A New Spallation Ultracold Neutron Source at RCNP

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- UCN Production with Super-fluid Helium
- Current UCN Source at RCNP
  - Storage lifetime
  - UCN density
- Next UCN Source at RCNP
  - Horizontal extraction
  - Large heat exchanger
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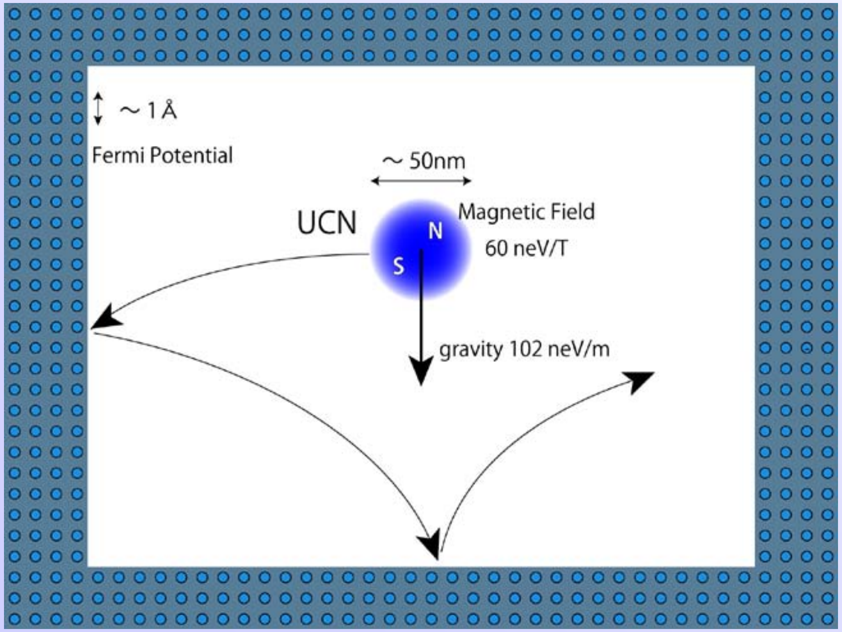
Ultra Cold Neutron



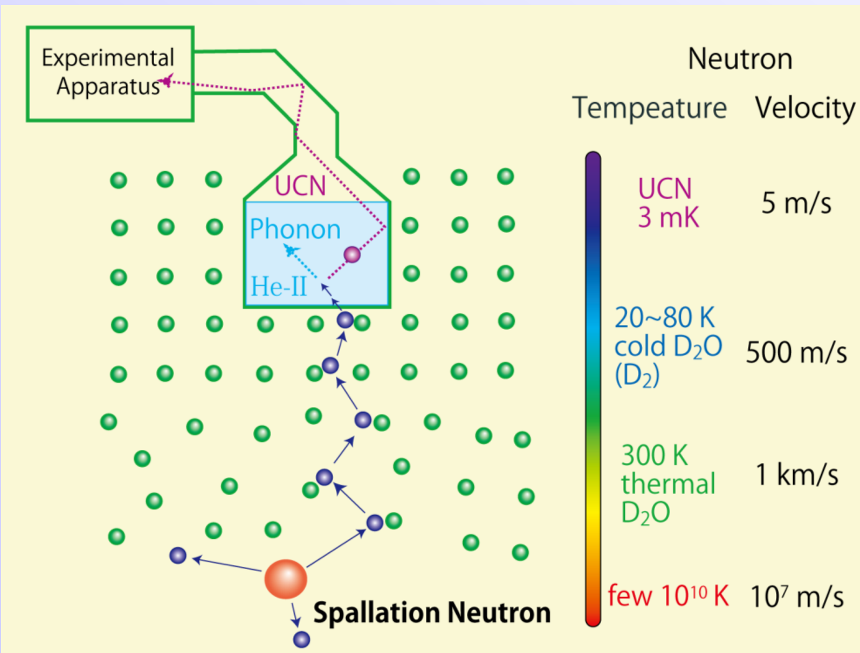
Ultra Cold Neutron
- energy ~ 100 neV
- velocity ~ 5 m/s
- wave length ~ 50 nm

Interaction
- gravity 100 neV/m
- magnetic force 60 neV/T
- Weak interaction
  - β-decay $n \rightarrow p + e$
- Strong interaction
  - Fermi potential 335 neV (58Ni)

UCN can be confined in material bottle.
→ used for various experiment
nEDM, gravity, neutron lifetime, …

High UCN density is essential

Our UCN Source



UCN Production

Spallation Neutron

↓ D_2O Moderator (300K, 20K)

Very Cold Neutron ～meV

↓ Phonon scattering in He-II

Ultra Cold Neutron ～100neV

Features

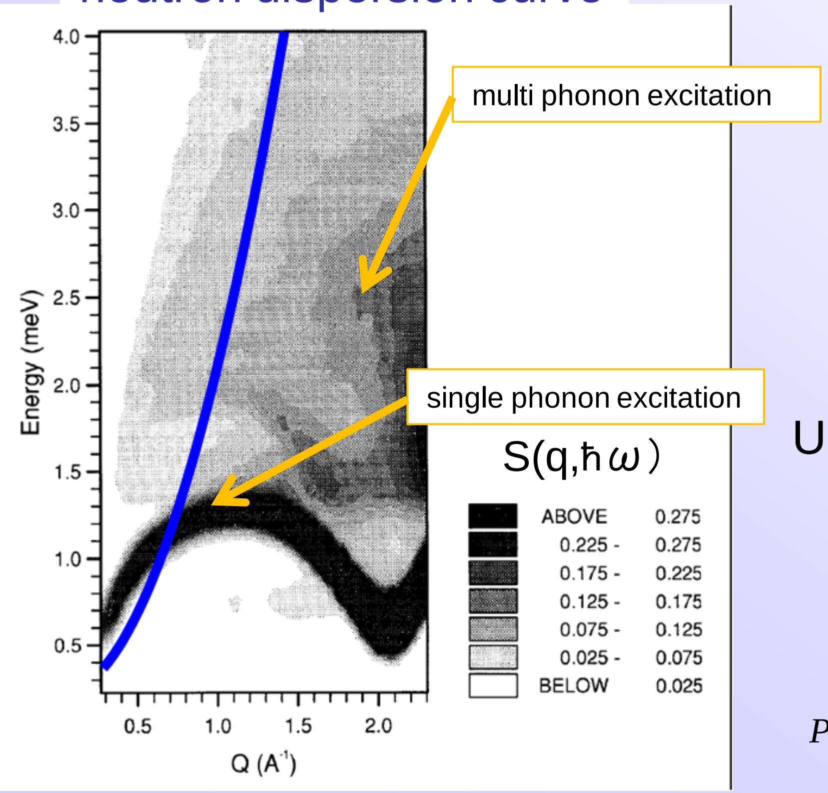
- Spallation Source
  - High cold neutron flux
- Superfluid He for UCN converter
  - Long storage lifetime
    - τ_s = 36 s at T_{HeII} = 1.2 K
    - τ_s = 600 s at T_{HeII} = 0.8 K
    - by phonon up-scattering

important to keep T_{HeII} < 1K

UCN Production with Supre-fluid He

Cold neutron excite phonon in super-fluid He and become UCN
Free from Liouville's theorem : use large phonon phase space in He-II

neutron dispersion curve



dispersion curve of phonon

M. R. Gibbs, et al
J. Low Temp. Phys. 120 (2000) 55

$$\frac{d\sigma}{dE} = 4\pi b^2 \frac{k_f}{k_i} S(q,\hbar\omega)$$

k_i, k_f : wavenumber

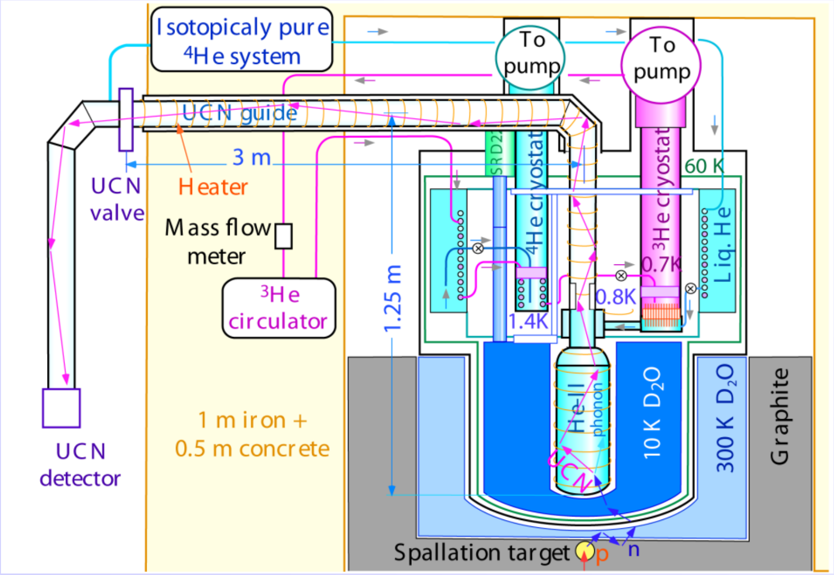
$S(q,\hbar\omega)$: Dynamic stracture factor

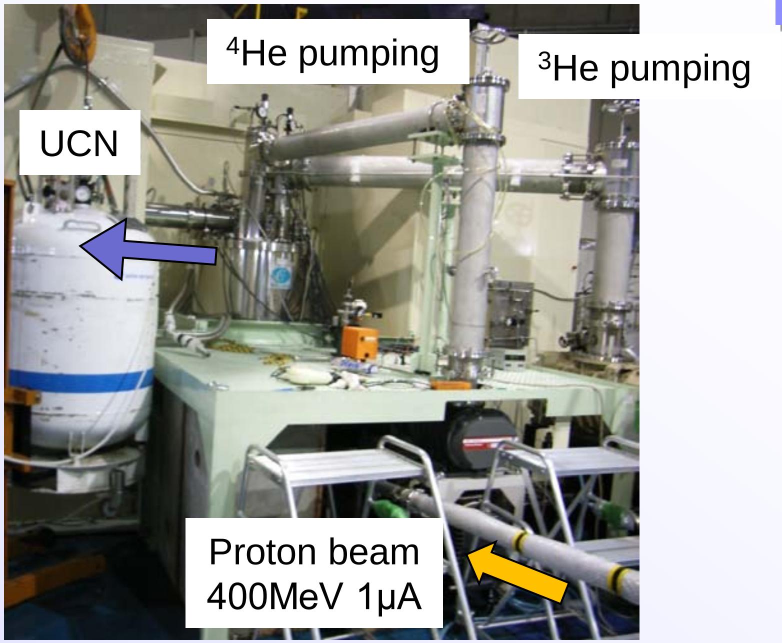
UCN Production rate

$$P(E_u)dE_u = \left[\int \frac{d\Phi(E_i)}{dE} N_{\mathrm{He}} \frac{d\sigma}{dE}(E_i \to E_u)dE_i\right] dE_u$$

$$P = \int p(E_u)dE_u = N_{\mathrm{He}} 4\pi b^2 \left(\frac{\hbar}{m_n}\right)^2 \frac{k_c^3}{3} \left[\int \frac{d\Phi(q)}{dE} S\left(q, \hbar\omega = \frac{\hbar^2 q^2}{2m_{\mathrm{n}}}\right) dq\right]$$

Current UCN Source

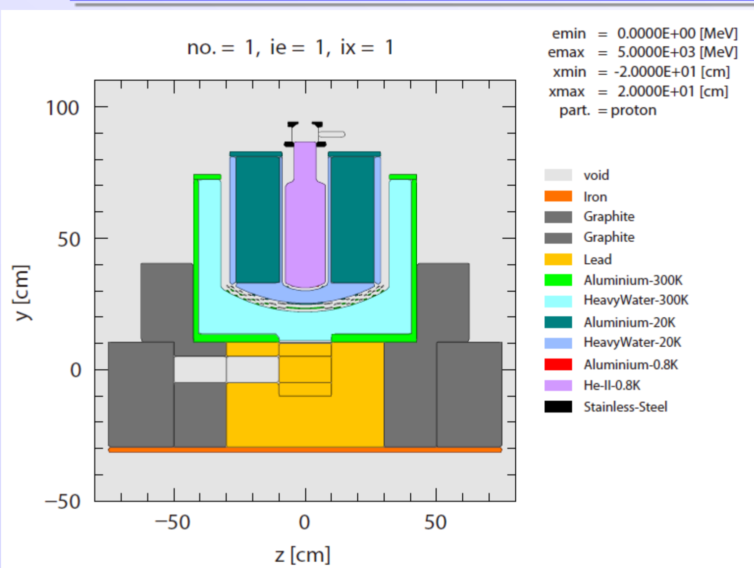




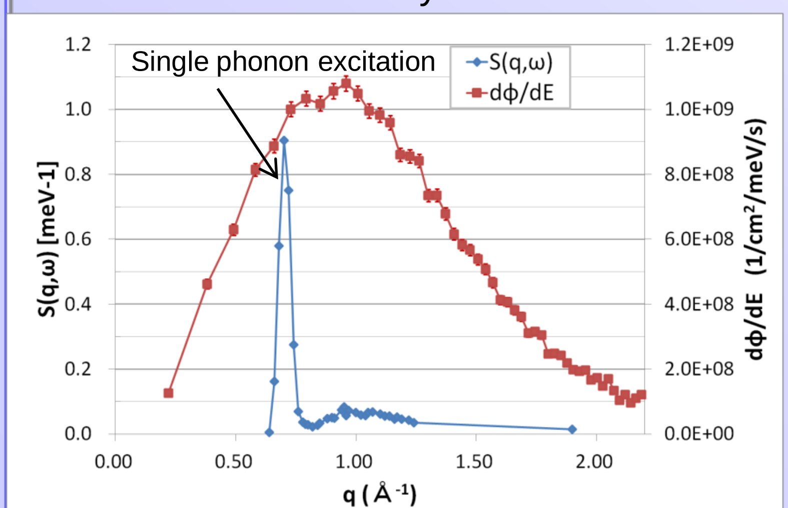
UCN source

He-II bottle	Φ16cm , L 41cm, Volume = 8L
	Al of 2mm thickness, inner wall coated with nickel
	Surrounded by D_2O moderator (ice, water)
Cryostat	keep He-II the temperature by ^{3}He pumping
	^{3}He is pre-cooled by ^{4}He pumping
UCN guide	Φ8.5 cm, L = 3 m
	1.25m high from He-II bottle

Flux simulation



Geometry



Simulated flux and phonon structure factor

PHITS Simulation

20K D_2O : Free gas model

Flux at resonant energy

$$\frac{d\Phi(E_i)}{dE} = 9.3\times10^{8}\,\mathrm{n/cm^2/meV/s}$$

proton beam : 400MeV × 1μA

$$P = \int p(E_u)dE_u = N_{\mathrm{He}} 4\pi b^2 \left(\frac{\hbar}{m_n}\right)^2 \frac{k_c^3}{3}\left[\int \frac{d\Phi(q)}{dE} S\left(q, \hbar\omega = \frac{\hbar^2 q^2}{2m_{\mathrm{n}}}\right)dq\right]$$

$$N_{\mathrm{He}} = 2.19\times10^{22}\,\mathrm{cm^{-3}}$$

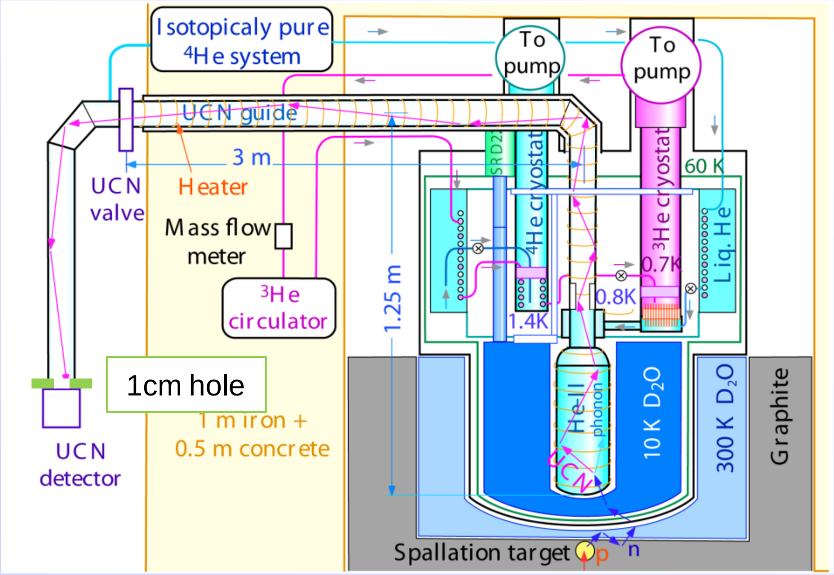
$$\sigma = 4\pi b^2 = 1.34\mathrm{b}$$

$$\hbar^2/m_{\mathrm{n}} = 4.14\,\mathrm{meV/A}$$

$$k_c = 0.01\mathrm{A}^{-1} \qquad V_{\mathrm{Ni}} = 210\,\mathrm{neV}$$

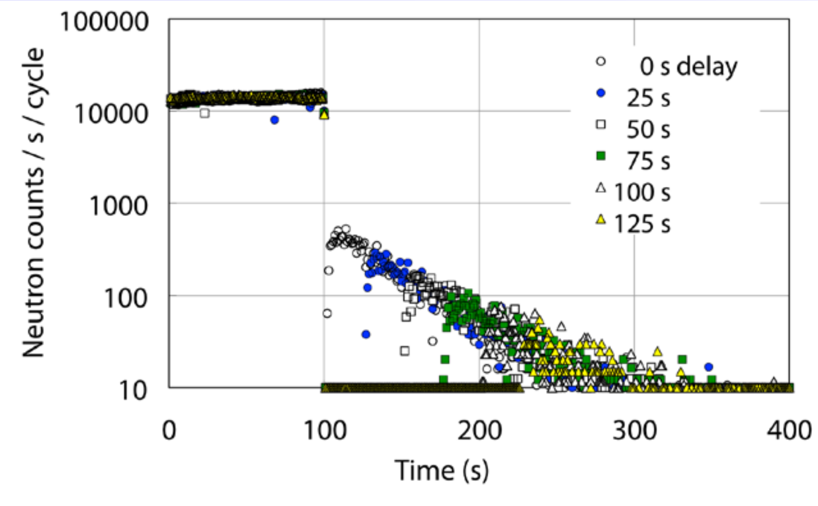
Production rate
9 UCN/cm3/s
single phonon excitation
14 UCN/cm^3/s
including multi phonon excitation

UCN Production in 2008



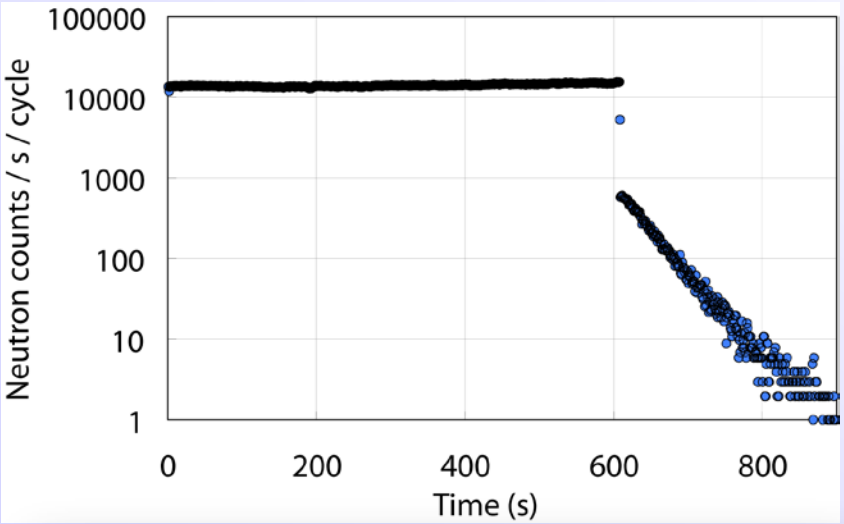
Storage life time measurement
Counting UCN after valve opening
proton beam : 0.2μA, 100s

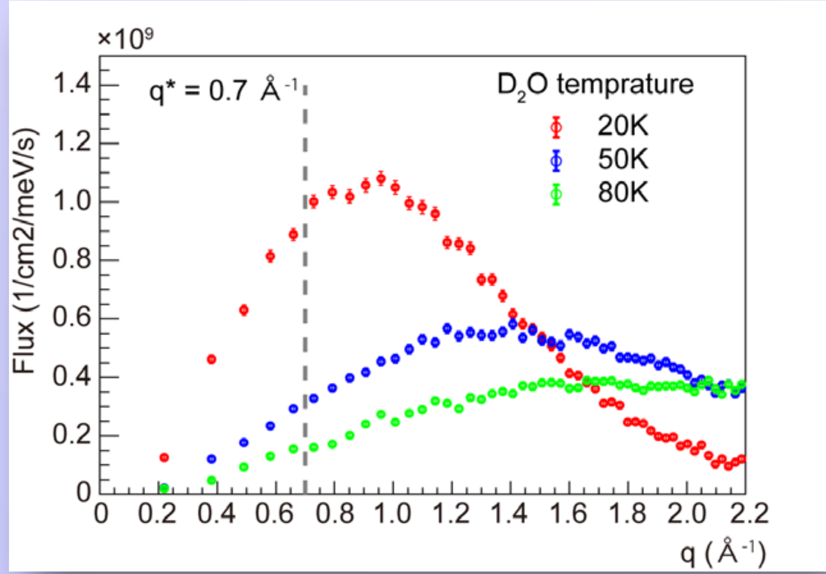
UCN is produced and hold in the
UCN bottle and guide
After time delay UCN valve open



Storage Lifetime : 47 sec
wall loss rate

UCN Production in 2008





proton beam 1μA × 600 sec

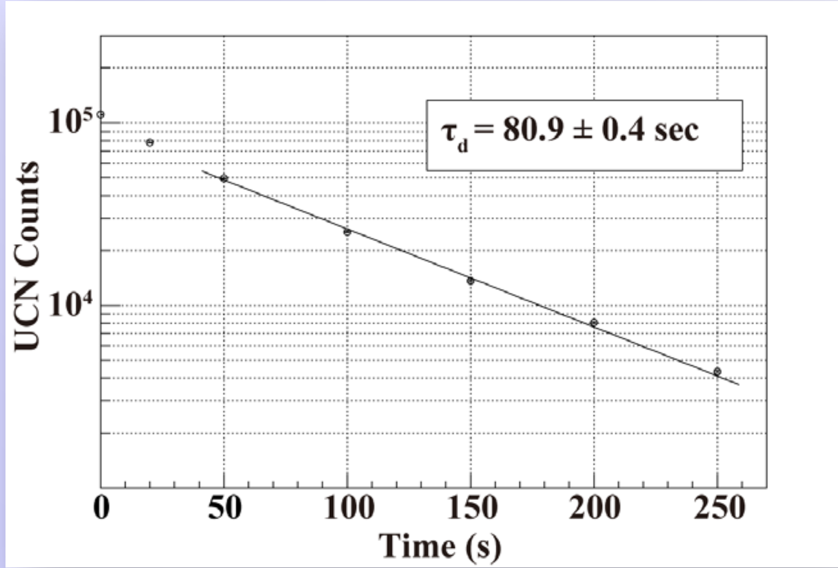
UCN density 15 UCN/cm^3 Ec = 90neV
180 UCN/cm^3 @ UCN bottle

UCN production rate 4 UCN/cm^3/s
(14 UCN/cm^3/s : simulation)

Free gas model is used in simulation
effective temperature is more higher

Assuming
50K D_2O 6 UCN/cm^3/s
80K D_2O 4 UCN/cm^3/s

UCN Production in 2011



UCN count after valve opening
proton beam : 1μA × 40s

Storage Lifetime : 81 sec

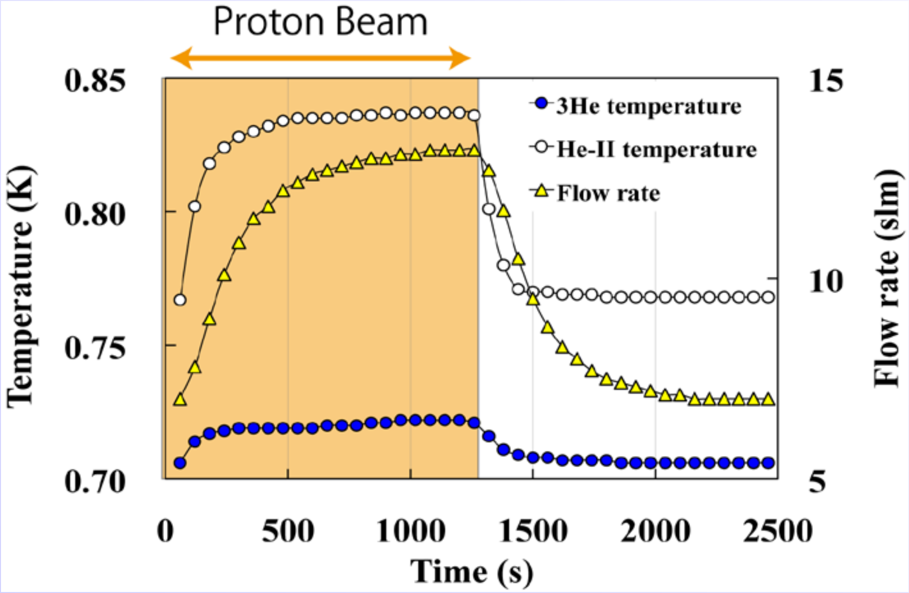
Improvement of bottle surface
- ✓Alkali cleaning
- ✓baking temperature 140℃

UCN density

15 → 26 UCN/cm^3 Ec = 90neV

180 → 310 UCN/cm^3 @ UCN bottle

Cooling Power of cryostat



Temperature and Flow rate
after proton beam impingement
proton beam : 400MeV, 1μA, 1200s

Heat load on super fluid He
Super fluid film flow
thermal radiation etc.
is balanced with cooling power of cryostat
T = 0.77K

During proton beam impingement
extra heat road from
neutron-capture γ heating

Extra heat load
→ He-II temperature rise up
→ ^{3}He temperature rise up
→ ^{3}He flow rate rise up
→ balance at new point T = 0.83K

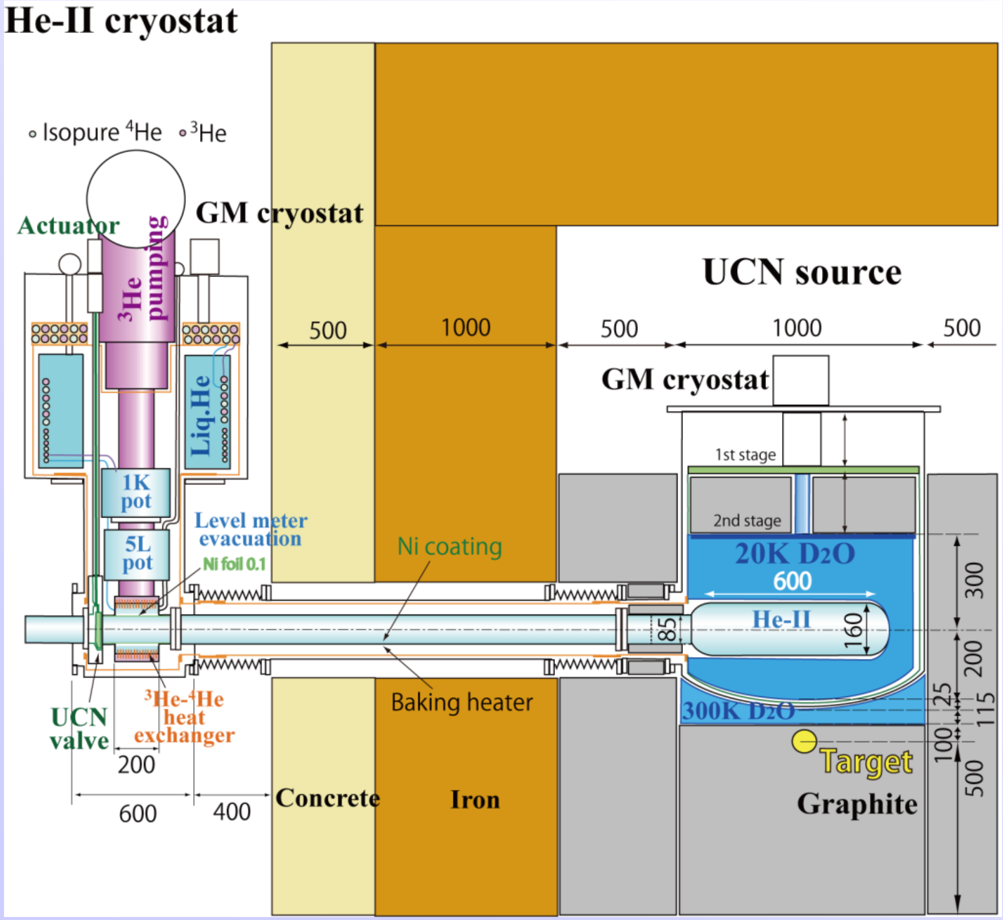
UCN Source Improvement

$$\rho_{\mathrm{UCN}} = \text{Production rate } P \times \text{ Storage lifetime } \tau$$

Year	I_P	τ_s	T_{HeII}	Improvement
2002	200nA	14 s	1.2K	
June 2006	1μA	29 s	0.9K	^{3}He cryostat
Nov. 2006	1μA	34 s	0.8K	Reduce HeII film perimeter (8.5 cm → 5 cm)
July 2007	1μA	39 s	0.8K	Remove ^{3}He contamination
April 2008	1μA	47 s	0.8K	Fomblin coating
Dec. 2009	1μA	61s	0.8K	Alkali cleaning
Feb. 2011	1μA	81s	0.8K	High temperature baking (140℃)

Finally,
UCN density 26 UCN/cm^3 Ec = 90neV

New UCN source



Improvements

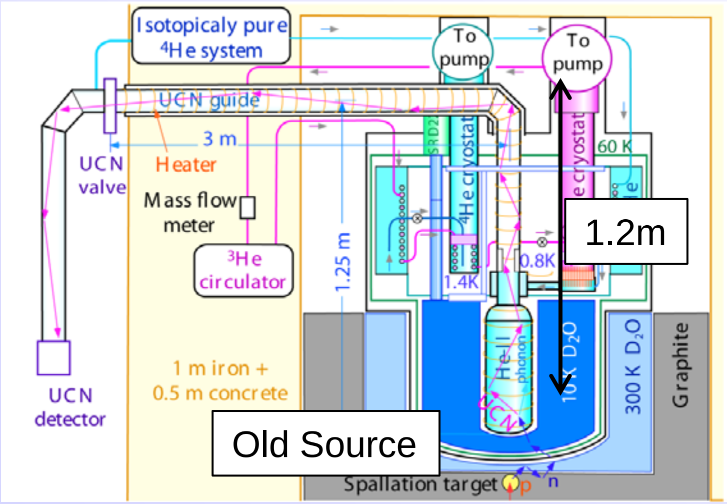
✓Horizontal extraction
avoid gravity potential

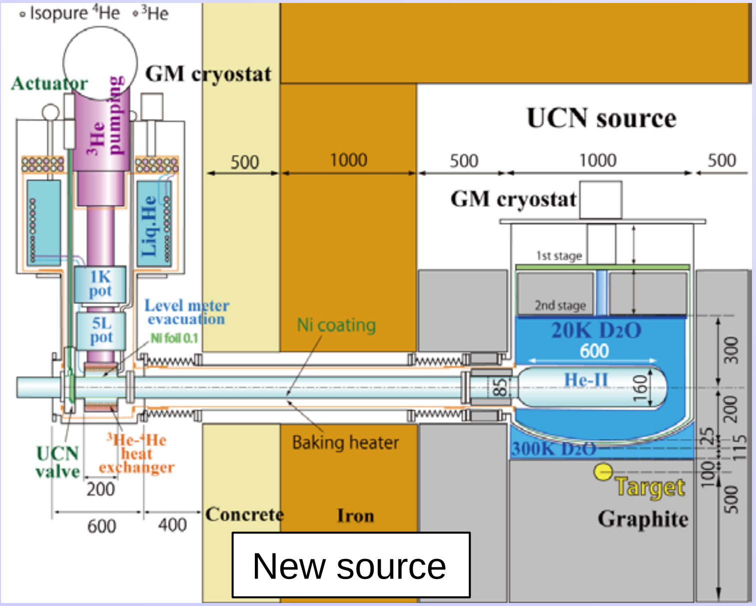
✓D_2O moderator optimization
more cold neutron flux

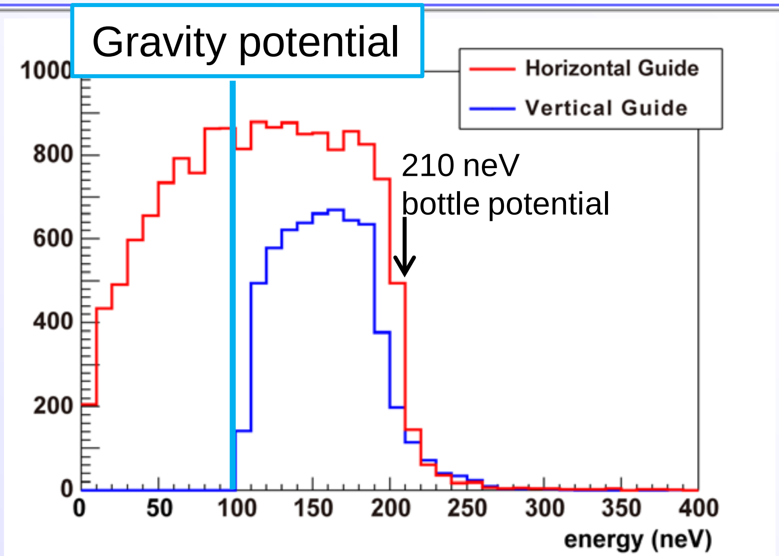
✓Increase volume of He-II bottle
more production volume

✓Large heat exchanger
keep He-II temperature lower

Horizontal extraction







UCN energy spectrum (Geant 4 simulation)

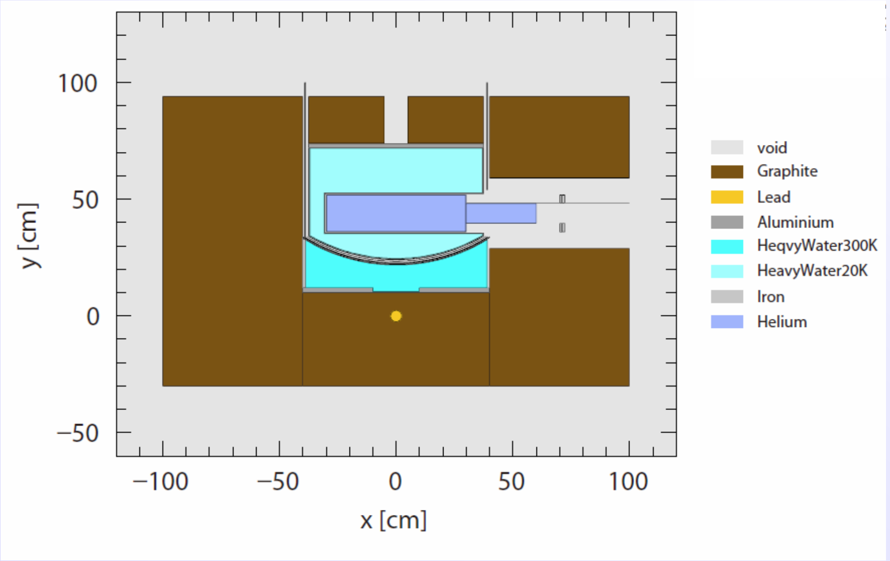
Current source : vertical extraction
Gravity potential 102 neV/m × 1.2 m

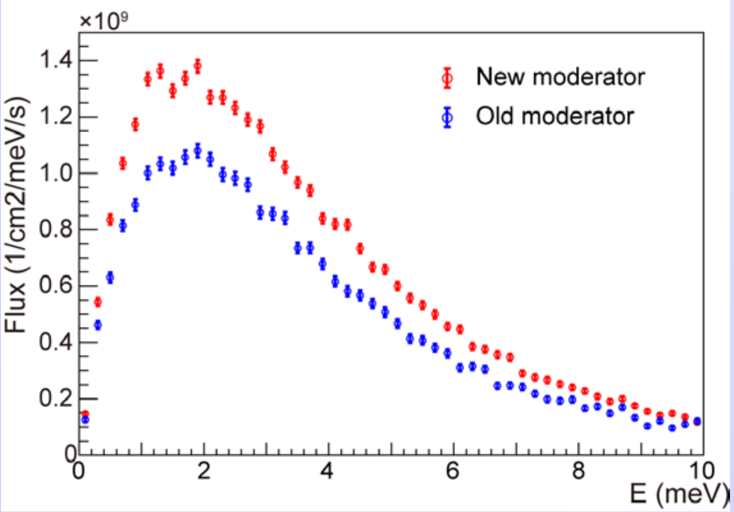
New source : horizontal extraction

- Avoid gravity potential
- improve conductance

× 2.5 effective transport

D_2O Moderator





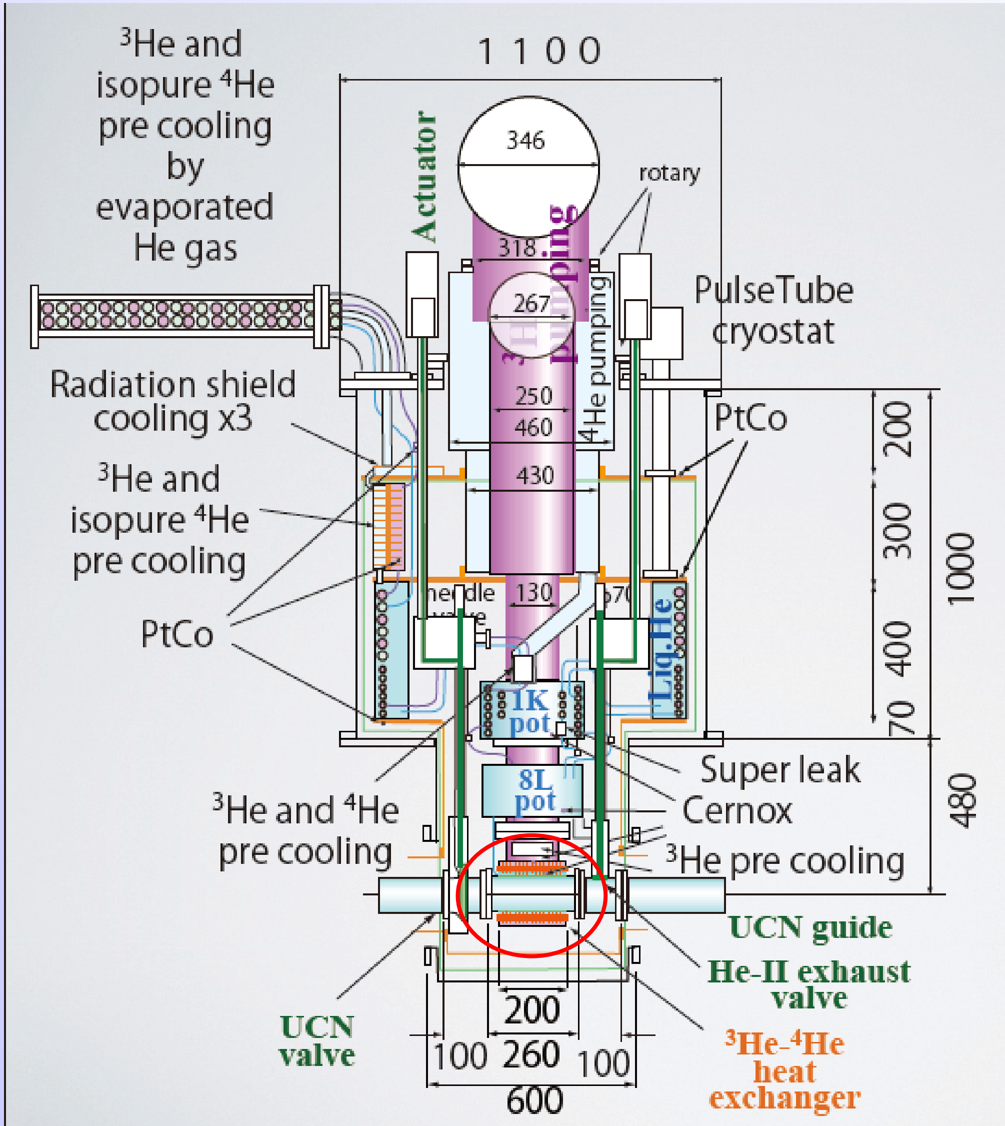
PHITS simulation

D_2O moderator thickness and position

→ Optimization

×1.2 times improvement

He-II Cryostat



Improvements

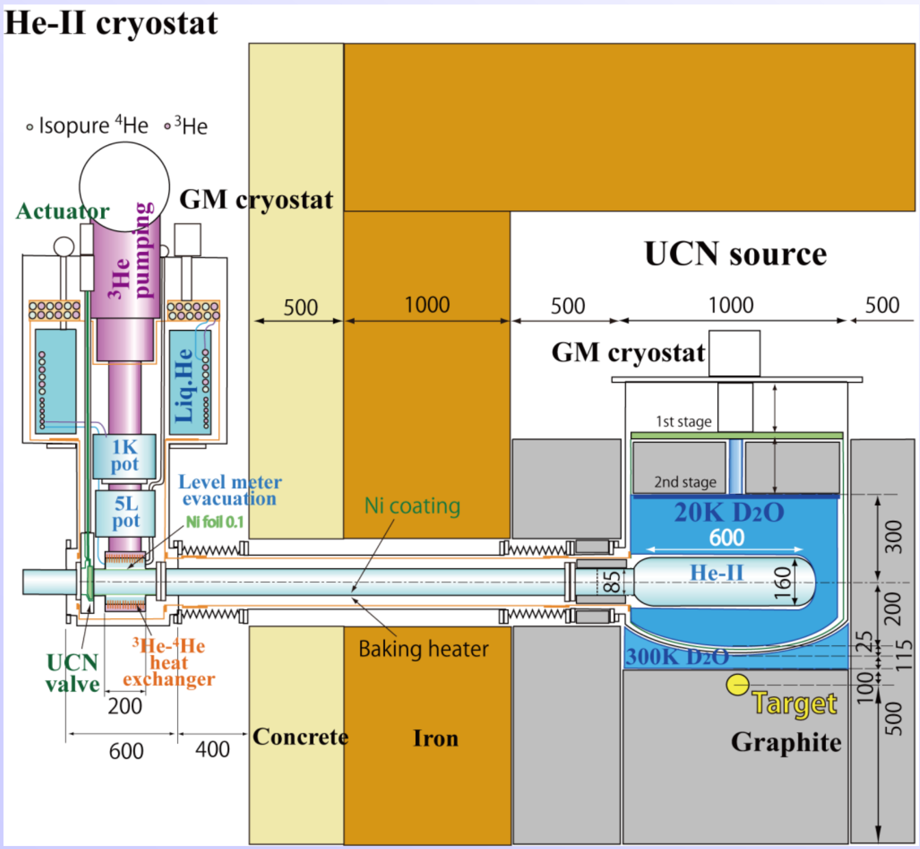
- Large heat exchanger
  - effective heat transfer from He-II
- Large exhaust duct
  - high power pumping

- Iso-pure He (light blue)
  - UCN Moderator
- ^{3}He (violet)
- ^{4}He (blue)
  - Coolant

iso-pure He and ^{3}He are cooled down by

- evaporated ^{4}He gas
- Liq. He
- 1K pot (^{4}He pumping)
- ^{3}He pumping

Summary of improvement



- UCN bottle volume ×1.5
- Increase cold neutron flux ×1.2
- Horizontal extraction ×2.5
  - avoid gravity
  - avoid reflection

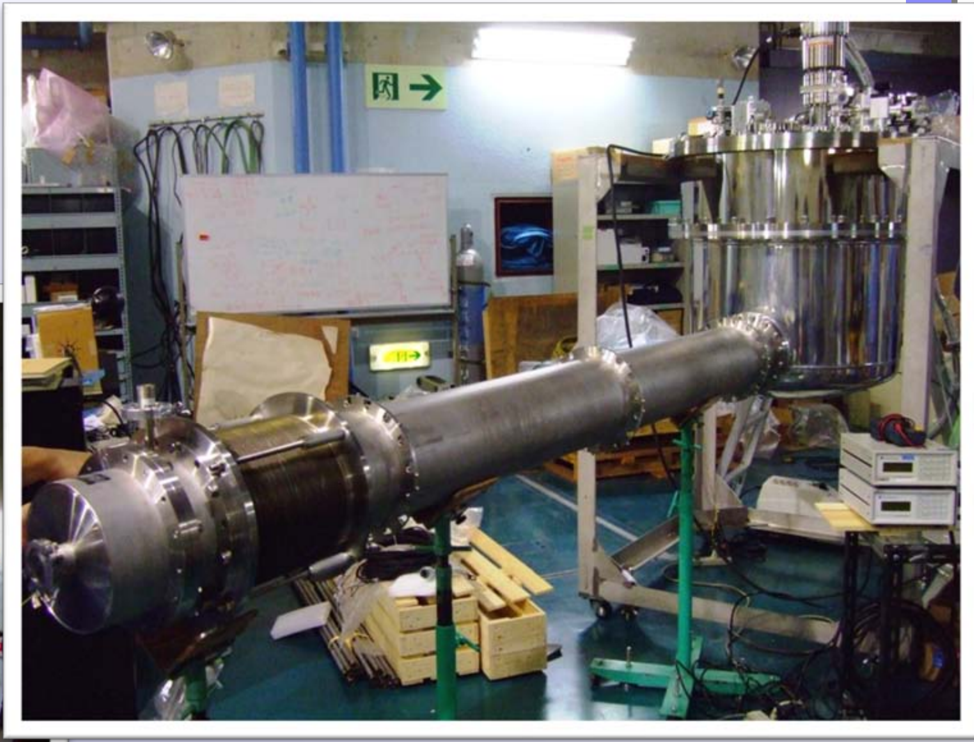
total ×5

same proton current

and more proton current

Construction

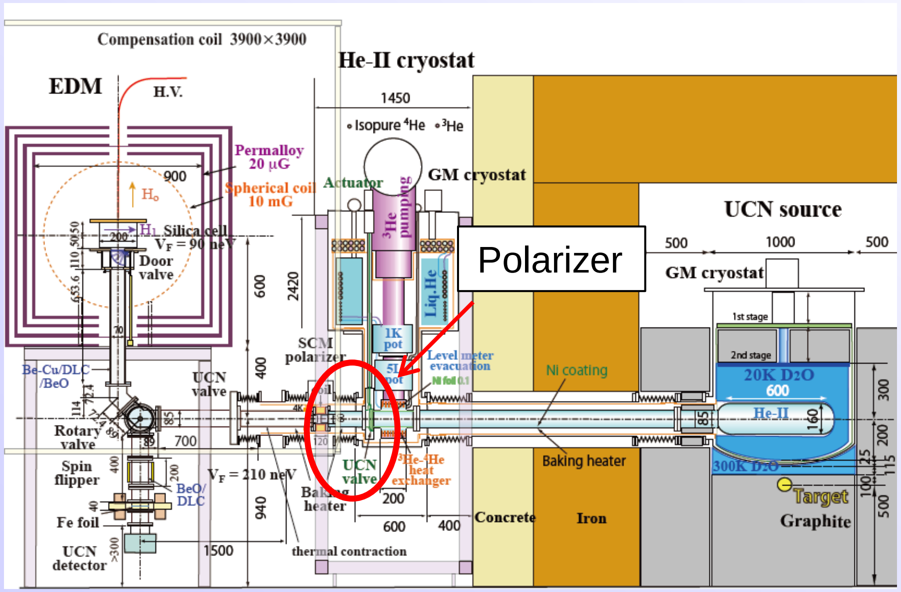
HeII cryostat
finish manufacturing
now testing



D_2O moderator and UCN guide

constructed and installed on
proton beam line

UCN Polarizer

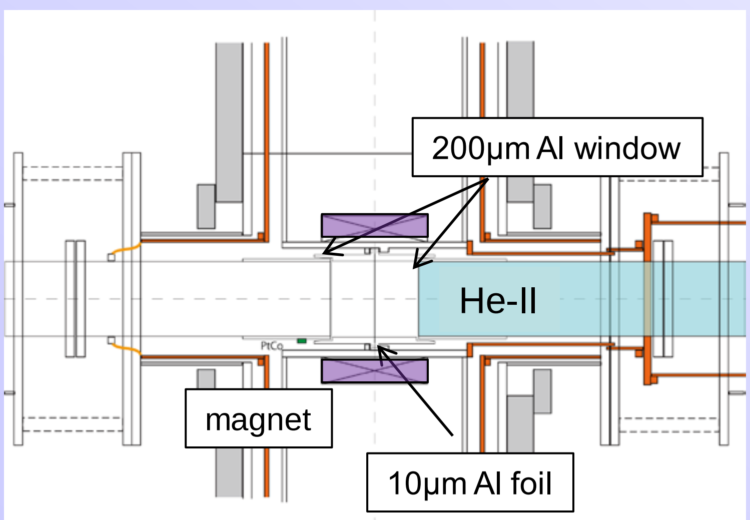


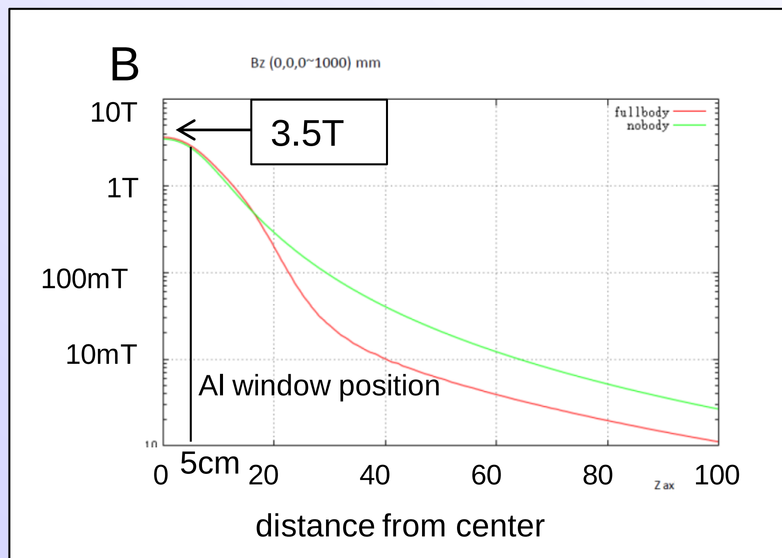
UCN Polarizer
using super conducting magnet
Serebrov et.al. NIM A *545* 490-492 (2005)

UCN energy < 210 neV (guide potential)

magnetic potential 60 neV / T
3.5T field → 210 neV

reduce reflection at Al window (54 neV)
effective transmission (gain energy)





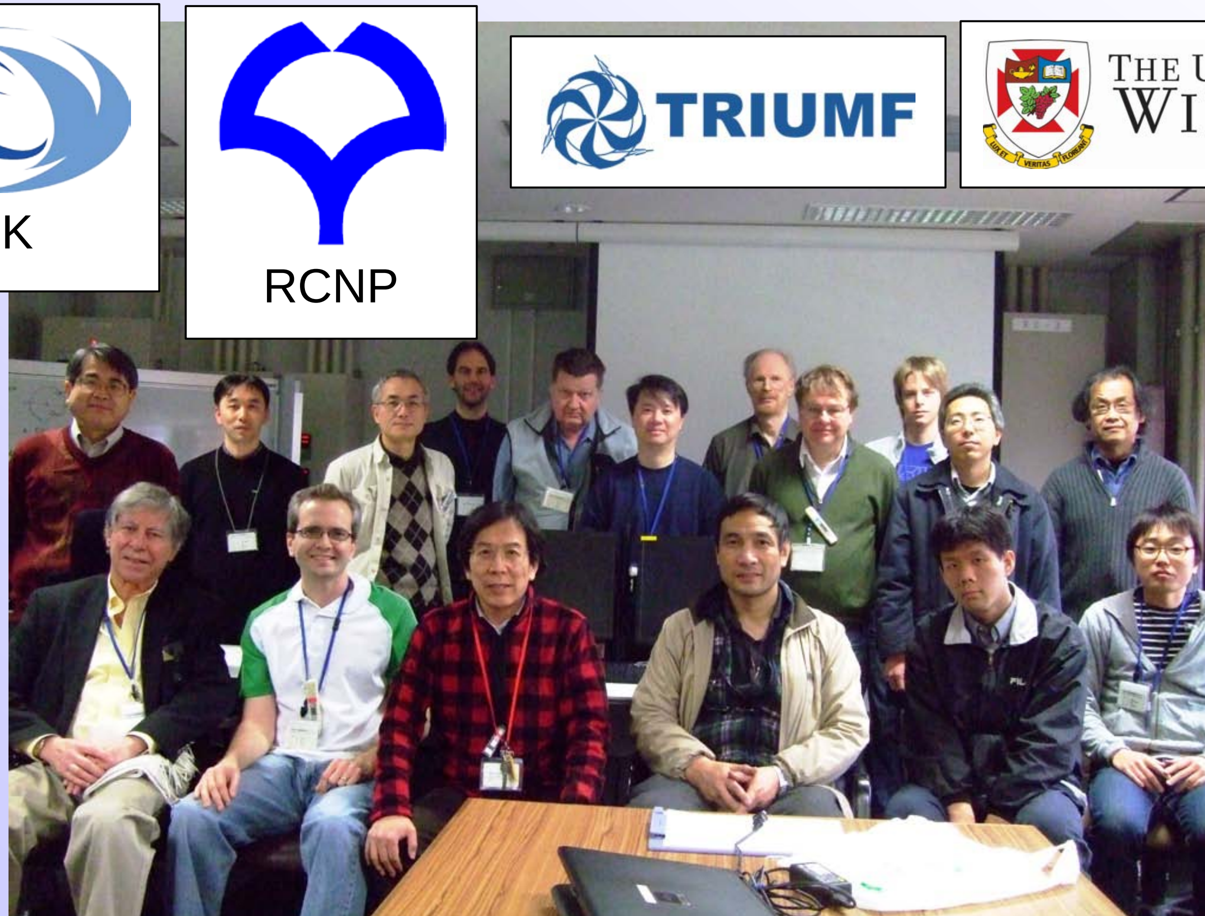
Collaboration

KEK

RCNP

TRIUMF

THE UNIVERSITY OF WINNIPEG



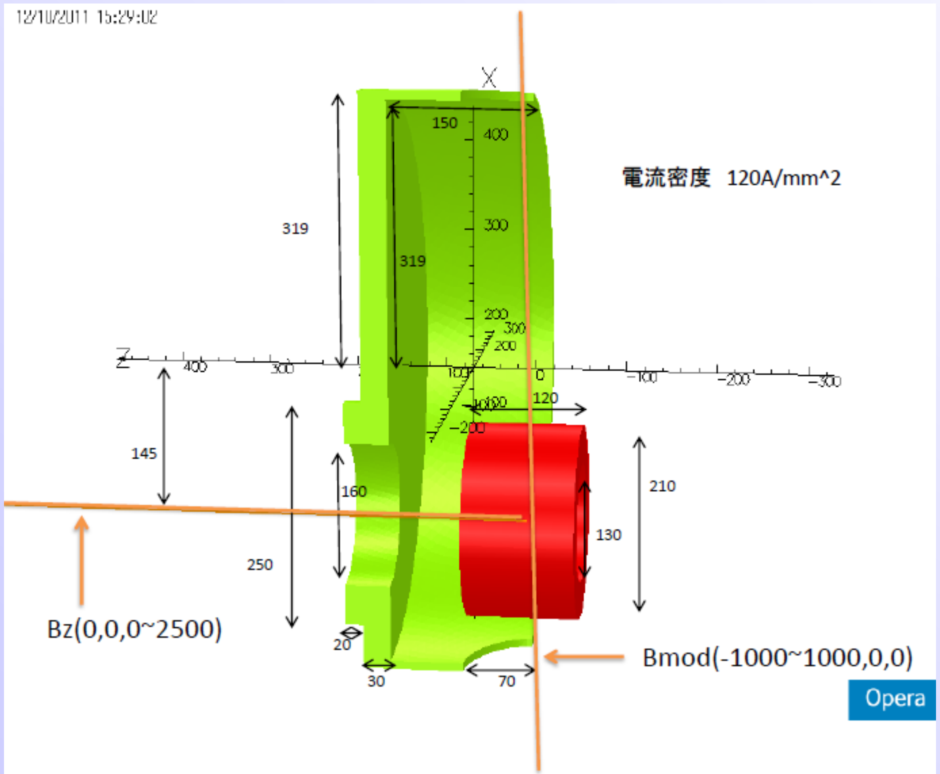
Summary and Future Plan

- Current UCN source
  - storage life time : 81 s
  - UCN density : 26UCN/cm^3 @ E_C = 90 neV
- New UCN Source
  - Horizontal extraction
  - 5 times UCN at the same proton power
  - Polarizer
- Future plan
  - 2013 UCN Production at RCNP
  - 2014 or 2015 Transport to TRIUMF
    - beam power 1 μA @ RCNP → 40μA @ TRIUMF

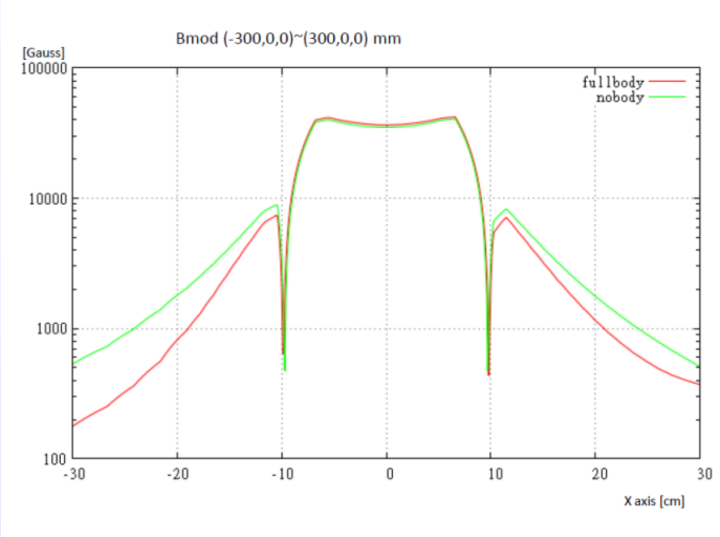
Thanks

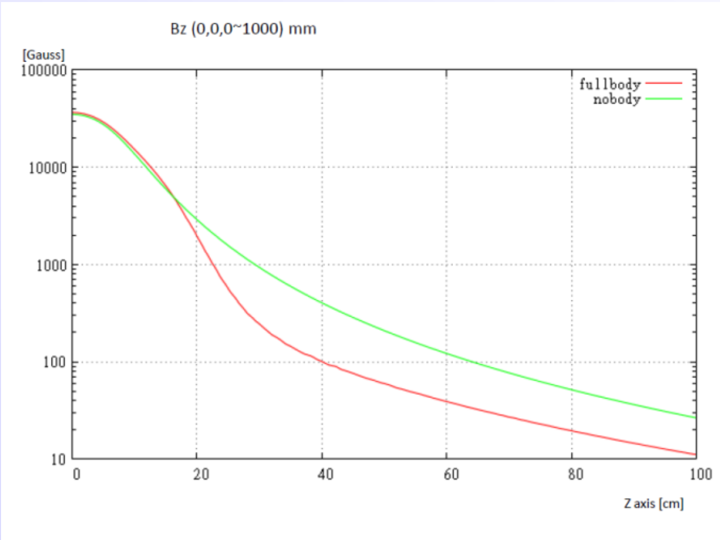
buck up slide

Super conducting magnet



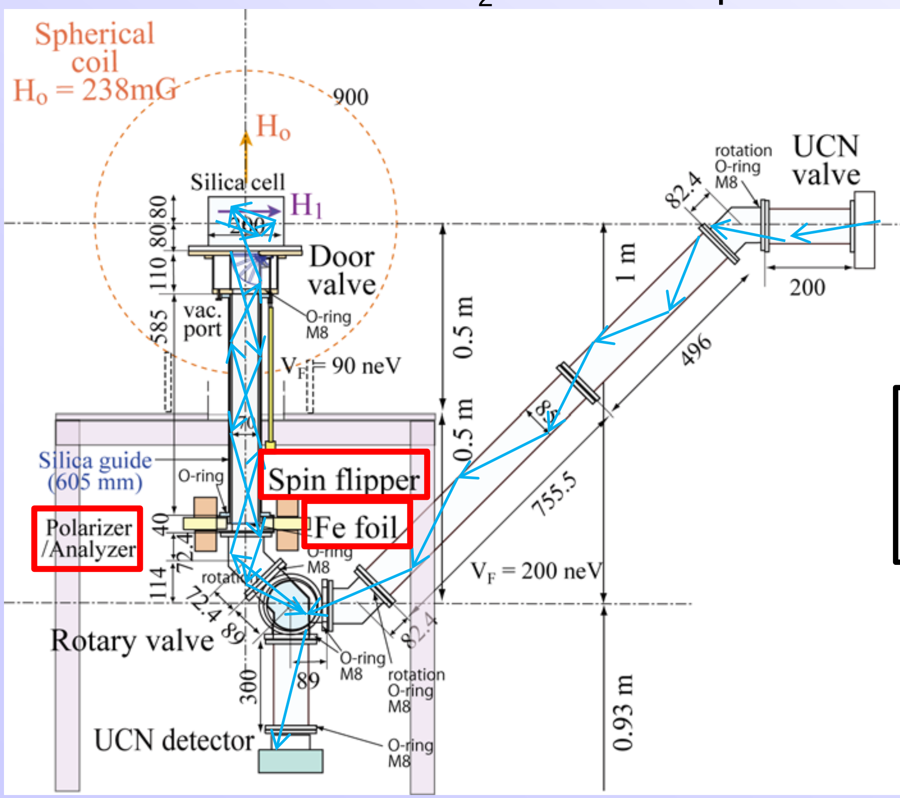
Magnet design





Polarized UCN transportation

- Good material for polarized UCN transportation
  - large potential
  - long spin holding time
- Store UCN in cell and measure spin holding time
  - SiO_2 cell ＋ sample

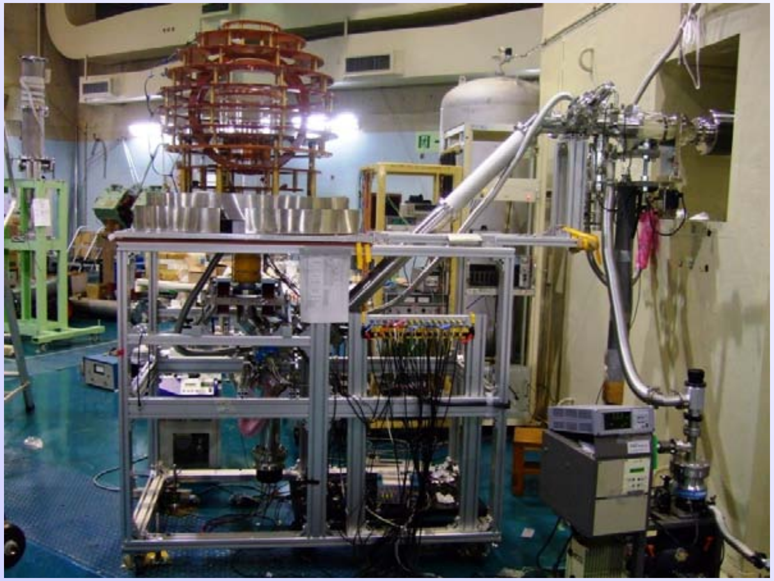


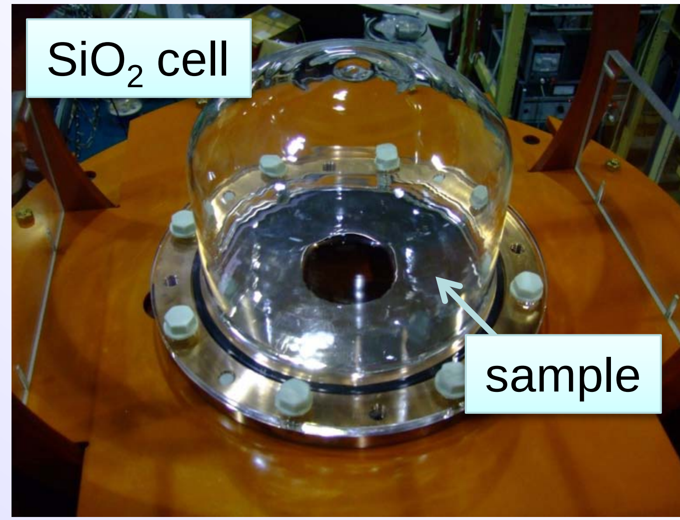
UCN Polarizer
Fe foil : potential V_F = 210 neV
inner field 2T
$V_F + \mu H$ = 210 neV ± 120 neV
330 neV or 90 neV

UCN energy
V_{max} = 170 neV
only one spin component can transmit Fe foil

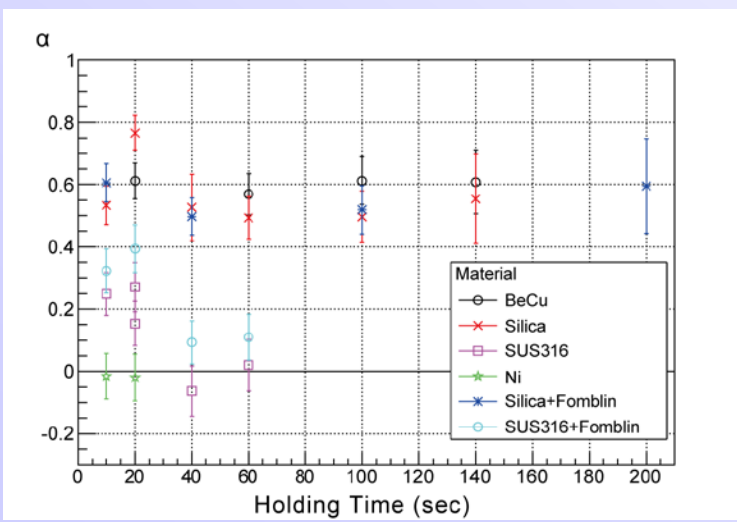
Spin Flipper
spin flipped UCN cannot transmit Fe foil

Material for Polarized UCN Transport





$$\alpha \equiv \frac{N_{off} - N_{on}}{N_{off} + N_{on}}$$



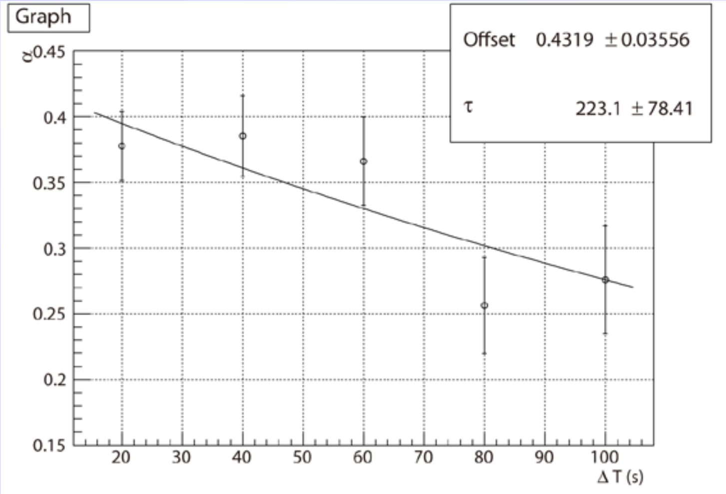
Fermi potential

Ni	210neV
SUS316	190neV
BeCu	168neV
SiO_2	90neV

(BeCu and SiO_2 boxed) OK

DLC Coating

- CuBe coated DLC(Diamond Like Carbon)
  - H free DLC
    - Pure C
    - C_6F_6
  - Fermi potential ～250neV (depend on density)



H0 = 20mGauss
BeCu+DLC(C_6F_6)
Spin Holding time ～200sec