line for UCN source(BL1U 500MeV, 40μA)
✓ 2016	commissioning proton beam line and cold neutron production
2017	UCN production by Vertical source (~ 1μA)
- 2020	High intensity UCN source (40μA)

Vertical UCN source

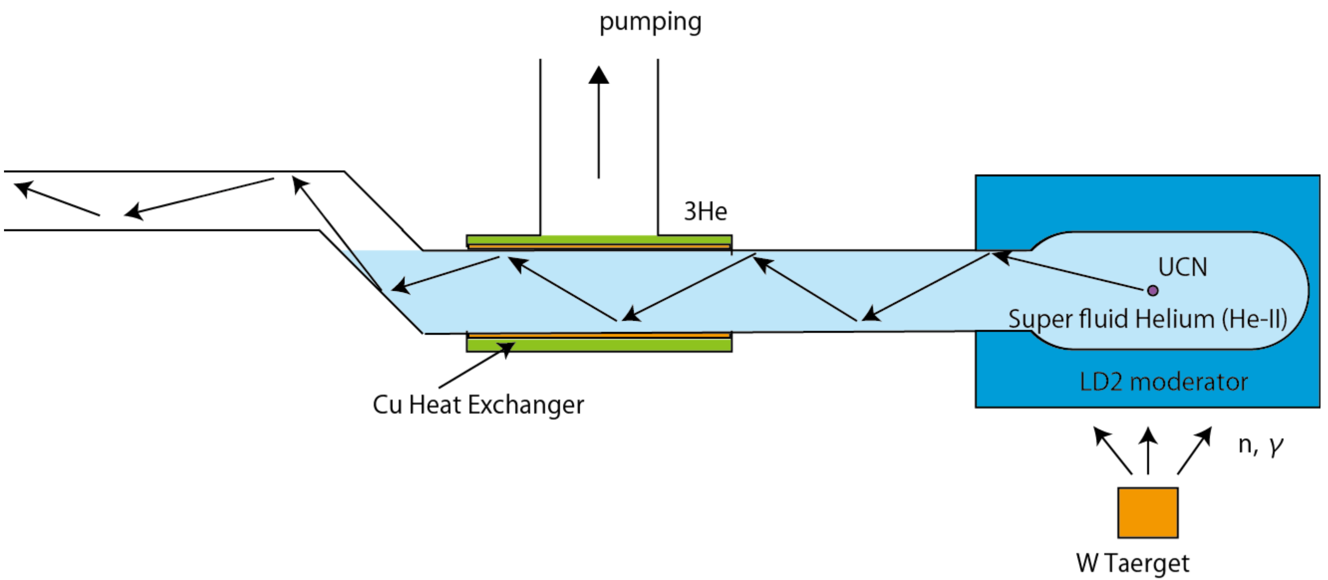
- Vertical UCN source
  - developed at RCNP
    - $T_{\text{He-II}}$: 0.8 K
    - UCN life time: 81 sec
    - UCN density: 9 UCN/cm^3
      - 400 MeV × 1 μA = 0.4 kW

Y, Masuda et. al., Phys. Rev. Lett. 108, (2012), 134801



- move to TRIUMF
  - modification for safety requirement
- 2017 Jan. – Apr. install at Meson hall
- 2017 Nov. UCN production

new UCN source



proton beam power

0.4 kW at RCNP -> 20 kW at TRIUMF

A new helium cryostat which has high cooling power is necessary

Heat load on He-II depends on geometry

- distance between target and He-II
- cold moderator
- gamma shield

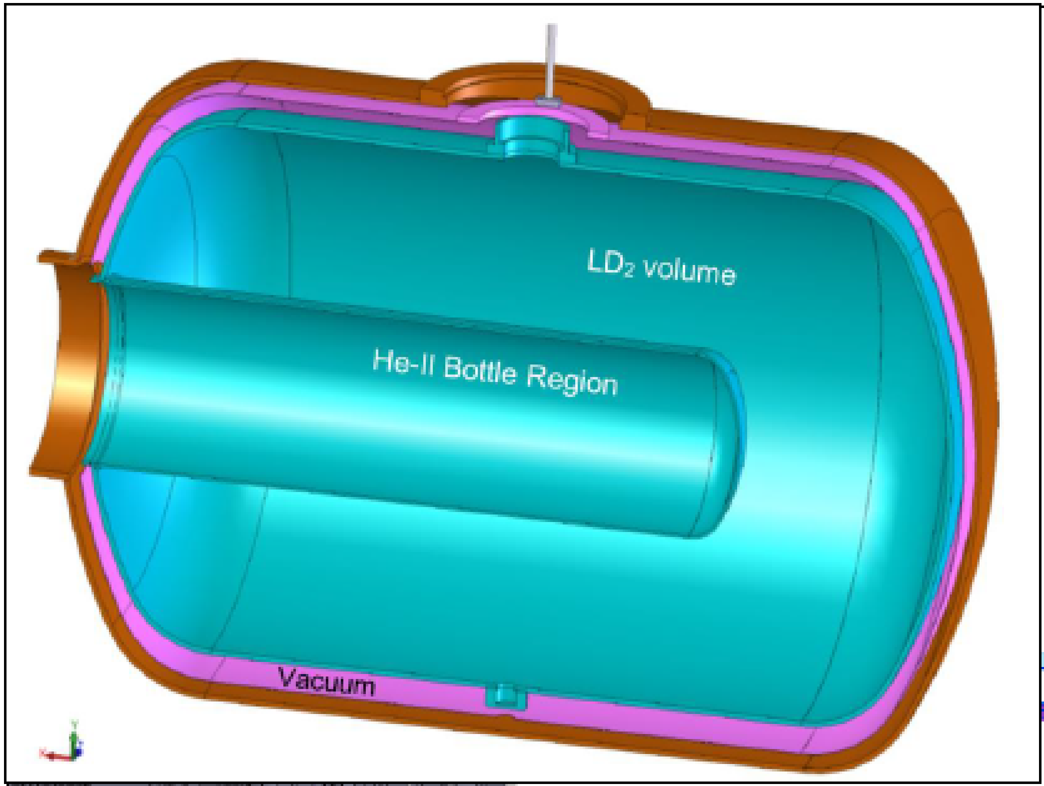
and so on

⇨

- higher cold neutron flux cause higher heat load
- ratio of this is constant in some region

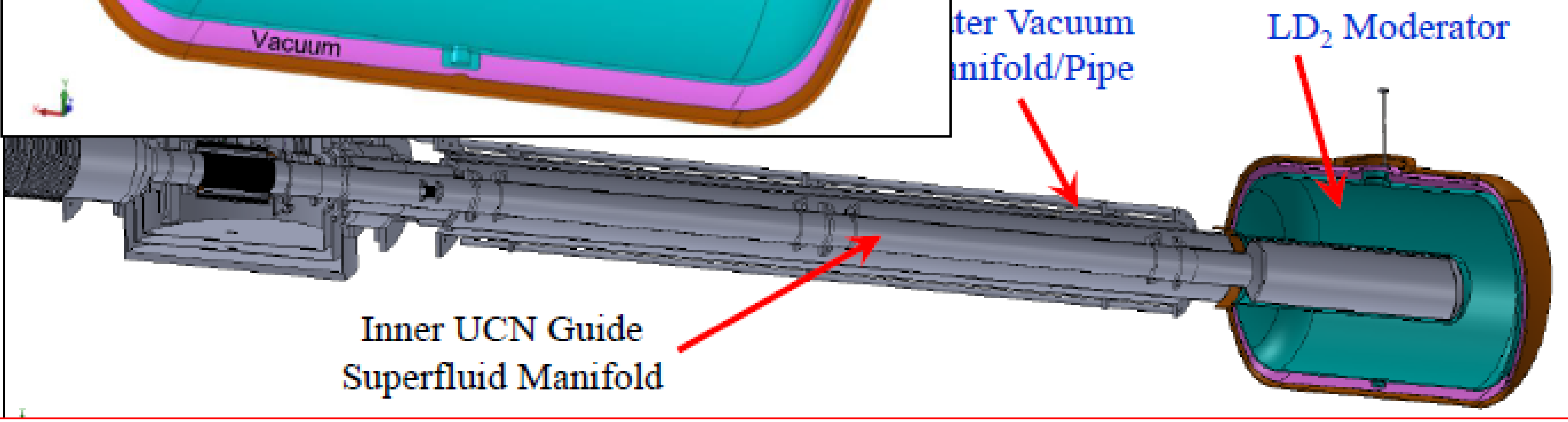
Optimization is necessary

LD_2 Moderator Cryostat



- Aluminum Cryostat
- 125 Liquid Litres of D_2
- 75 W Heat Load
- Circulate LD_2 to remote condenser + cryo-cooler

- $300k for LD2 cryostat system
- $250k for LD2



5 – 9 times large cold neutron flux is achivable compared with ice D_2O

UCN Production Figure of Merit

ideal case: ^{3}He temperature is same as UCN production volume

- UCN density $\rho \propto P \times \tau$
  - P : production rate

    $\propto$ cold neutron flux

    $\propto$ heat load

    = cooling power

    (function of T)

    $\propto$ Vapor pressure * latent heat
  - τ : UCN life time
    - $1/\tau = 1/\tau_\beta + r*1/\tau_{upscat} + 1/\tau_{wall}$
      - $\tau_\beta = 880$s
      - $\tau_{upscat} \propto T^{-7}$
      - $1/\tau_{wall}$: ~100sec (depend on surface quality)

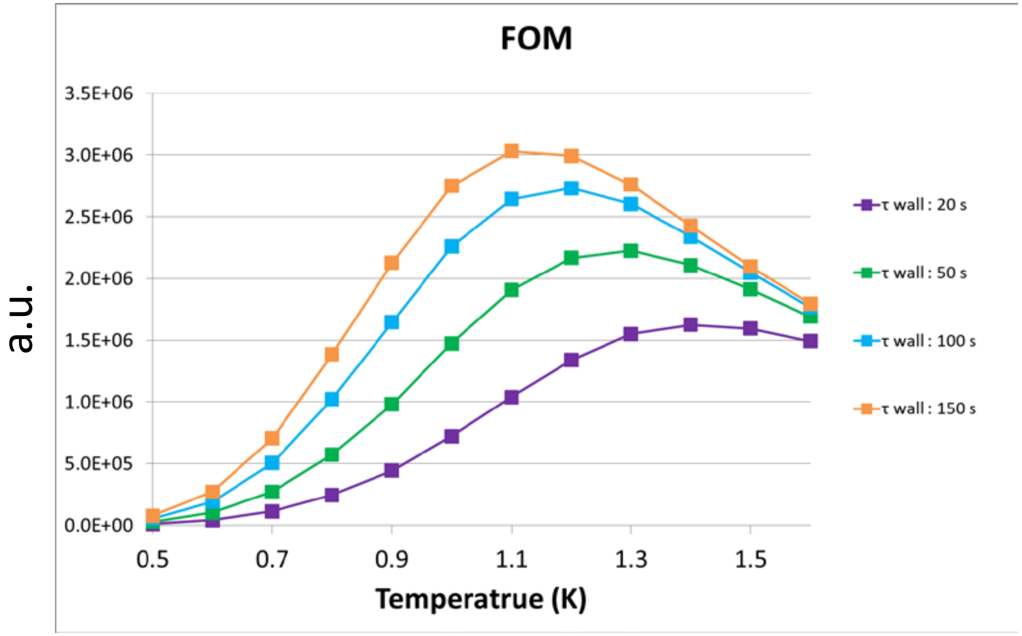


Figure of Merit (FOM) as a function of T
FOM = Cooling power x τ

In Reality

- There is temperature difference between UCN production volume and ^{3}He
  - UCN lifetime
    - temperature at UCN production volume
  - cooling power
    - ^{3}He temperature
- The temperature difference is caused by following reason
  - deposit heat at UCN production volume
  - Heat transfer in He-II
  - Kapitza conductance of heat exchanger

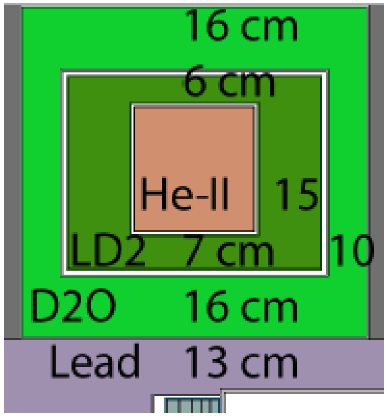
Heat load on UCN production volume

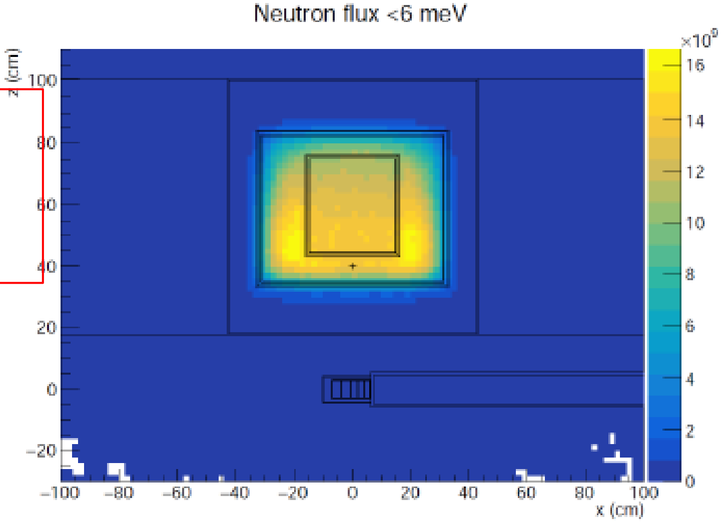
TRIUMF Preliminary results

Will be discussed by S. Wolfgang

- Radial LD_2 layer more important than lower
- Best He-II-bottle height 30-40 cm, radius 15-20 cm (for current cooling scheme)
- Limited by amount of LD_2!
- For He-II height 30 cm, radius 15 cm, 40 µA beam:
  - 20.6 l He-II, 115 l LD_2
  - $3.9 \cdot 10^7$ UCN/s
  - 7.9 W max. heat in He-II
  - 65 W max. heat in LD_2
- Best strategy to reduce LD_2: reduce He-II size and go closer to target

deal with such a huge heat load around 1 K

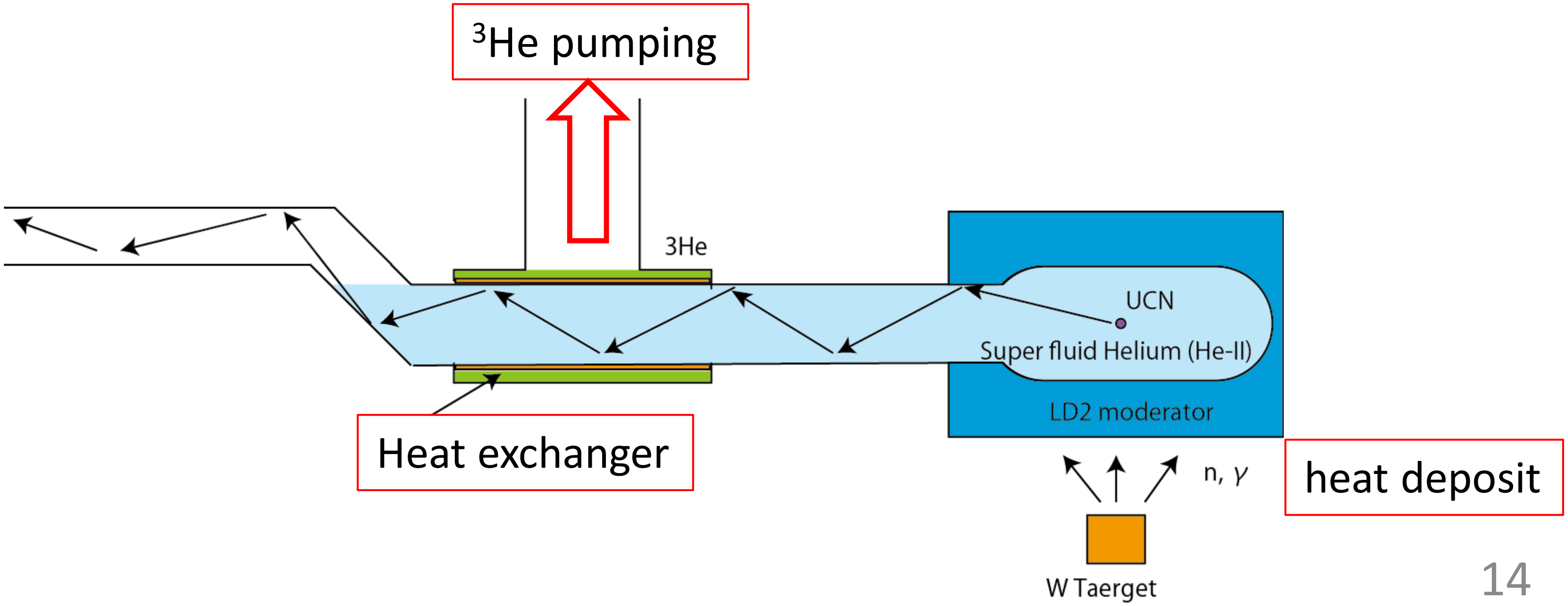




2017-10-18

Heat transfer between heating point and cooling point

- Heat transfer in He-II
  - below 1 K, heat transfer is not good because of low fraction of normal fluid which convey heat (two fluid model)
- Kapitza conductance of heat exchanger
  - Conductance at the surface between liquid and solid is small at low temperature



^{3}He pumping

Heat exchanger

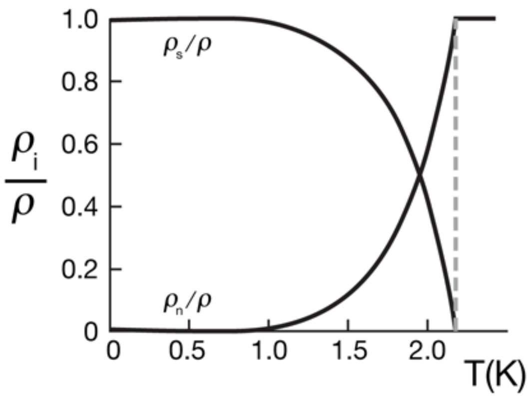
heat deposit

Superfluid Helium

Two Fluid Model

	Normal fluid	**Superfluid**
Viscosity	H_n	$\eta_s = 0$
Entropy	S_n	$S_s = 0$

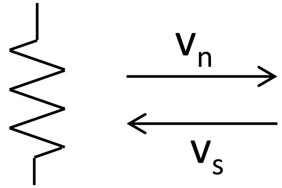
- Ratio of super/normal component depends on temperature dependence.
- fraction of normal mode become small in low temperature.



10.1103/Physics.3.5

Heat transport

- Since superfluid has no entropy, heat is transported only by normal fluid.
- Heat transport in low temperature (< 1K) become small because of small fraction of normal fluid

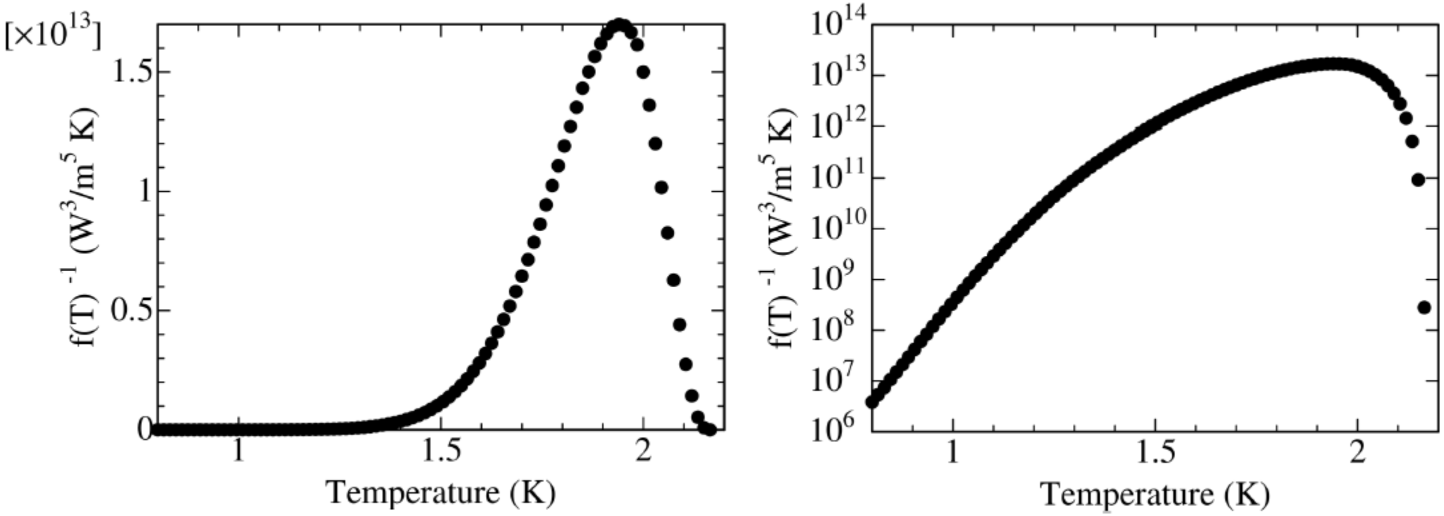


Heat source

Gorter-Mellink Equation

$$q_j(\mathbf{r}) = -\left(f(T)^{-1} \frac{\partial T(\mathbf{r})}{\partial x_j} \right)^{1/3}, \quad f(T) = \frac{A_{gm}\rho_n}{\rho_s^3 s^4 T^3}$$

$q_j(\mathbf{r})$: [W/m^2] Heat Flux vector at $\mathbf{r}$.
$f^{-1}(T)$: [W^3/m^5 K] Heat transfer function. $(\Leftrightarrow \; q_j = -\lambda \partial_j T)$
A_{gm}: Gorter-Mellink mutual friction parameter, [m·sec].



$f(T)^{-1}$: Heat transfer function of He-II based on Two fluid model

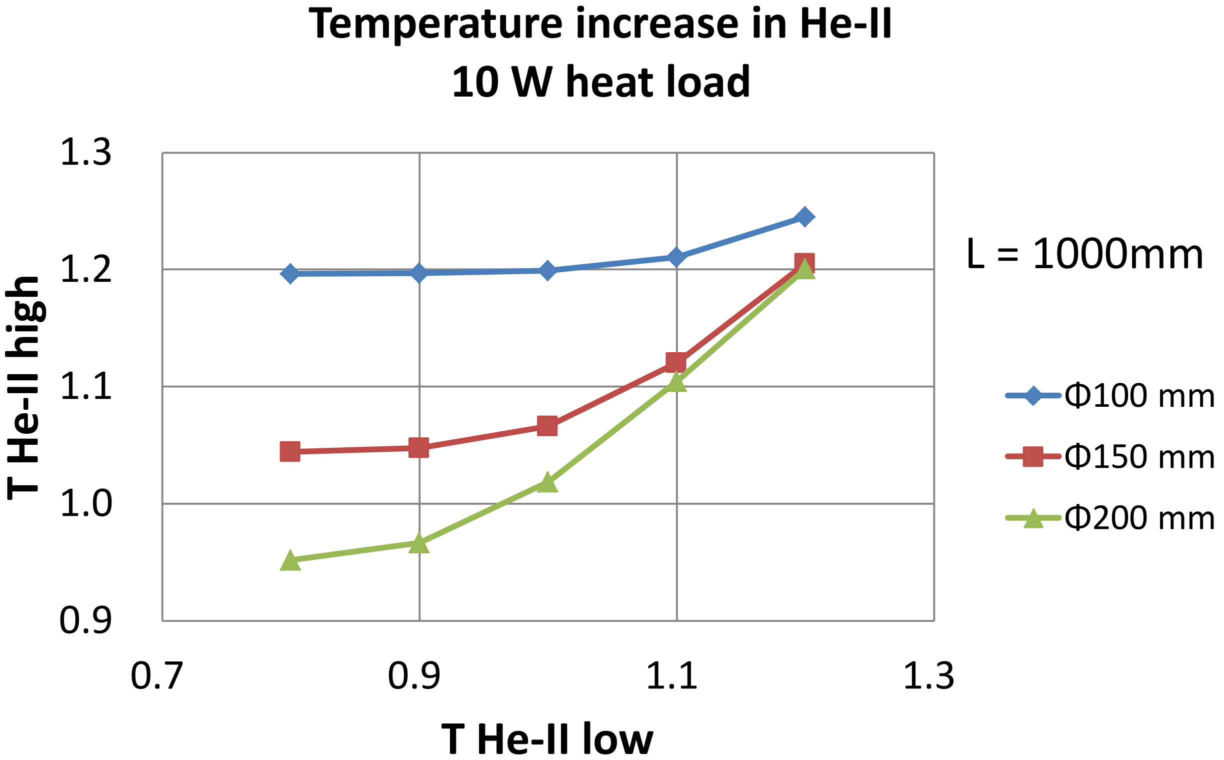
Temperature difference in He-II

Chamber temperature, T_H, can be solved numericall using following Gorter-Mellink equation.

$$Q_{in} = \left(\frac{A^3}{L} \int_{T_L}^{T_H} f(T)^{-1} dT \right)^{1/3}$$

A : cross section of He-II

L : distance of heat transfer

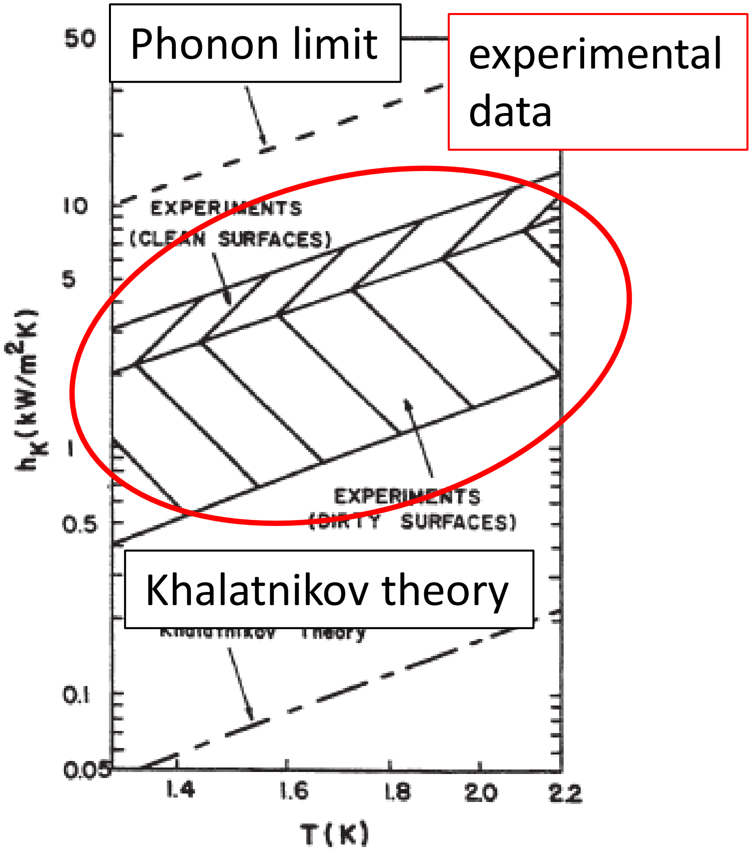


Temperature increase in He-II
10 W heat load

L = 1000mm

Kapitza Conductance

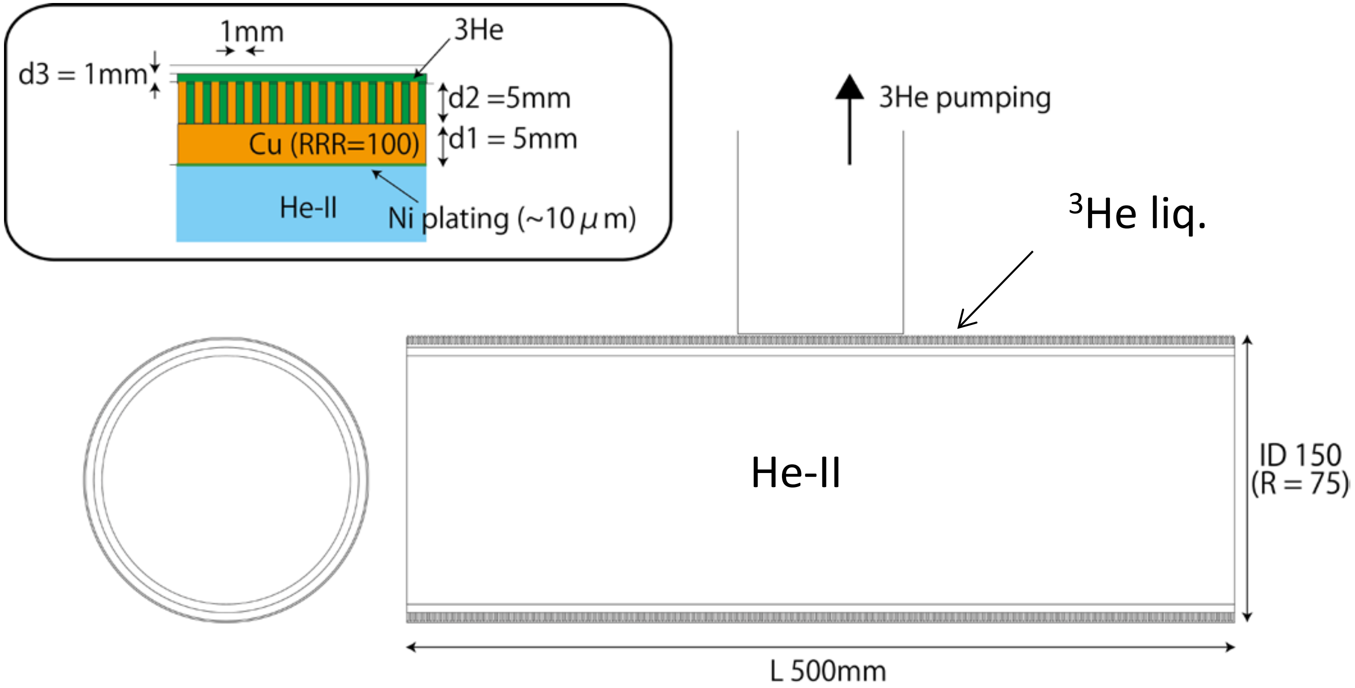
- Kapitza conductance, $h_K(T)$ is a function of temperature.
- There are several theory on Kapitza conductance.
  - Phonon limit
    - $h_K(T) \sim 4500\, T^3$ [W/m^{2}K]
      - 2 - 10 times larger than measured
  - Khalatnikov theory
    - $h_K(T) \sim 20\, T^3$ [W/m^{2}K]
      - 10 - 100 times smaller than measured
- Experimental data strongly depends on surface quality
  - plan to measure Kapitza conductance of material before fabricating a heat exchanger



Kapitza conductance between Copper and He-II

Helium cryogenics, Steven W. Van Sciver

Heat exchanger



Cu Heat exchanger should be plated by Ni

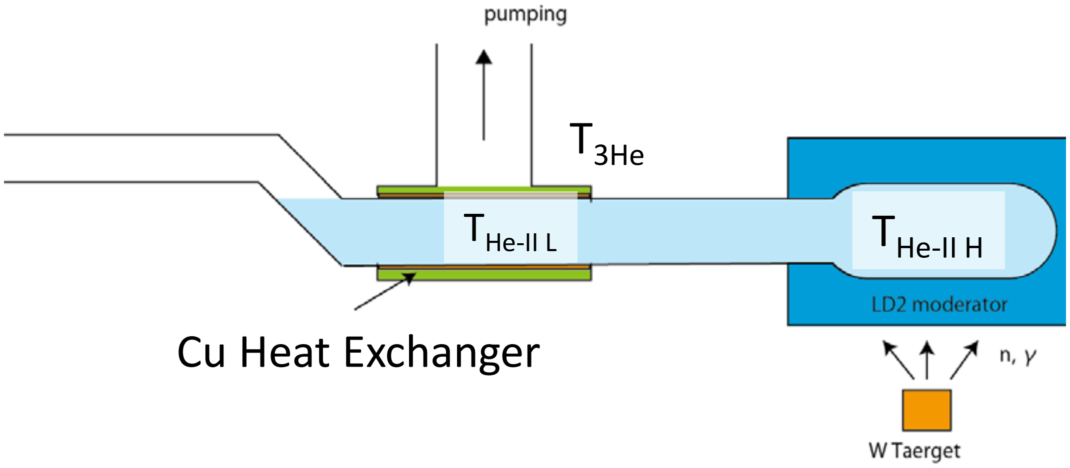
Kapitza conductance between Cu-Ni is large enough since junction is solid-solid

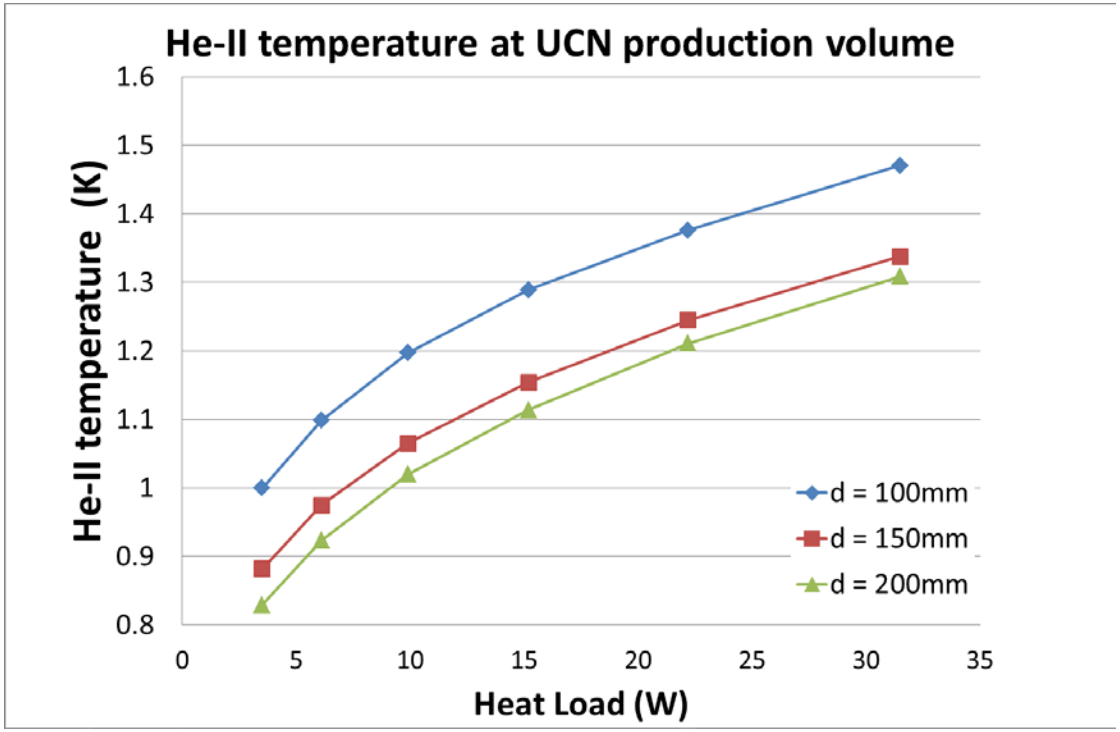
- Kapitza conductance between Ni and He-II
  $h_{K\ Ni}(T) = f*h\_K_{K\_Cu}(T)$ $f = 0.61$
- Kapitza conductance between Cu and 3He
  $h_K(\mathrm{HeII}) = (1.2 - 2.6)\ h_K(\mathrm{3He})$

ex) average quality of Cu, 10 W heat load

- junction between He-II and Ni
  - $h_{K\ Ni}$ (1.0K) = 244 [w/m2 K]
  - $\Delta T_{\text{He-II – Ni}} = 0.16$ K
  - $T_{Ni} = 0.84$ K
- junction between Cu and 3He
  - $h_{K\ Ni}$ (0.84K) = 232 [w/m2 K]
  - $\Delta T_{\text{He-II – Ni}} = 0.09$ K
  - $T_{3He} = 0.75$ K

Equilibrium temperature





Equilibrium temperature can be calculated as a function heat load.

example)

d = 150 mm, L = 1,000 mm
pumping speed 10,000 m^3/hour
Heat load : 10 W case

Temperature distribution

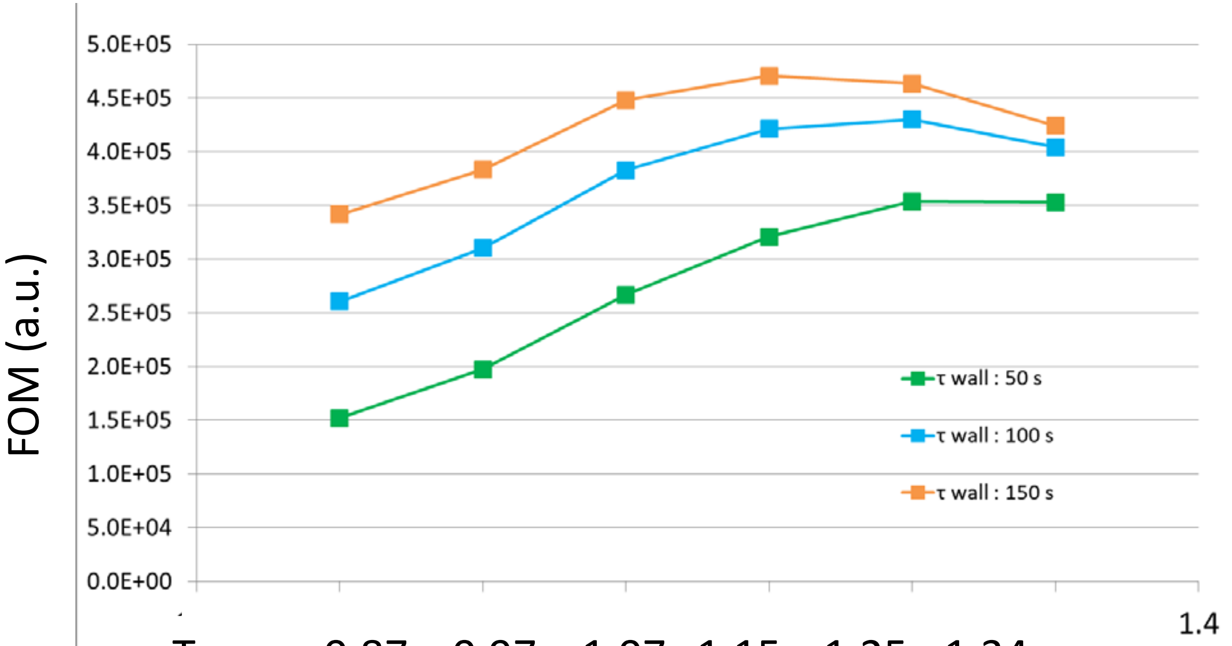
$T_{He\text{-}II\ H}$: 1.06 K ($\tau_{up\text{-}scat}$ = 87 sec)
$T_{He\text{-}II\ L}$: 1.00 K
$T_{Cu\ H}$: 0.84K
$T_{Cu\ L}$: 0.83 K
T_{3He} : 0.75 K
ΔT = 0.31 K

FOM in real case

temperature increase between UCN production volume and ^{3}He is take into account

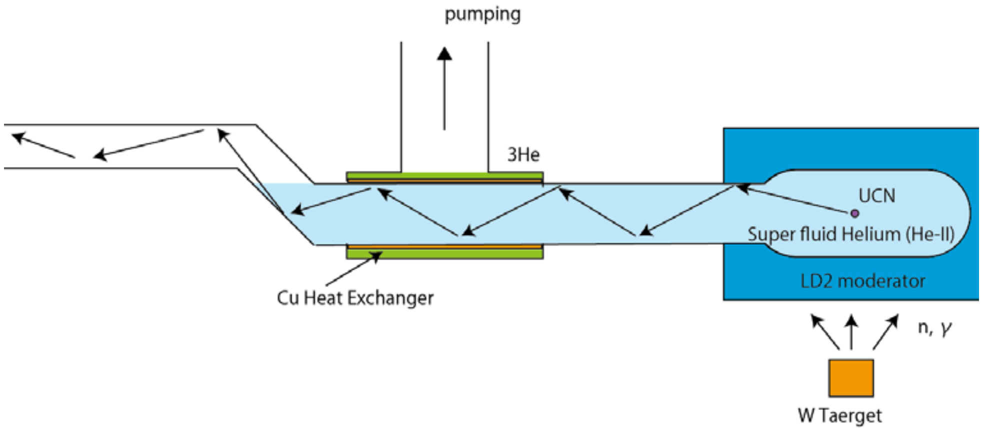
L = 1000mm, d = 150 mm

FOM = Cooling power x τ

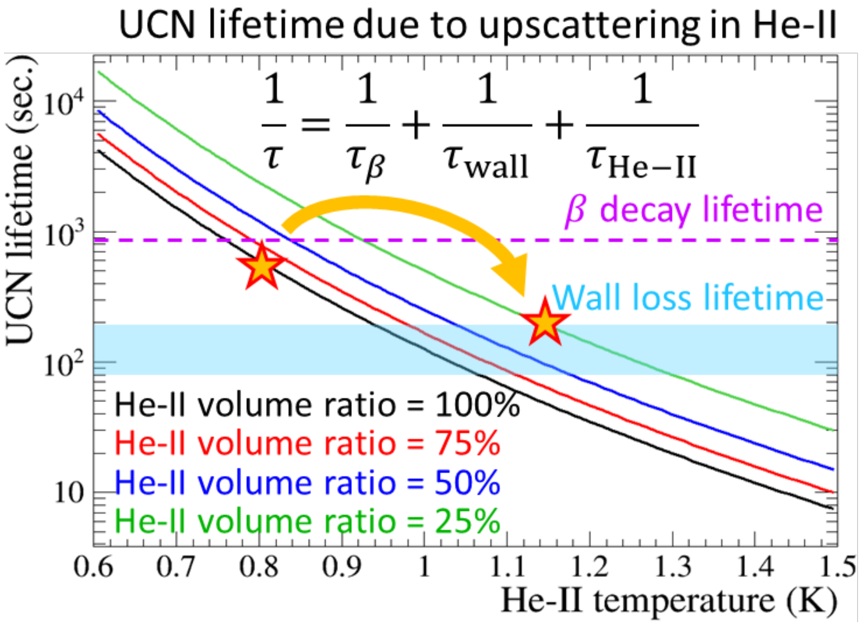


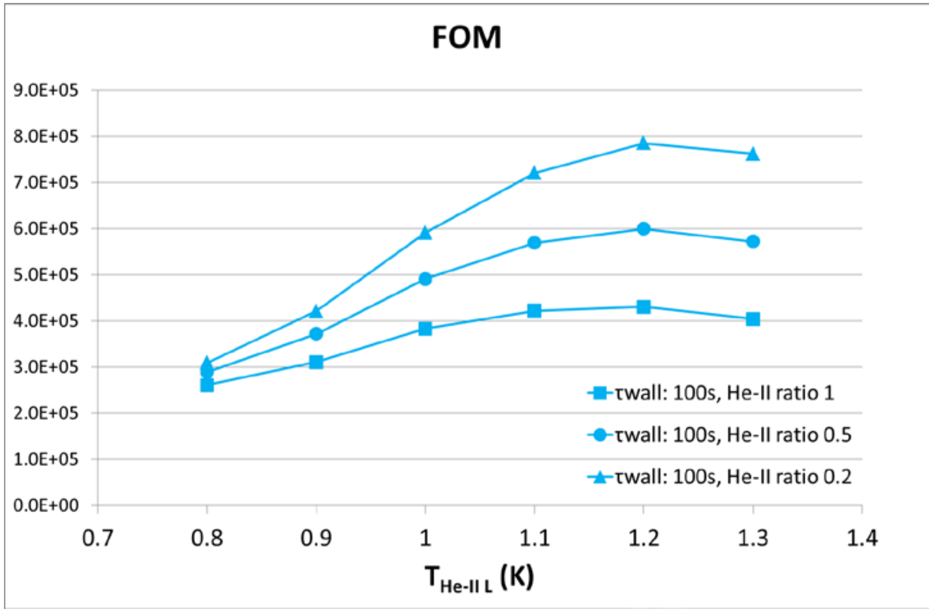
Temperature [K]	$T_{He\ H}$	0.87	0.97	1.07	1.15	1.25	1.34
	$T_{He\ L}$	0.80	0.90	1.00	1.10	1.20	1.30
	T_{3He}	0.65	0.69	0.75	0.81	0.87	0.92
$\tau_{up\text{-}scatt}$ [s]		340	160	58	24	11	6
cooling power [W]		4.1	6.1	9.8	15	22	31

Effect of He-II Volume ratio



- Volume ratio of He-II and Vacuum is also important parameter.
- Total lifetime is increase when volume ratio is small
- UCN scattering with vapor He become serious when He-II temperature above 1.4 K





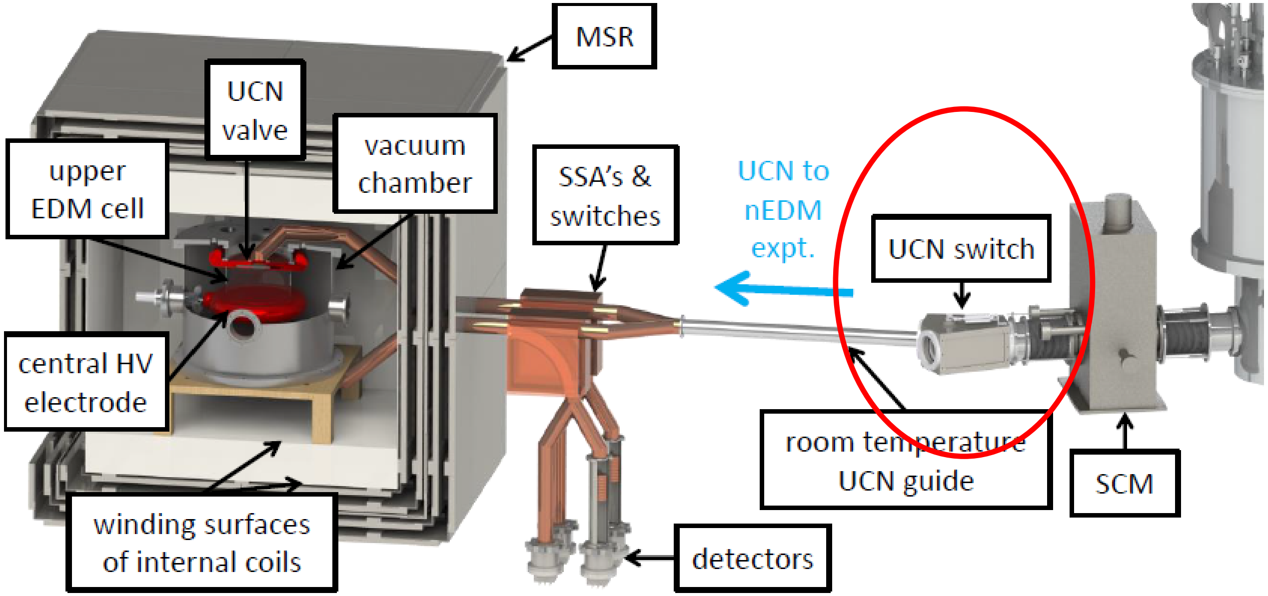
He-II cryostat

- A new He-II cryostat is been developing
  - TRIUMF proton beam line BL1U

    500 MeV × 40 μA = 20 kW
  - necessary cooling power is around 10 W at 1.0 K
  - Heat conductance is important
    - inside He-II
    - Kapitza conductance between He-II/3He and heat exchanger
  - FOM can be calculated as a function of temperature

    FOM = cooling power × UCN life time
  - Optimum working temperature is around 1.0 – 1.2K

Second UCN port : Y switch



- Bend is necessary for radiation protection
  - not to see target area directly
- Y switch can be diverted UCN to another area.
  - R&D for UCN guide, detector and so on
  - open for user facility in future

Summary

- We will start UCN production with vertical UCN source comes from RCNP
  - limit of proton beam power is ～0.5 kW due to small cooling power
- High intensity UCN source is been developed
  - proton beam power : 500 MeV * 40 µA = 20 kW
  - new ^{3}He cryostat with higher cooling power
    - necessary cooling power : ~10 W at 1.0 K
  - FOM can be calculated as a temperature
    - optimum temperature is 1.0 – 1.2 K
  - Final optimization is on going
    - > 2.3×10^7UCN/sec.
    - > 600 UCN/cc at EDM cell -> statistical error of 10^{-27} ecm / 100 MT day
  - Plan to produce UCN from 2020