neutron electric dipole search at TRIUMF

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for TUCAN collaboration

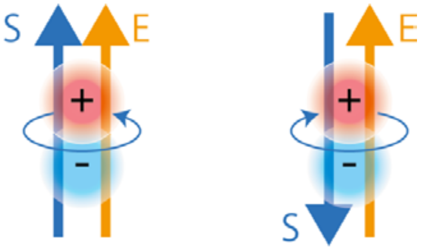
outline

- Neutron electric dipole moment
- Ultra-cold Neutron (UCN)
- UCN production by super thermal method
- UCN source at TRIUMF
  - Vertical source
    - developed at RCNP
    - first UCN production at TRIUMF on November 13, 2017
  - UCN source upgrade
    - LD2 moderator
    - High cooling power helium cryostat
    - expected statistics

Neutron Electric Dipole Moment (nEDM)

Sakharov conditions
Baryogenesis

1. Baryon number violation.
2. C-symmetry and CP-symmetry violation.
3. Interactions out of thermal equilibrium.



s → -s

d → d

T reversal

- Electric Dipole moment
  - Vector derived from charge distribution

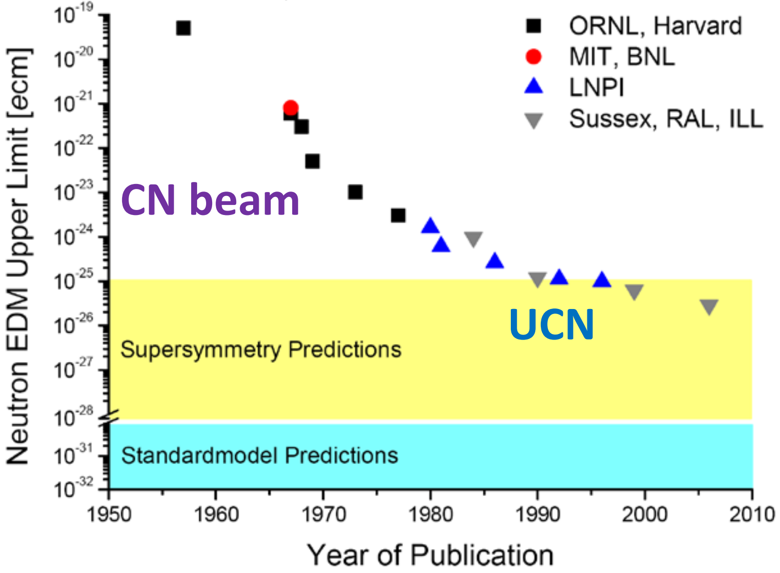
$$\vec{d} = d\frac{\vec{s}}{|\vec{s}|}$$ unit: e cm

d≠0 → T violation

Assume CPT conservation

→ CP Vioration

history nEDM measurement



nEDM prediction
SM ∼10^{-32} ecm

Probe of beyond SM physics

current upper limit of nEDM

3.0×10^{-26} ecm **@ILL, Grenoble**

statistics 1.5×10^{-26} ecm

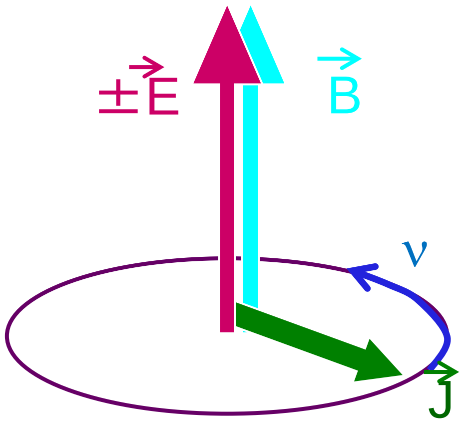
systematics 0.7×10^{-26} ecm

Statistically limited
–> necessity of high intensity UCN source

How to measure nEDM?

Measure precession frequency under electro-magnetic field

$$H = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}$$



$\hbar\omega = 2\mu_n B \pm 2d_n E$

precession frequency

$$\hbar\omega = 2\mu_n B \pm 2d_n E$$

difference

$$\Delta\omega = \omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow} = \frac{4dE}{\hbar}$$

in case of E = 10kV/cm, d = 10^{-27}ecm

$$\Delta\omega = 4 \times 10^{-7} Hz$$

cf. Larmor frequency of neutron
30Hz @ B_0 = 1μT

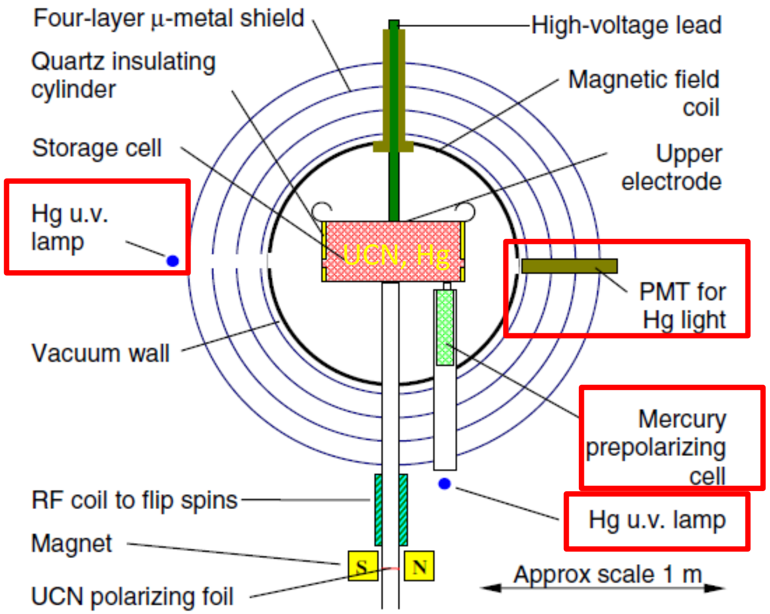
accuracy of 10^8

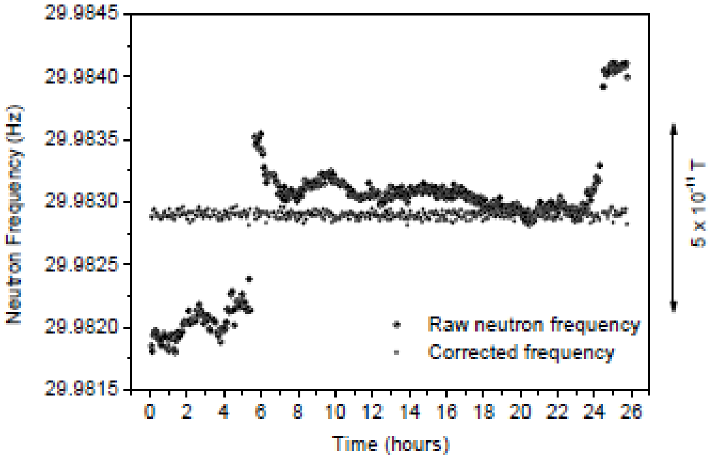
→ High frequency determination accuracy
(Ramsey resonance technique)

and

→ High field stability
→ Co-matnetometer

co-magnetometer





P. G. Harris *et al.*, Phys. Rev. Lett. **82**, 904 (1999).

frequency shift

$$\Delta\omega = 4 \times 10^{-7} Hz$$

(E = 10kV/cm, d = 10^{-27}ecm)

cf. Larmor frequency of neutron

30Hz @ B_0 = 1μT

required magnetic field stability : 10^{8}!!

1μT * 10^{-8} = 10 fT

It is difficult to stabilize magnetic field to such an accuracy

-> monitor and correct magnetic field

co-magnetometer

- feels same magnetic field as UCN

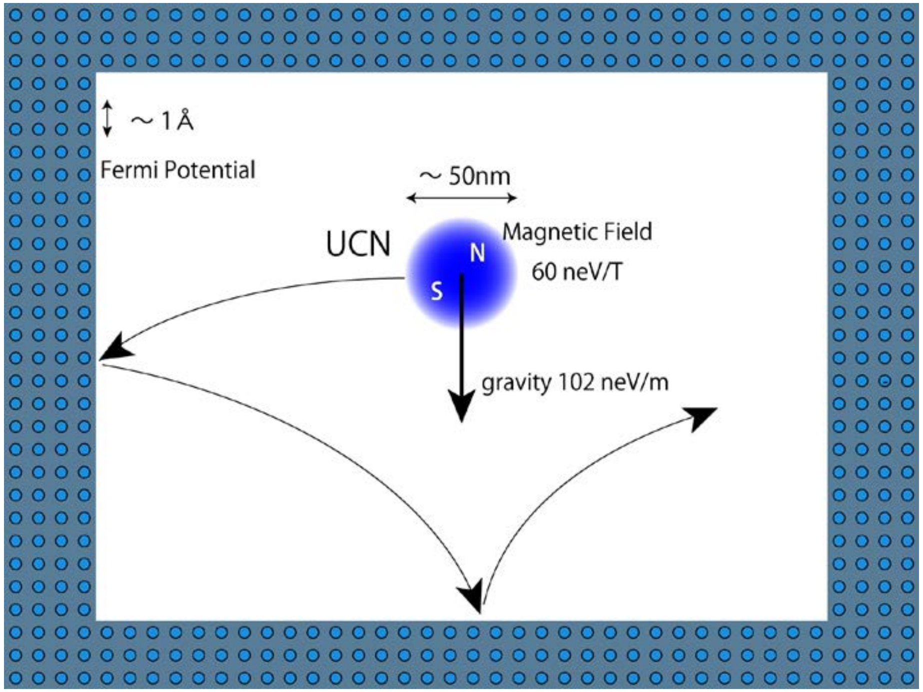
ILL use ^{199}Hg co-magnetometer

- polarization is measured by UV laser

Our plan : ^{199}Hg, ^{129}Xe dual co-magnetometer

- monitor magnetic field strength and gradient

Ultra Cold Neutron



Ultra Cold Neutron

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

Interaction

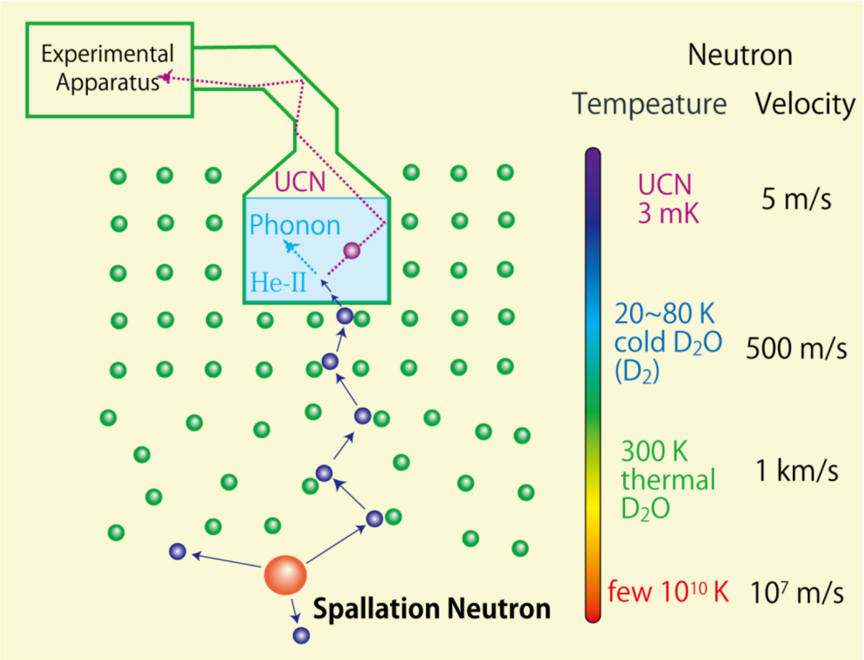
- Gravity 100 neV/m
- Magnetic field 60 neV/T
- Weak interaction
  - β-decay n → p + e
- Strong interaction
  - Fermi potential 335 neV (^{58}Ni)
    - atom distance : ~ Å
    - UCN feels average nuclear potential

UCN can be confined material bottle

→Use in various experiments

nEDM, neutron lifetime, gravity, ...

UCN production by super fluid Helium



UCN production

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 (He-II) converter
  - long storage lifetime
    - important to accumulate UCN
  - Helium 4
    - no neutron absorption cross section
    - up-scattering by phonon

$\tau_s = 600$ s at $T_{\mathrm{HeII}} = 0.8$ K

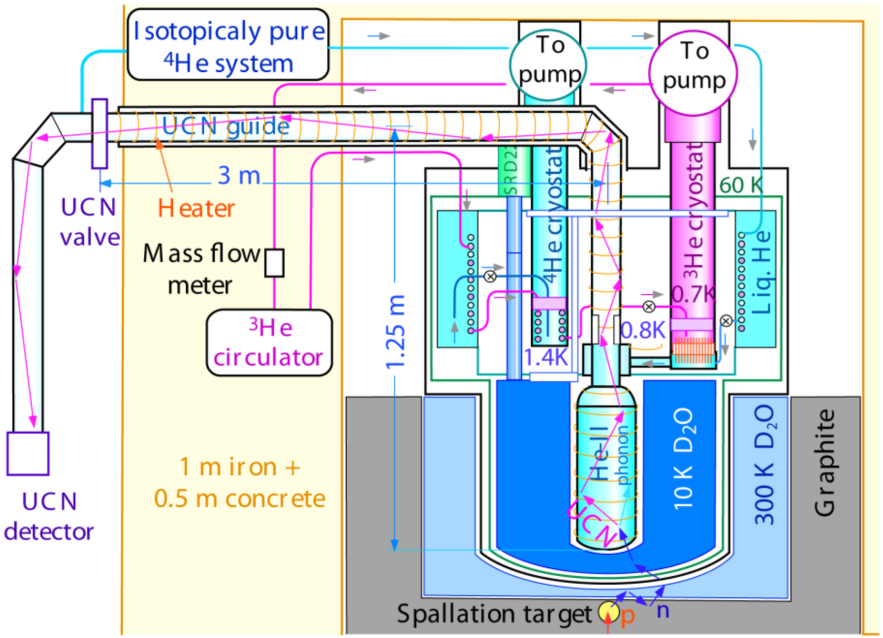
$\tau_s = 36$ s at $T_{\mathrm{HeII}} = 1.2$ K

$1/\tau_s \propto T^7$

Vertical UCN source

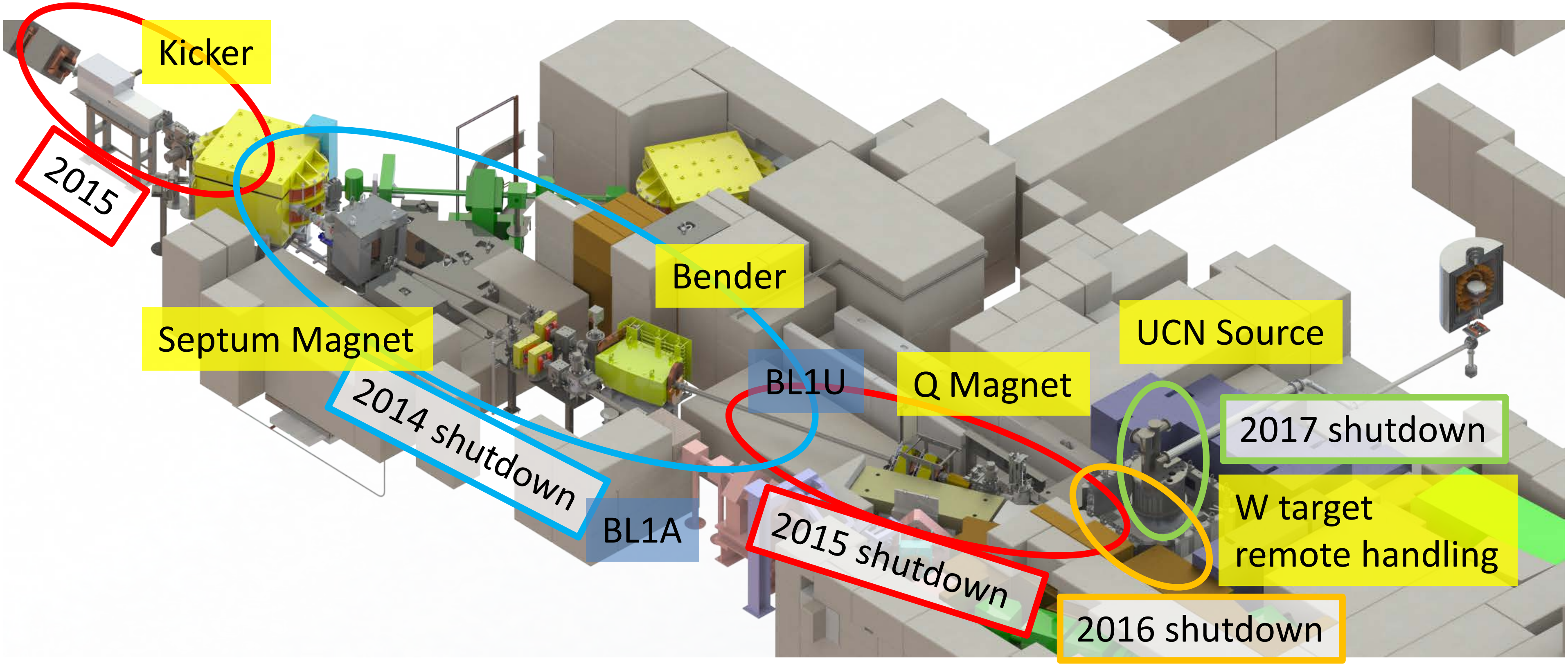
- Vertical UCN source
  - developed at RCNP
    - $T_{\text{He-II}}$: 0.8 K
    - UCN life time: 81 sec
    - UCN density: 9 UCN/cm^3
      - 400 MeV × 1 μA = 0.4 kW

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   SUCCEEDED!!

UCN Source @ TRIUMF

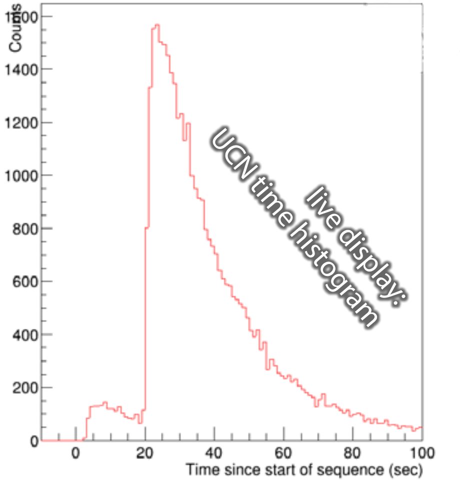


Major Milestone

✓ - 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)

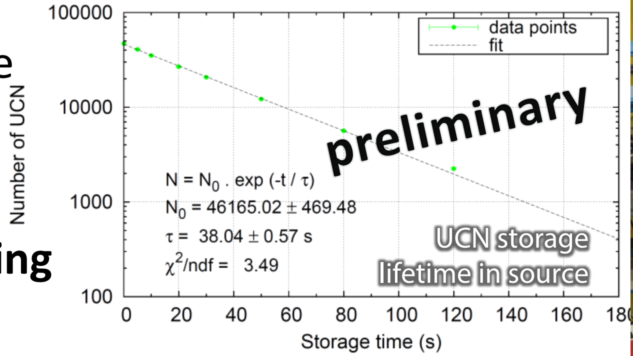
First UCN production at TRIUMF

- 2014 - 2017: installation of beamline and source
- **Nov 13, 2017: first UCN produced at TRIUMF**
- Approx. 5×10^4 per shot at 1 µA and $> 3 \times 10^5$ at 10 µA
- experimental program: source and UCN hardware characterization
- UCN source is quite stable for more than one month
- **Detailed analysis is ongoing**



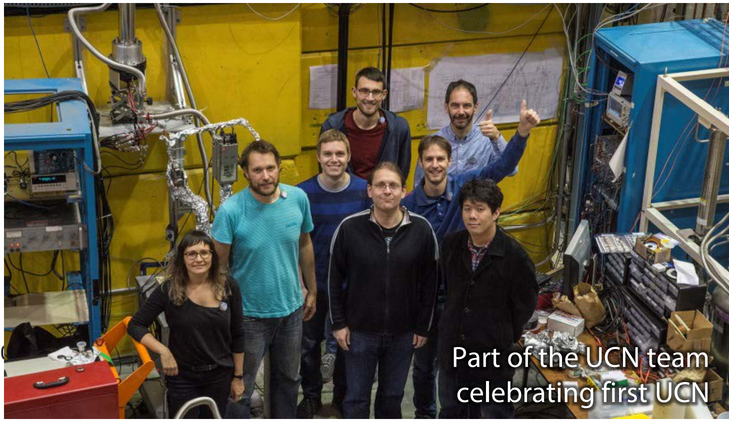
live display: UCN time histogram

UCN guide penetrating the UCN source shielding and ^{6}Li UCN detector



preliminary

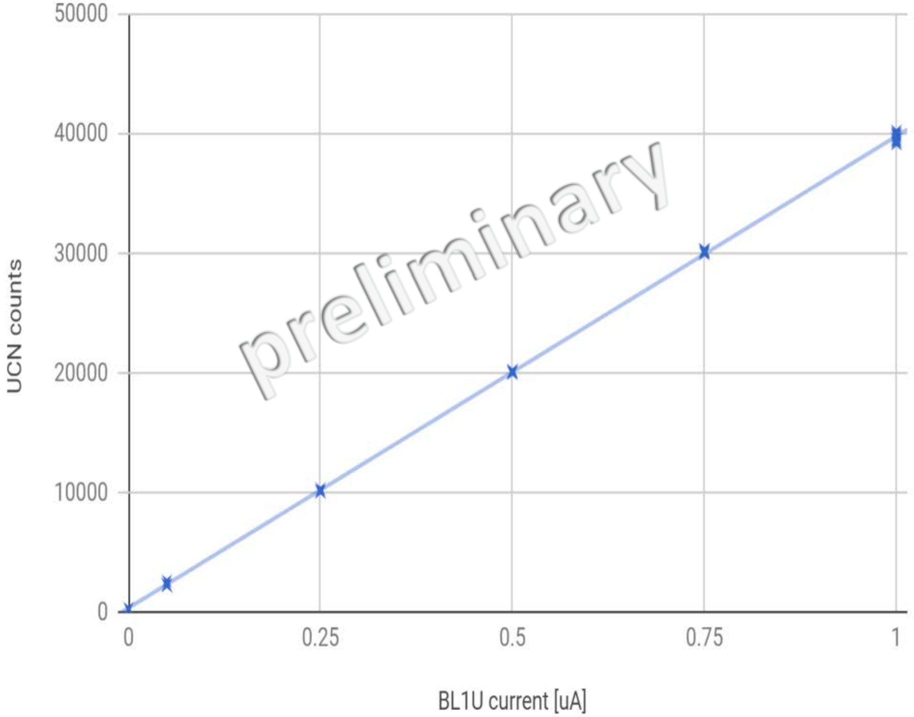
UCN storage lifetime in source



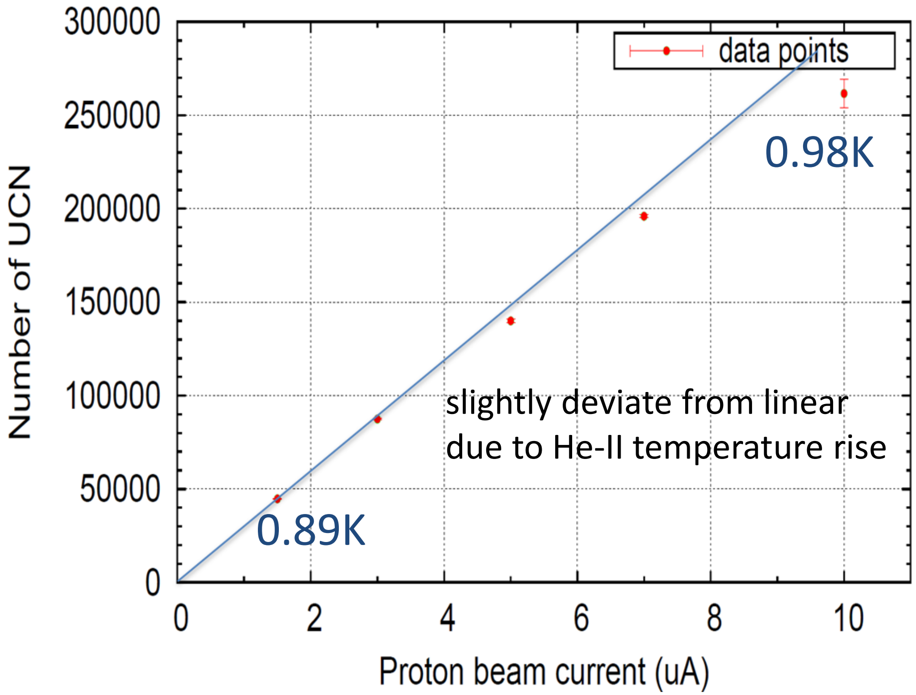
Part of the UCN team celebrating first UCN

UCN will be used for R&D for Upgrading facility and EDM apparatus

UCN yield linearity in beam current



0.05μA – 1μA, 60 sec beam irradiation



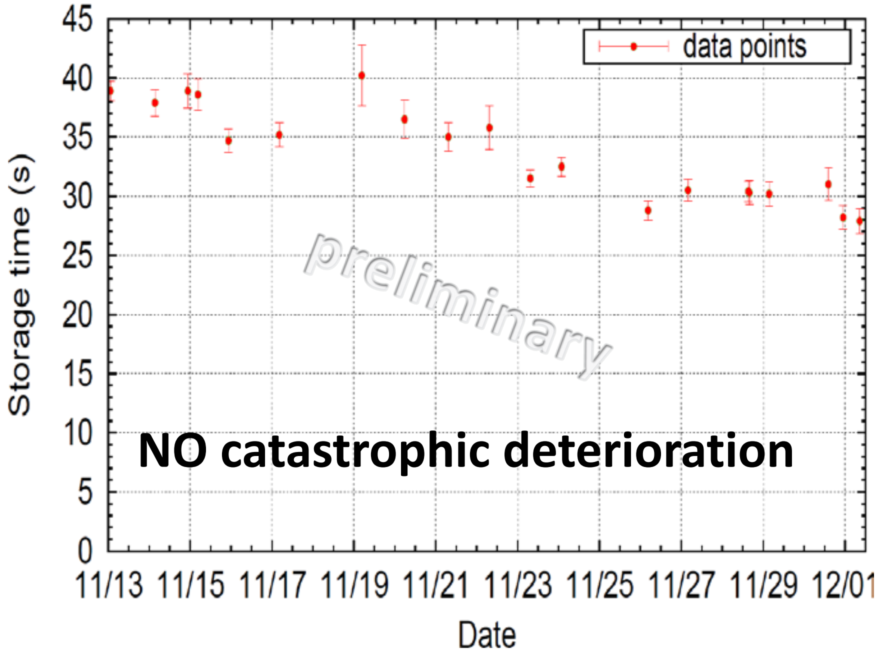
slightly deviate from linear due to He-II temperature rise

1μA – 10μA, 30 sec irradiation time

- Maximum UCN count rate 47000 at 1uA (RCNP best shot 80000)
- We have non optimized UCN valve, longer UCN guides and an aluminum foil before the detector
- By far enough UCN to do our measurement program
- Vertical Source is capable of sustaining higher currents and the UCN yield can be increased significantly.
- Highest number for 60 s irradiation and 10 μA: 3.25×10^5

Other experimental program

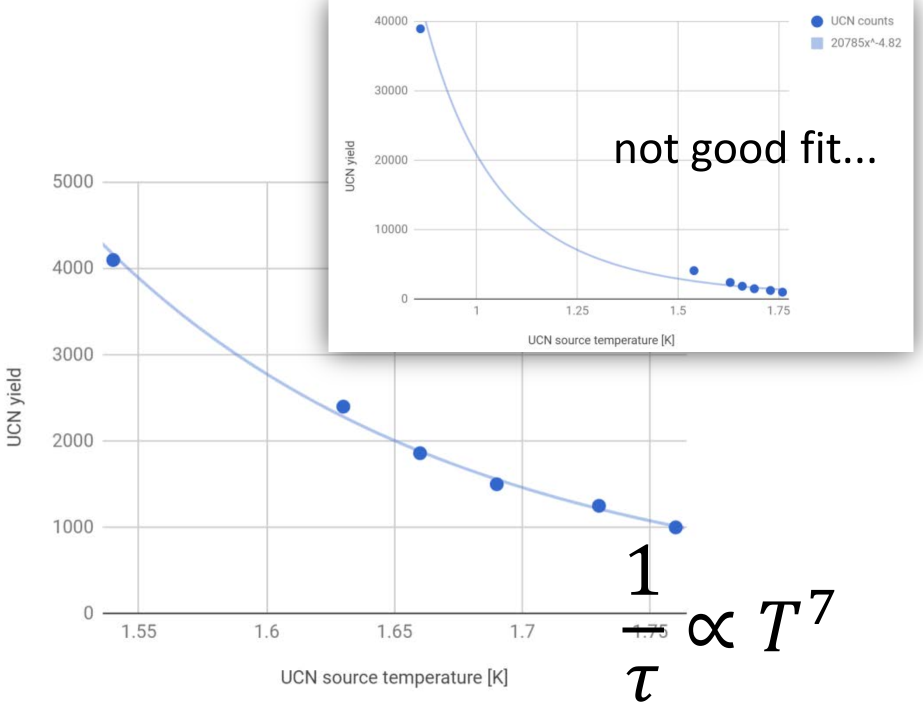
Storage lifetime evolution



NO catastrophic deterioration

This is the first time we run the vertical source for more than 1 week

UCN production in higher temperature

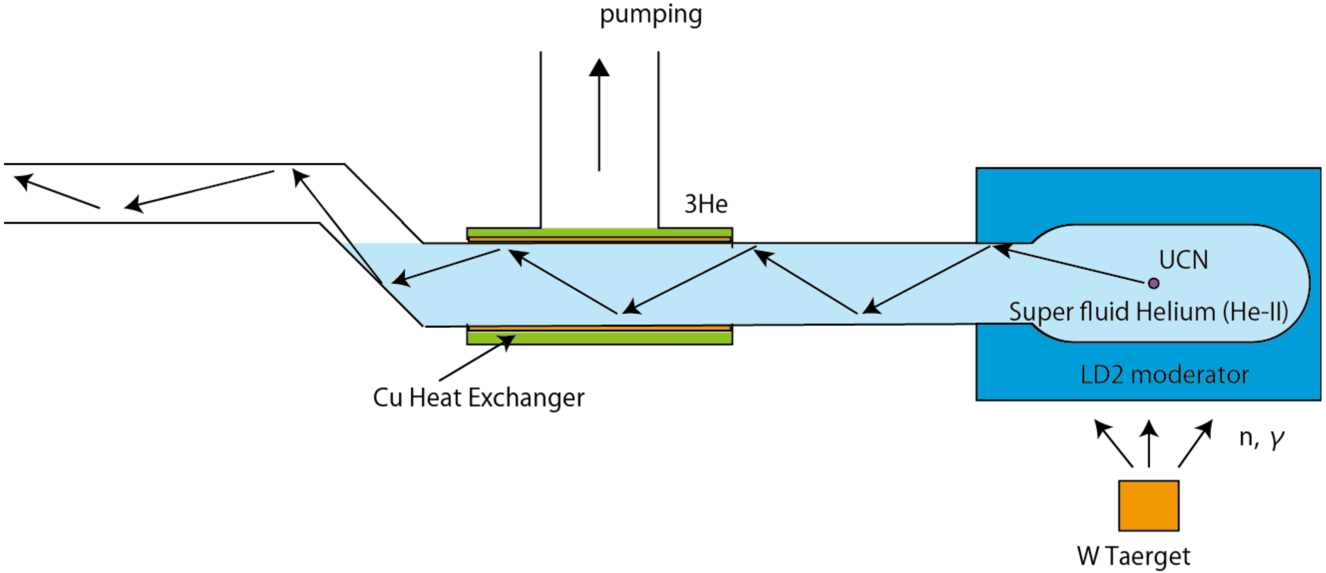


not good fit...

$$\frac{1}{\tau} \propto T^7$$

- Detector characteristic (^{3}He gas, ^{6}Li grass)
- UCN guide characteristic
- and so on, detailed analysis is ongoing

UCN source up-grade



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

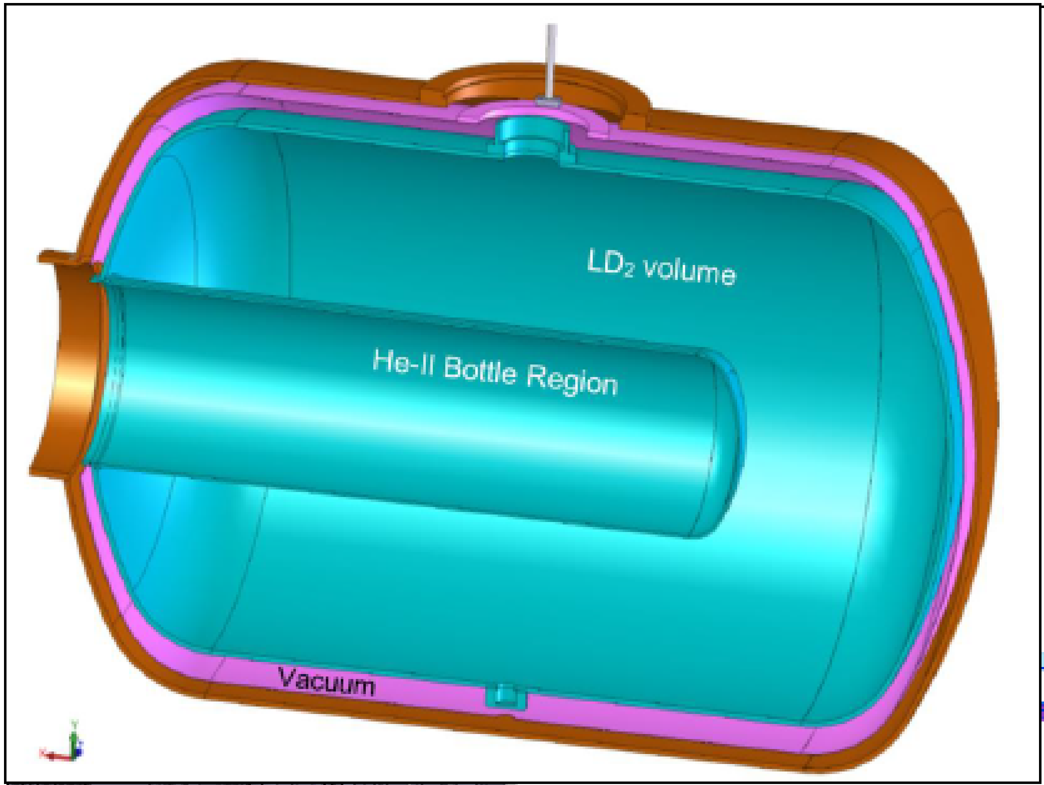
- distance between target and He-II
- cold moderator
- gamma shield

and so on

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

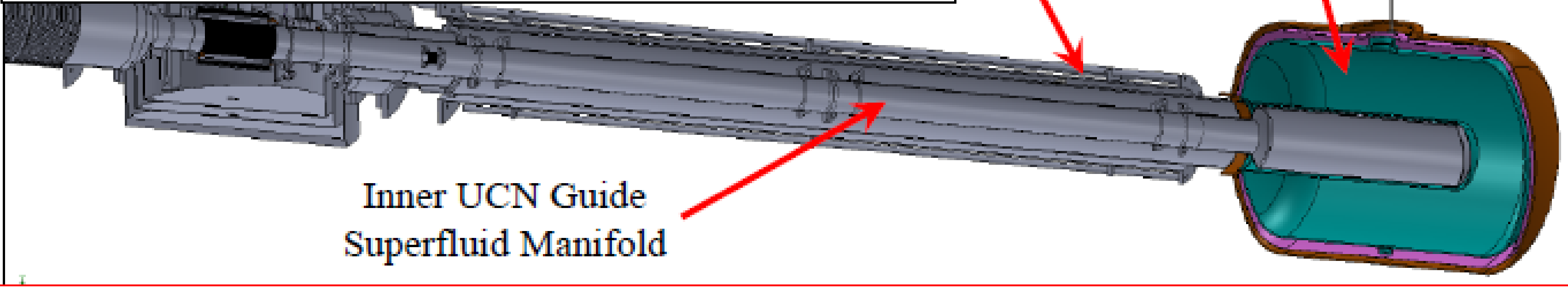
Optimization is necessary

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



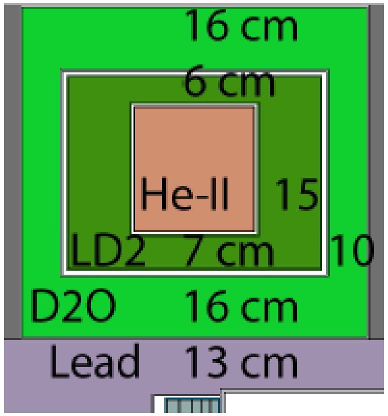
5 – 9 times larger cold neutron flux is achievable compared with ice D_2O

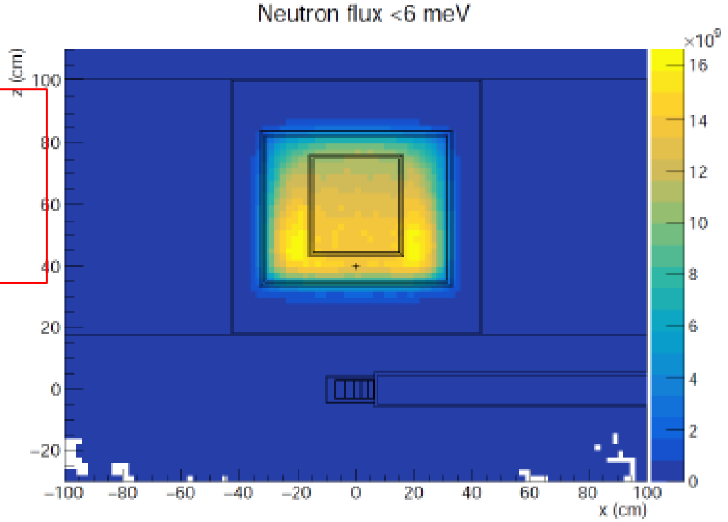
Heat load on UCN production volume

TRIUMF Preliminary results

- 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



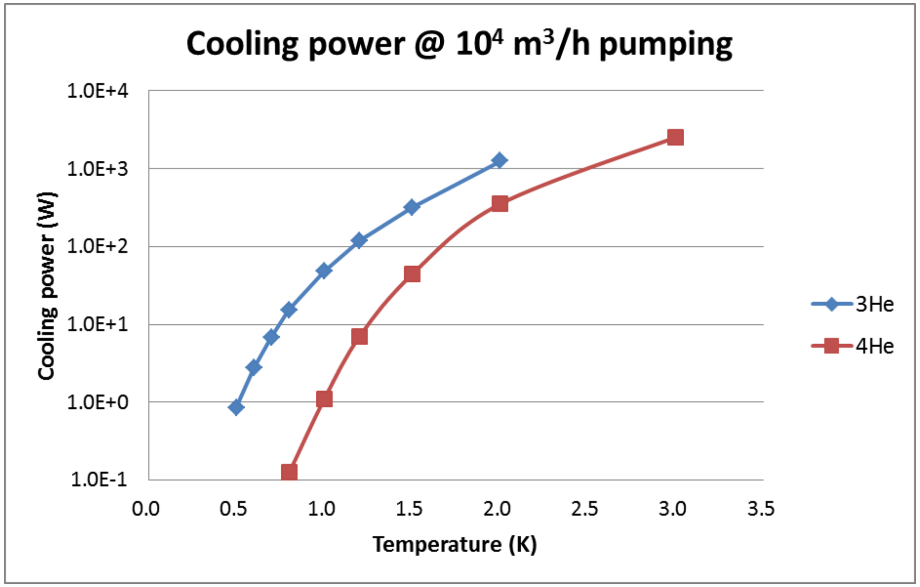


2017-10-18

He cryostat

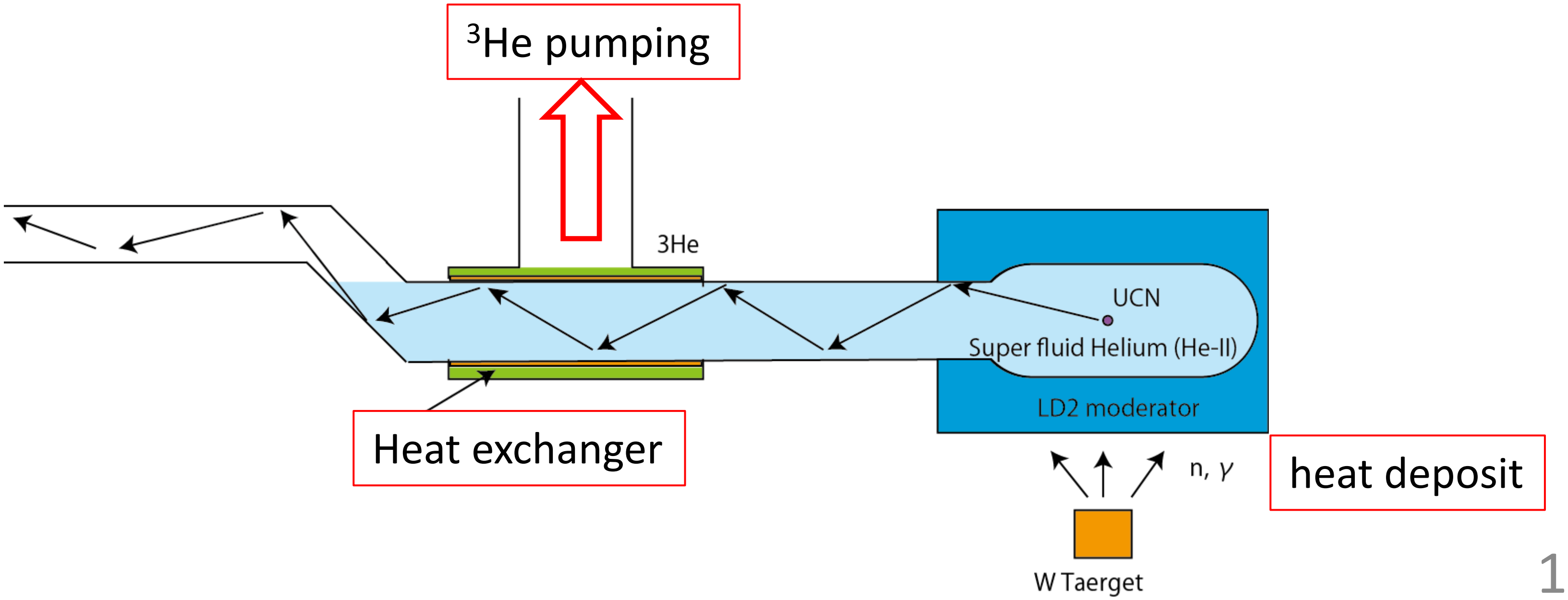
- to keep He-II temp. ~ 1.0 K
- decompressed Helium 3
- ^{3}He vs ^{4}He
  - vapor pressure @ 0.8K
    - ^{3}He: 3 Torr
    - ^{4}He: 0.01 Torr
  - cooling power

    @ 0.8K with 10, 000 m^3/hour pumping
    - ^{3}He: 15W
    - ^{4}He: 0.13 W



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

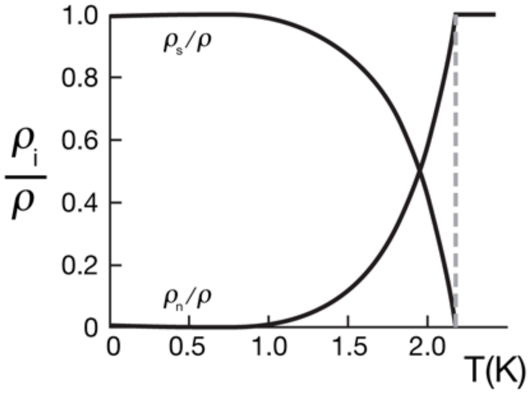
heat deposit

Superfluid Helium

Two Fluid Model

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

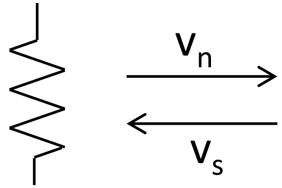
- Ratio of super/normal component depends on temperature.
- fraction of normal mode become small in low temperature.



10.1103/Physics.3.5

Heat transport

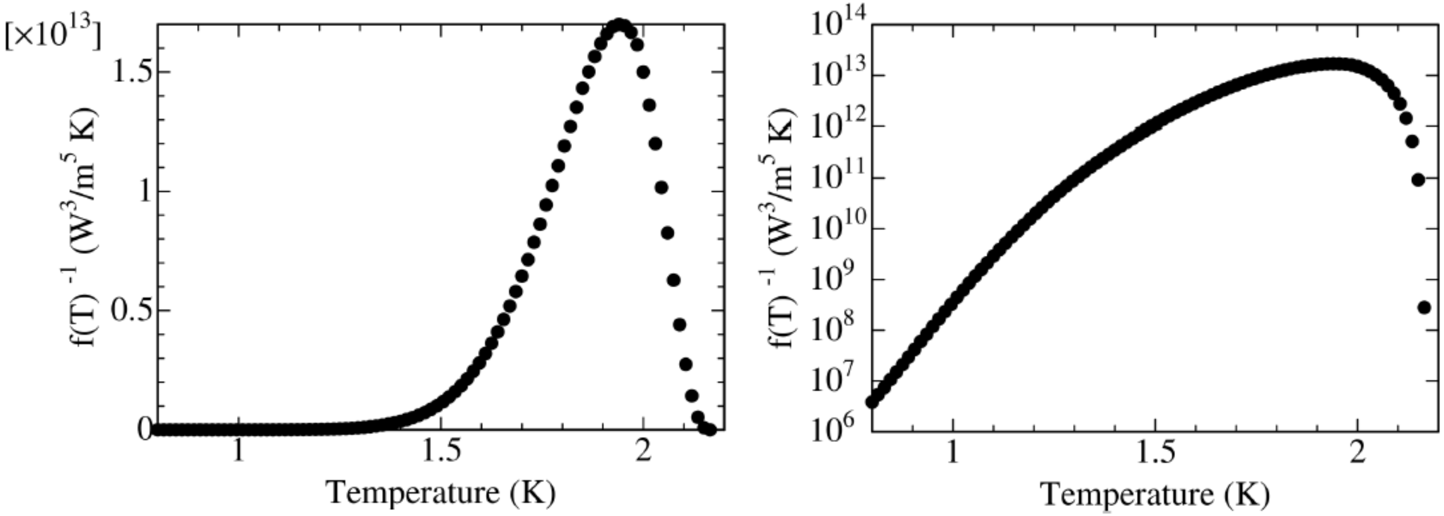
- Since superfluid has no entropy, heat is transported only by normal fluid.
- Heat transport in low temperature (< 1K) become small because of small fraction of normal fluid



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

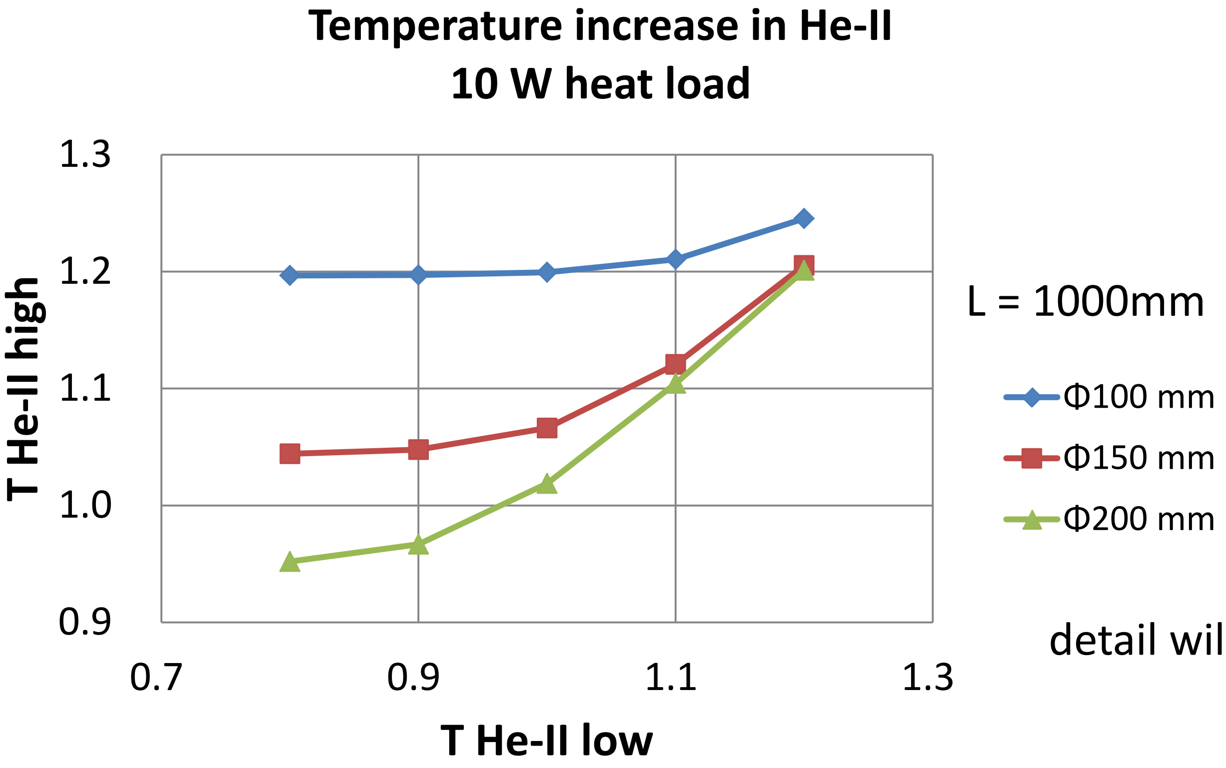
Temperature difference in He-II

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

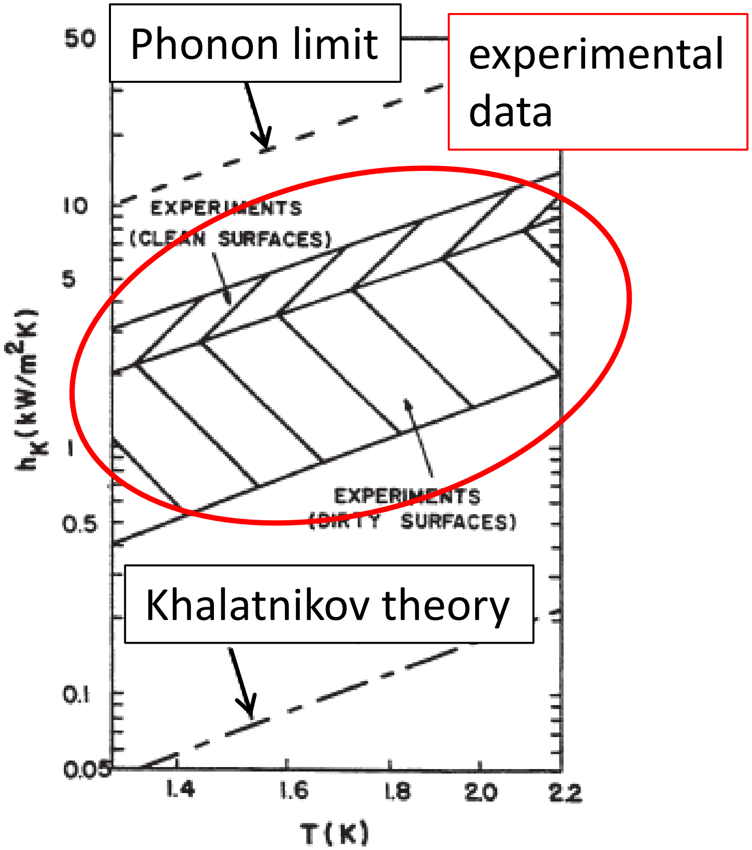
L : distance of heat transfer



detail will be discussed by T. Okamura

Kapitza Conductance

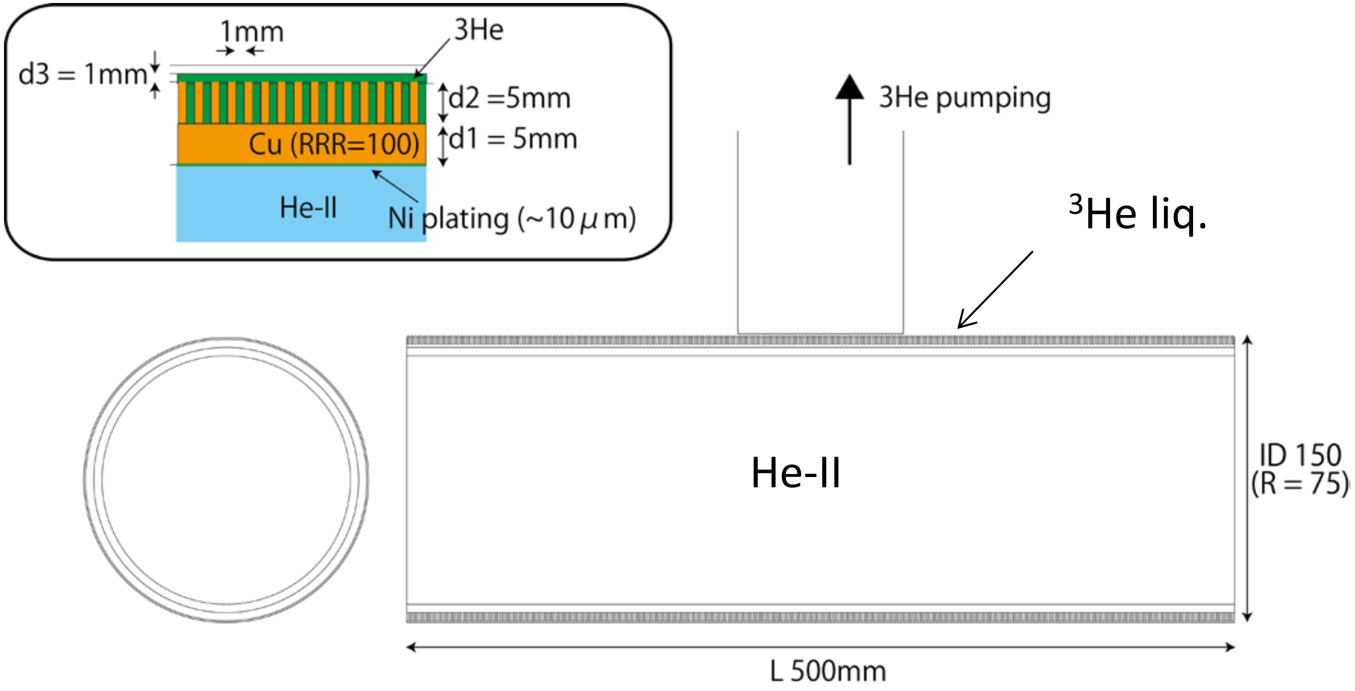
- Kapitza conductance is Conductance at the junction between liquid and solid is small at low temperature
- Kapitza conductance, $h_K(T)$ is a function of temperature.
- There are several theory on Kapitza conductance.
  - Phonon limit
    - $h_K(T)$ ~ $4500\ T^3$ [W/m^{2}K]
      - 2 - 10 times larger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



Kapitza conductance between Copper and He-II

Helium cryogenics, Steven W. Van Sciver

Heat exchanger



Cu Heat exchanger should be plated by Ni

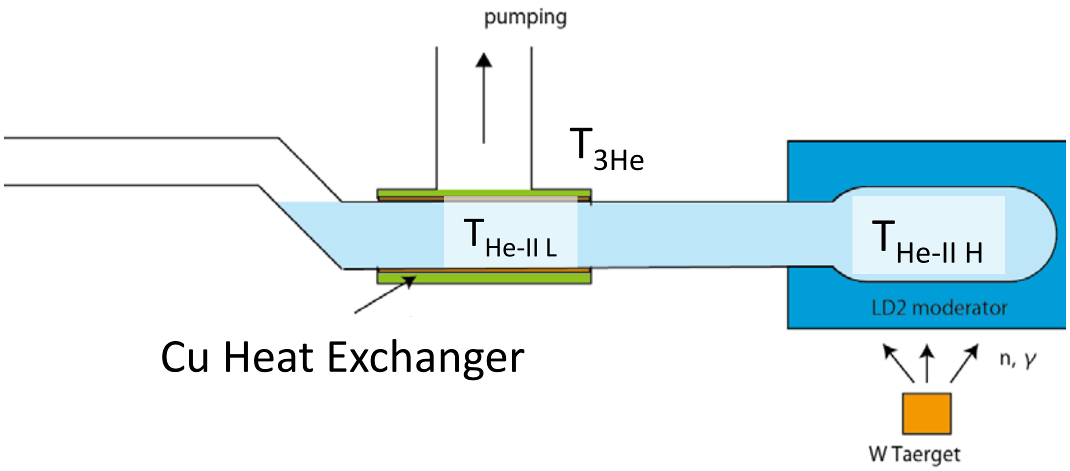
Kapitza conductance between Cu-Ni is large enough since junction is solid-solid

- 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(HeII) = (1.2 – 2.6) h_K(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]
  - $\Delta T_{He\text{-}II - Ni}$ = 0.16 K
  - T_{Ni} = 0.84 K
- junction between Cu and 3He
  - $h_{K\,Ni}$ (0.84K) = 232 [w/m2 K]
  - $\Delta T_{He\text{-}II - Ni}$ = 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 = 1,500 mm
pumping speed 10,000 m^3/hour
Heat load : 10 W case

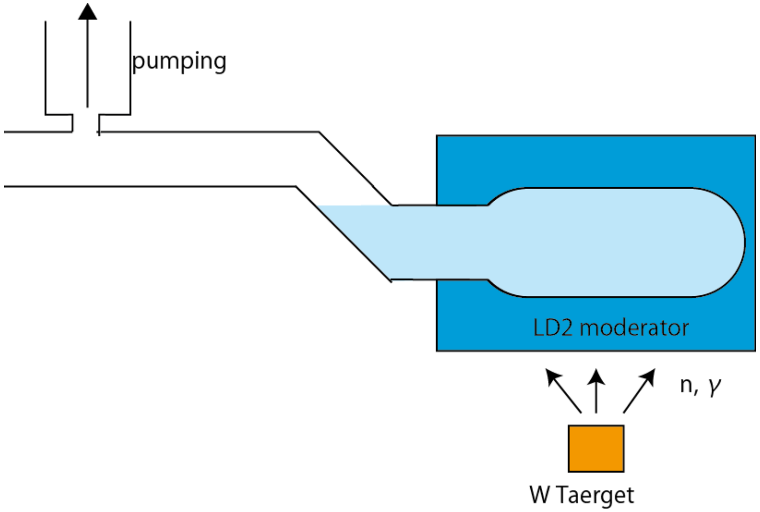
Temperature distribution

$T_{He\text{-}II\ H}$: 1.15 K ($\tau_{up\text{-}scat}$ = 50 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 = 0.40 K

Large uncertainty in parameter (Kapitza, GM)
-> have to be tested
-> we will have experiments at the beginning 2018

Alternative plan : direct pumping

- direct pumping of He-II
  - another way to cooldown He-II
    - There is no effect of Kapitza conductance since they have no heat exchanger
      - if Kapitza conductance is found to be smaller than expected, the direct pumping have large advantage
    - He-II volume can be small
      - temperature difference in He-II become small
  - Cooling power : 7 W at 1.2 K with 10,000 m^3/hour pumping
    - upscattering life time at 1.2 K : 36 sec



High cooling power cryostat

- A new He-II cryostat is being developed
  - 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

- Isopure ^{4}He direct pumping is an alternative method

Expected statistics after UCN source upgrade

- New He cryostat will be made for 20 kW operation
- LD2 moderator increase cold neutron flux by factor 5 – 9
- UCN guide coating facility will be established at U. Winnipeg

	vertical source	horizontal source	factor
proton beam	0.4 kW	20 kW	× 50
production volume	8 L	12 L	× 1.5
LD2 moderator	-	-	× 5 – 9
UCN production rate	**3.2×10^4 UCNs**	**2.3×10^7 UCN/s**	**～ 700**

statistical sensitivity

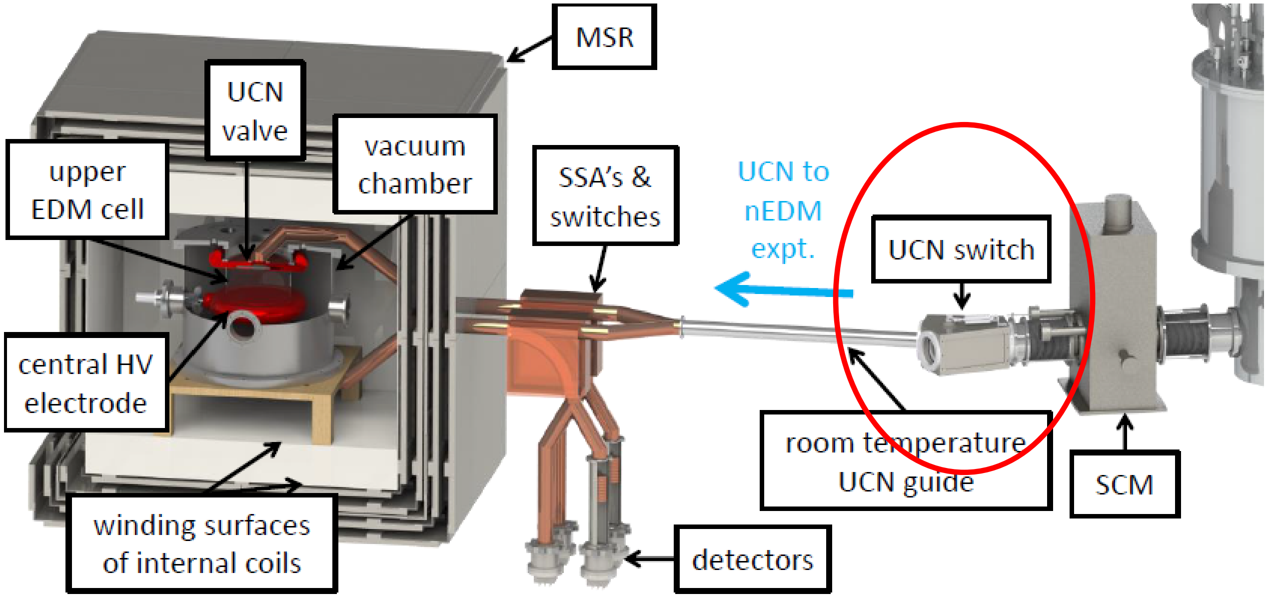
$$\boxed{\sigma_d = \frac{\hbar}{2\alpha E t_c \sqrt{N}}}$$

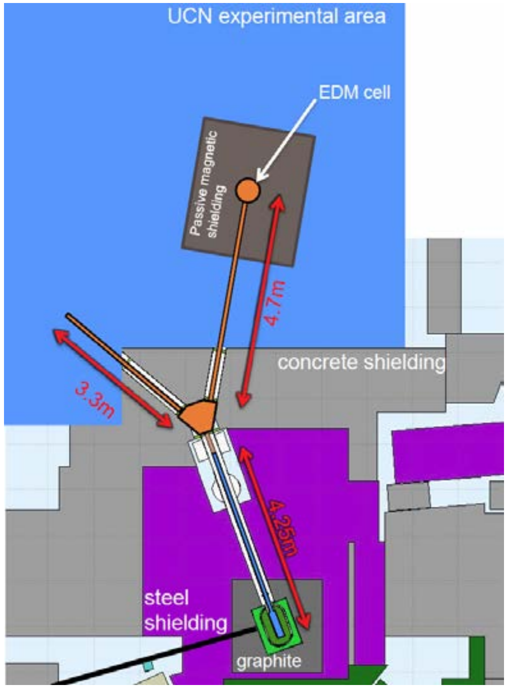
E = 10kV/cm
t_c = 130s
α = 0.8 (visibility)

N : number of UCN
ρ = 680 Pol. UCN/cm³ @20kW operation, TRIUMF
in cell of ϕ 36 cm and H 15 cm (15L) × double cell
N = 2.1×10^7 UCN/batch

$\sigma_d = 5.6 \times 10^{-26}$ ecm/cycle
(1 cycle : 8 fill to determine the resonant frequency)
assume stable running of 14 hours/day
$\sigma_d = 1 \times 10^{-27}$ ecm/100 MT day

Second UCN port : Y switch





beamline layout

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

If you have an interest idea to use UCN, please contact us!!

Summary

- High UCN density is essential to overcome current limit of neutron EDM measurement sensitivity
- UCN production in superfluid helium is a viable way to achieve a high density UCN source
- UCN production with the vertical UCN source succeeded
  - will use UCN produced for R&D for source and nEDM experiment
- High intensity UCN source is being developed
  - proton beam power : 500 MeV * 40 μA = 20 kW
  - new cryostat with higher cooling power
    - necessary cooling power : ~10 W at 1.0 K
      - 3He pumping, isopure 4He pumping
  - Final optimization is ongoing
    - statistical error of 10^{-27} ecm / 100 MT day
  - Plan to produce UCN from 2021