TRIUMF

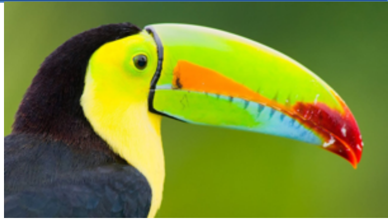
Canada's national laboratory
for particle and nuclear physics
and accelerator-based science

Towards the nEDM search at TRIUMF

Ryohei Matsumiya (TRIUMF)
for the TUCAN collaboration

Hadron 2018 workshop
July 26-30, 2018, Shandong University, Weihai, China

TRIUMF UltraCold Advanced Neutron source



S. Ahmed[3,4], T. Andalib[3,4], C. Bidinosti[3,8], J. Birchall[4], M. Das[3,4], C. Davis[5], E. Cudmore[5] A. Ezzat[2], B. Franke[5], M. Gericke[4], S. Hansen-Romu[3,4], K. Hatanaka[6], B. Jamieson[3], K. Katsika[5], S. Kawasaki[1], T. Kikawa[5], M. Kitaguchi[10], A. Konaka[5,8], F. Kuchler[5], E. Korkmaz[7], M. Lang[3,4], L. Lee[5], T. Lindner[3,5], Y. Makida[1], J. Mammei[4], R. Mammei[3], C. Marshall[5], J. W. Martin[3], R. Matsumiya[5], K. Mishima[1], T. Momose[2], R. Nagimov[5], T. Okamura[1], S. Page[4], R. Picker[5,9], E. Pierre[6,5], W. D. Ramsey[5], L. Rebenitsch[3,4], W. Schreyer[5], H. SHimizu[10], S. Sidhu[9], J. Sonier[9], I. Tanihata[6], W. T. H. van Oers[4,5], and Y. Watanabe[1]

[1]KEK
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[6]RCNP
[7]The University of Northern BC
[8]Osaka University
[9]Simon Fraser University
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TUCAN’s Goal & Outline of This Talk

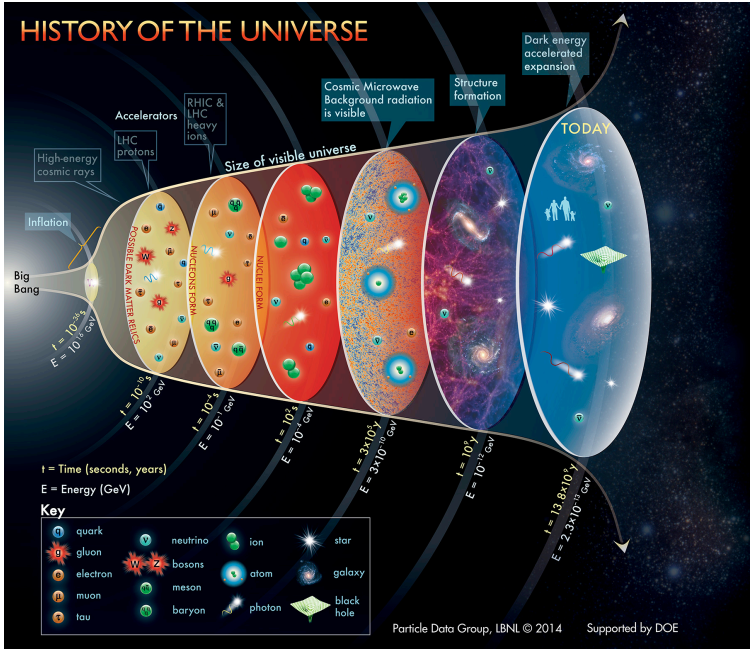
TUCAN’s Goal

- Develop world-leading intensity Ultra-Cold Neutron (UCN) source at TRIUMF
- Search for the neutron Electric Dipole Moment (nEDM) to a precision of 10^{-27} *e*cm

Outline

- Background, nEDM, Ultra-Cold Neutron (UCN)
- UCN source
  - ✓ Super-thermal UCN production
  - ✓ Prototype UCN source development at RCNP, Osaka U, Japan
  - ✓ New world-leading UCN source
- nEDM spectrometer
- Summary and Future Outlook

Baryon Asymmetry in the Universe



- Our universe: matter ≫ anti-matter
- Baryon asymmetry parameter - large discrepancy between observation and theory

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10}$$ Observation

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \leq 10^{-18}$$ Standard Model (SM) expectation

CP violation in the SM is not sufficient.
New source of CP violation is needed.

Sakharov's 3 conditions

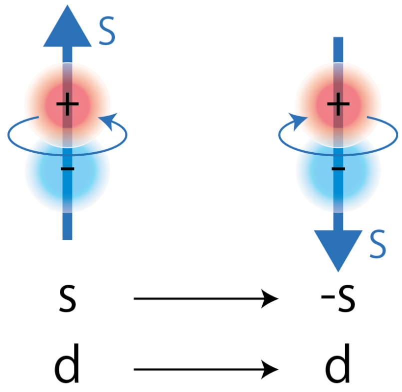
1. Baryon number B violation
2. C and CP violation
3. Interactions out of thermal-equilibrium

nEDM - Neutron Electric Dipole Moment

- New physics beyond standard model (BSM)
  - Supersymmetry, multi Higgs, LR model etc…
- Many BSM physics. How to test it?

nEDM can be a good probe to test BSM

Neutron Electric Dipole Moment (nEDM)



Time reversal

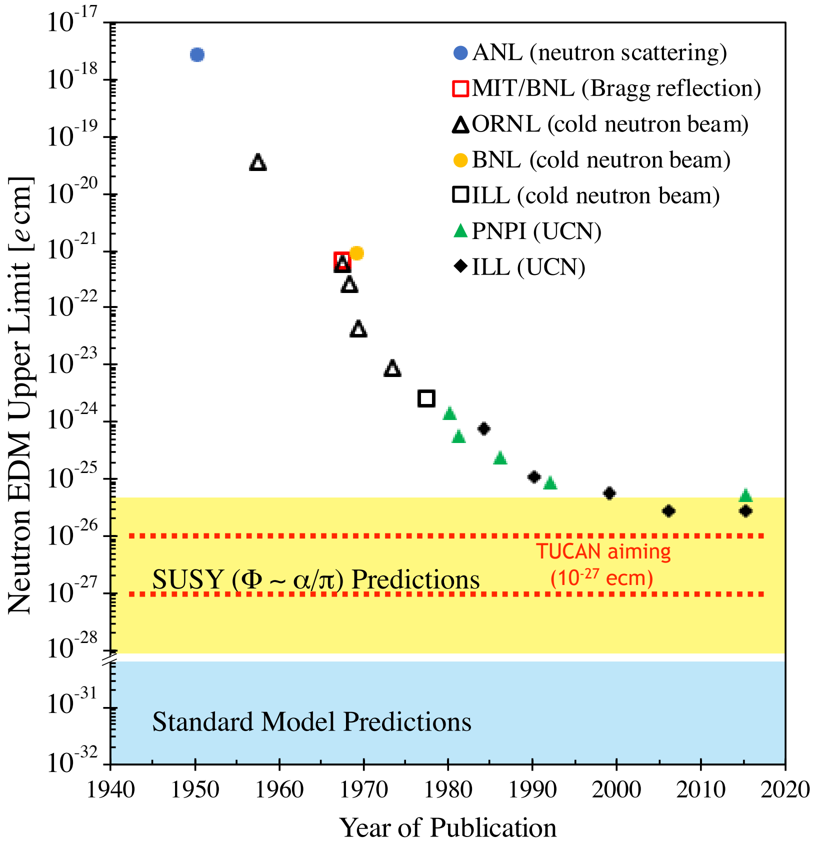
Finite EDM $d \neq 0$

⬍

T violation

⬍

CP violation



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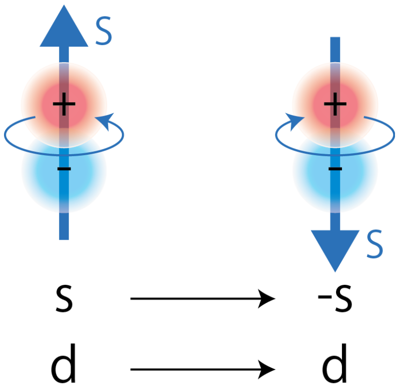

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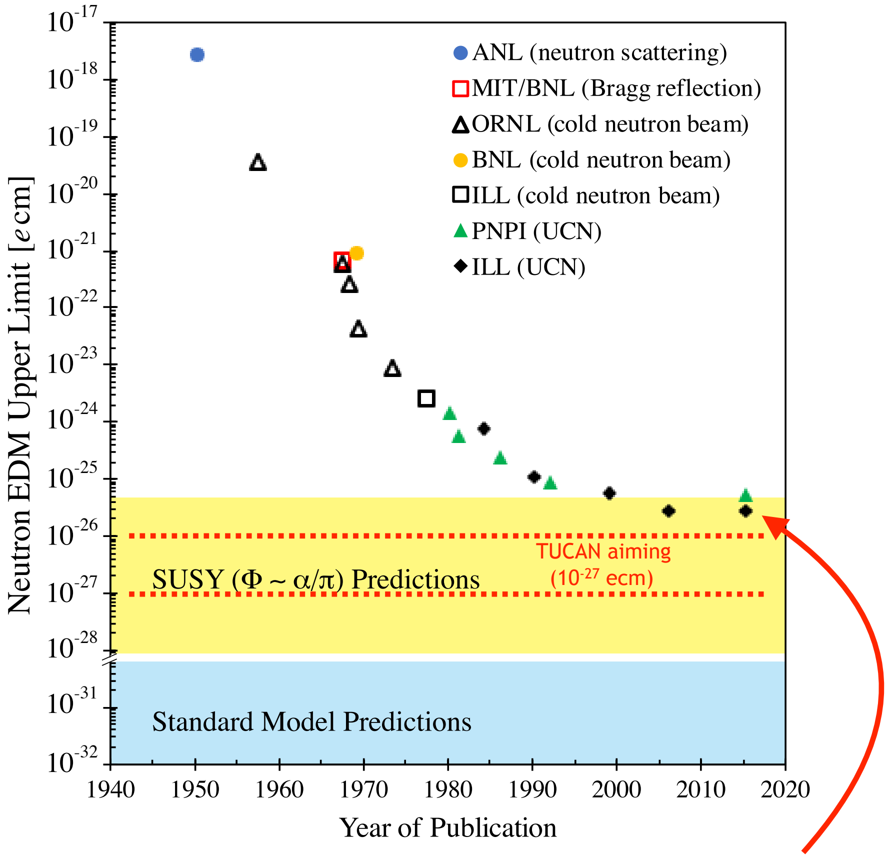

Current upper limit : $|d_n| < 3.0\times10^{-26}$ *e* cm (90%CL)
J.M.Pendlebury et al., Phys. Rev. D **92**, 092003 (2015)

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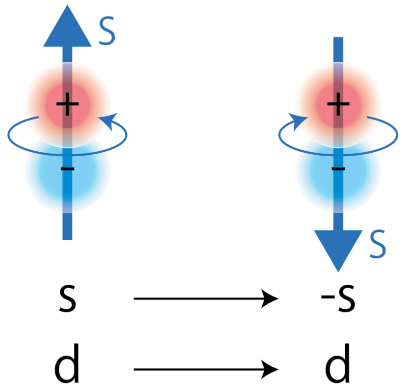

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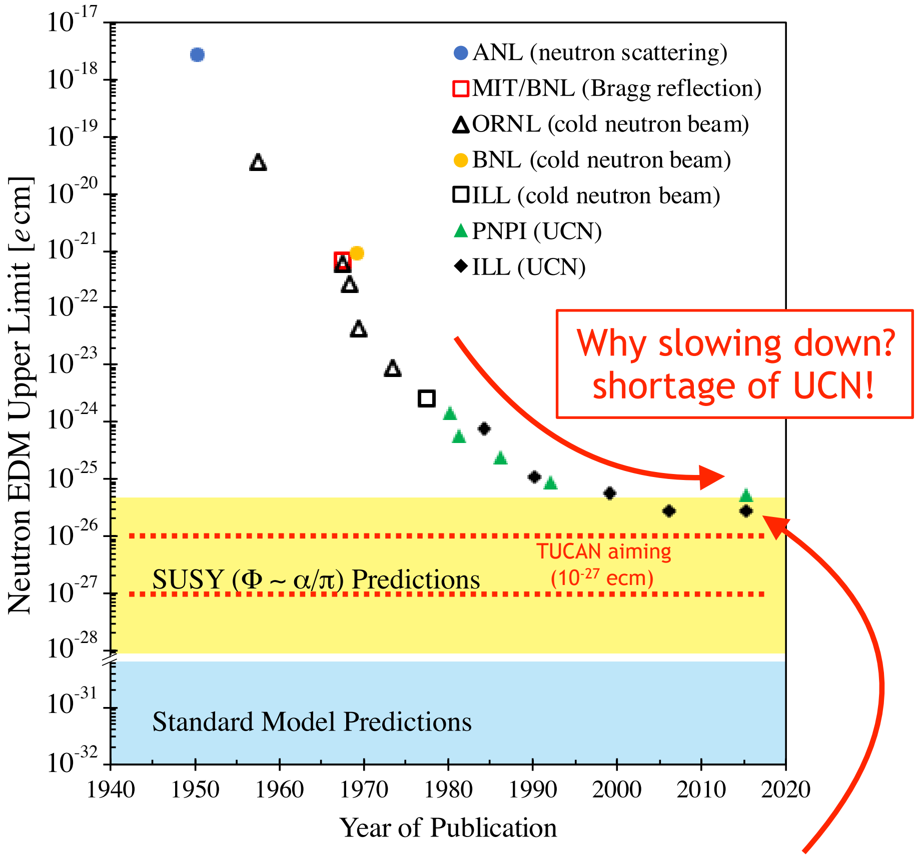

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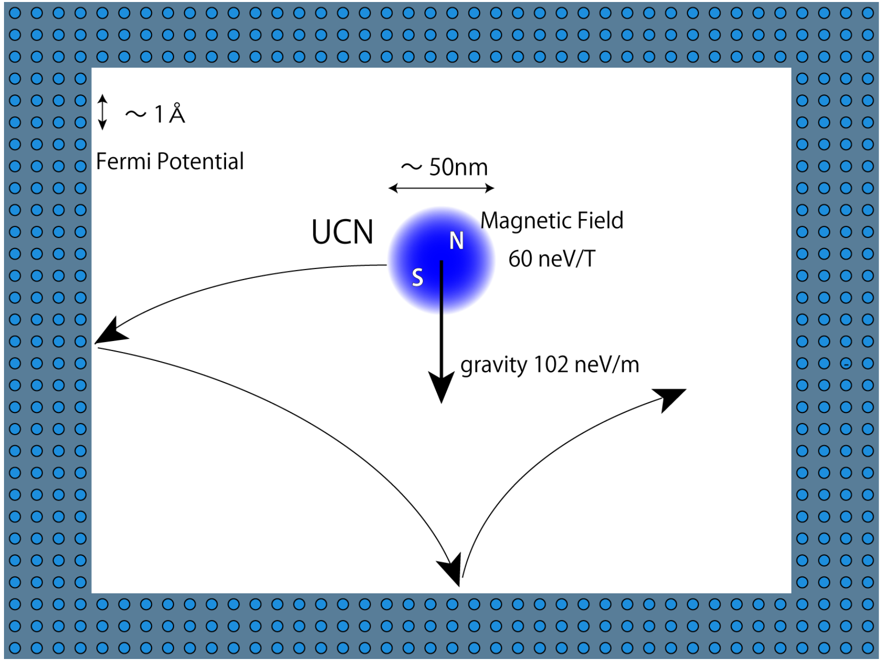
Ultra-Cold Neutron (UCN)



Ultracold Neutron (UCN)

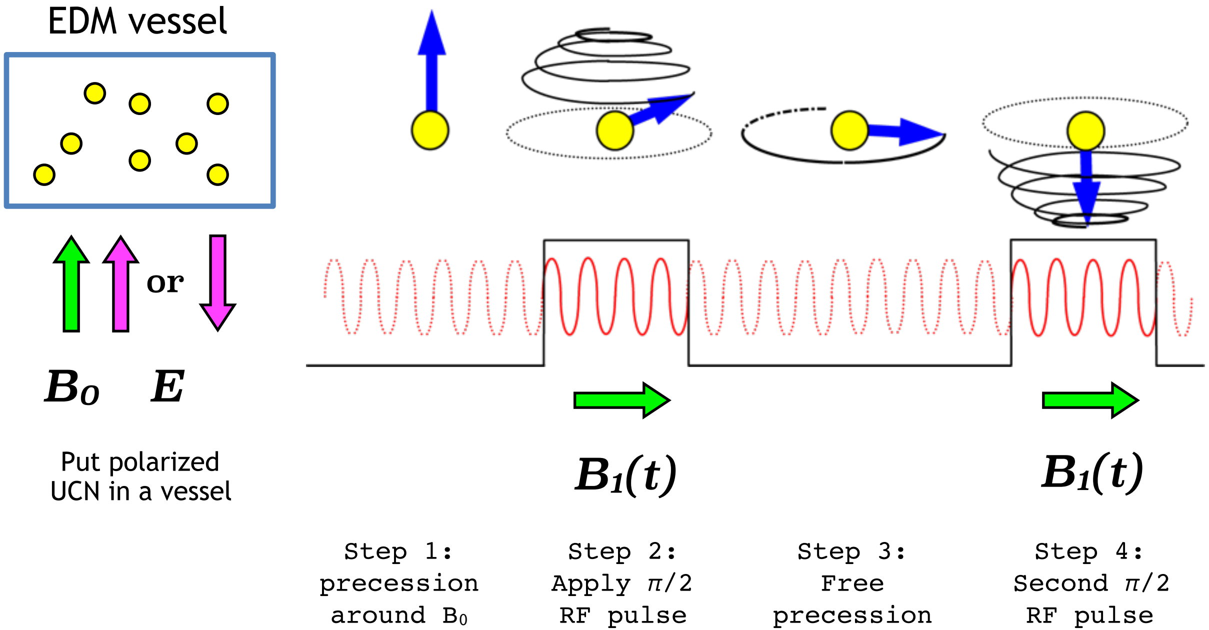
Energy ~ 100neV
Velocity ~ 5 m/s
Wavelength ~ 500 Å (50 nm)

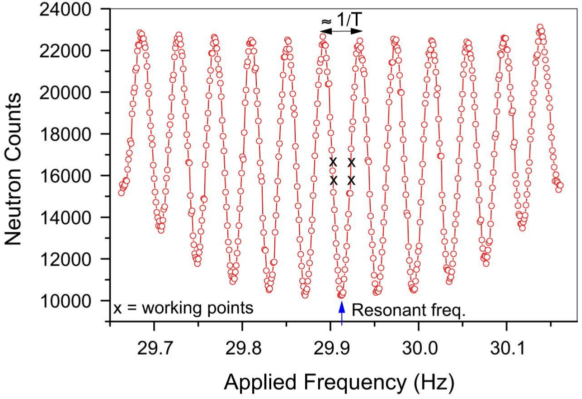
Interaction

Gravity ~ 102 neV/m
Magnetic field ~ 60 neV/T
Weak interaction: n → p + e + *v*
Strong interaction (Fermi potential)
^{58}Ni fermi potential: 335 neV
Stainless steel: 190 neV
Aluminum: 54 neV

UCN can be stored in a material vessel for a long time (~100 sec)
→ nEDM, n lifetime, Gravity etc…

Ramsey Resonance





$$\hbar\omega = \begin{cases} -2\mu_n B_0 - 2d_n E \ (E\uparrow) \\ -2\mu_n B_0 + 2d_n E \ (E\downarrow) \end{cases}$$

$$\Delta\omega = -\frac{4d_n E}{\hbar}$$

$\omega \sim 30$ Hz ($B_0 = 1$ µT),
$\Delta\omega \sim 1$ nHz
($d_n = 10^{-27}$ e cm, E=10kV/cm)

Statistical error:

$$\sigma(d_n) = \frac{\hbar}{2\alpha T_c E\sqrt{N}}$$

- α : polarization
- T_c : free precession time
- E : electric field strength
- N : number of UCN

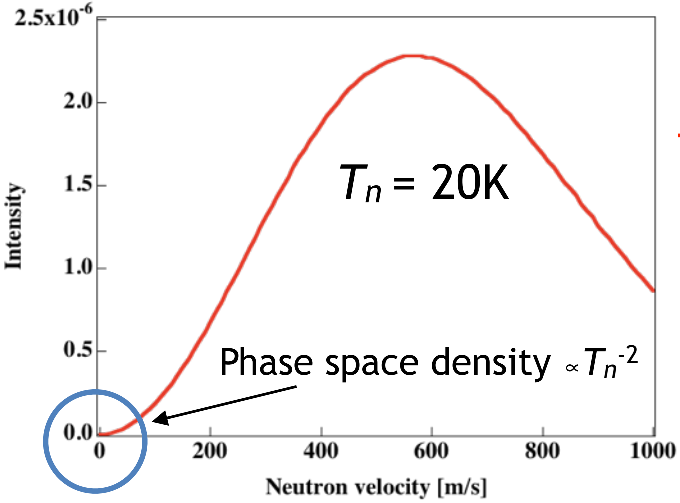
UCN density is important!

UCN Extracted from Reactor

58MW reactor

- Institute Laue Langevin (ILL), Grenoble, France
  - UCNs are extracted from low energy tail of cold neutrons
  - UCN density in the EDM vessel: 0.7UCN/cm^3 (E_c=90neV)
  - Phase space density is proportional to T_n^{-2}

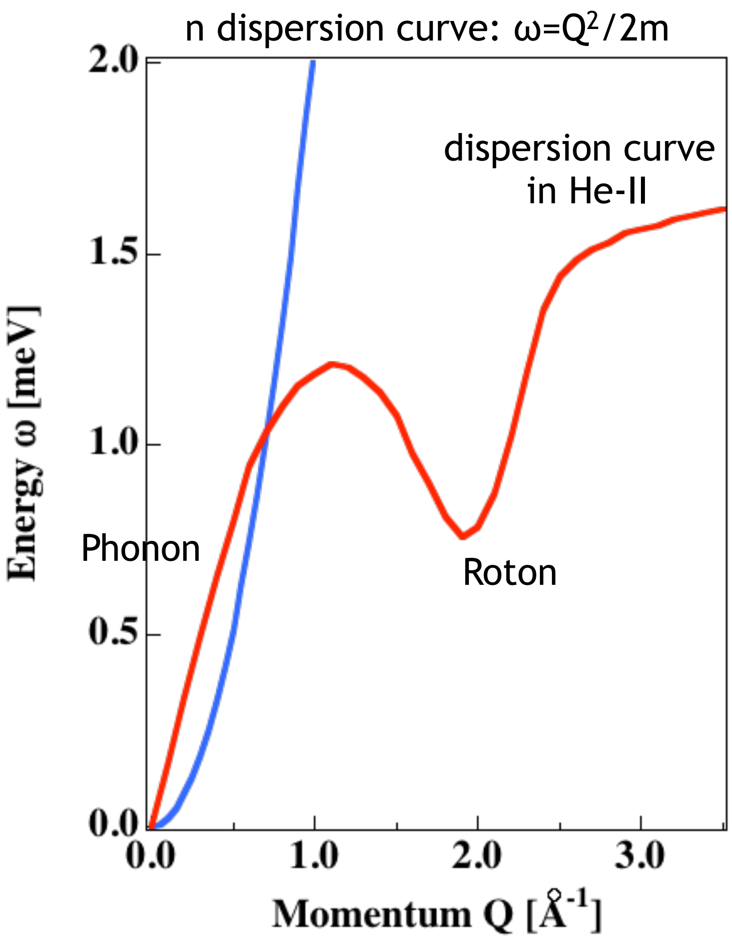
n velocity distribution



Phase space density is constant (Liouville's theorem).
To lower T_n in the reactor is difficult.

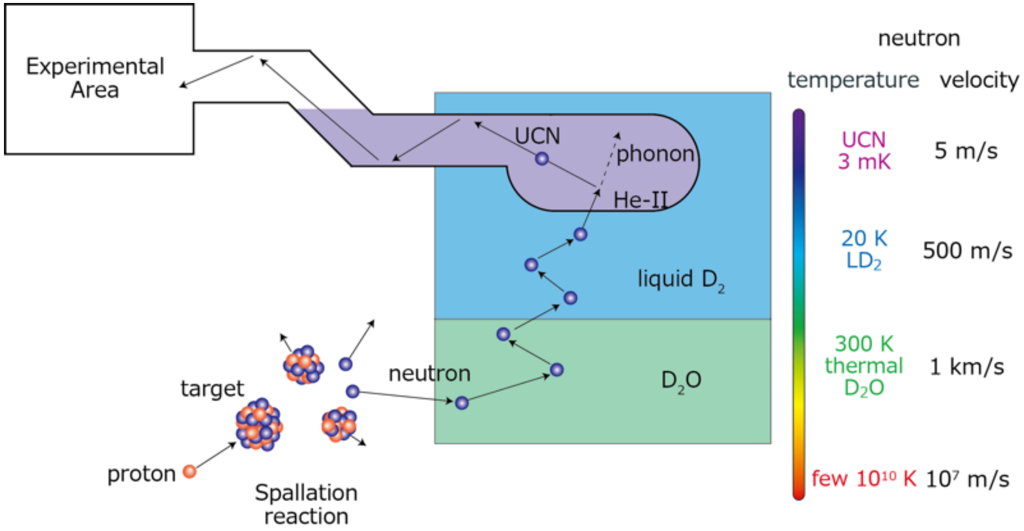
More efficient UCN production = Super-thermal UCN production

Super-thermal UCN Production in Superfluid Helium (He-II)



- Super-thermal UCN production (Golub & Pendlebury, 1977)
  - Phonon effective mass is same as the mass of a neutron at the intersection (1.1meV, 12K)
  - Momentum & energy of a cold neutron are passed to a phonon by single phonon scattering.
  - Effective UCN production becomes possible using phonon's phase space.

He-II Super-thermal UCN Source



- Produce fast neutrons by proton-induced spallation reaction

~ several MeV

- Moderate neutrons in 300K D_2O and 20K D_2O or LD_2

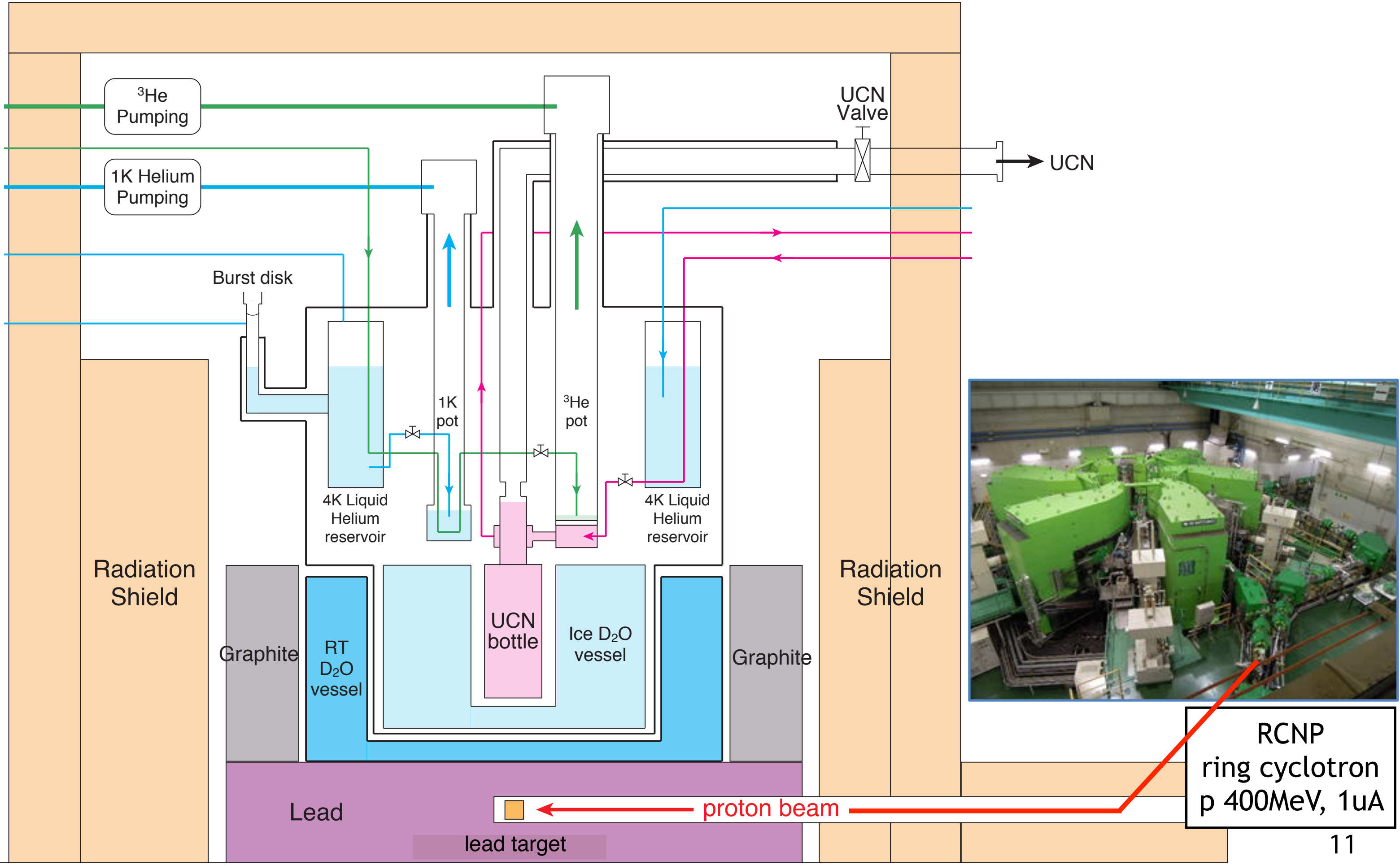
~ several meV

- Cold neutrons are down-scatterered to near zero energy by phonon scattering in superfluid helium (He-II)

< 300 neV

Prototype UCN Source at RCNP

- First UCN production in 2002
- Operation at RCNP finished in 2011



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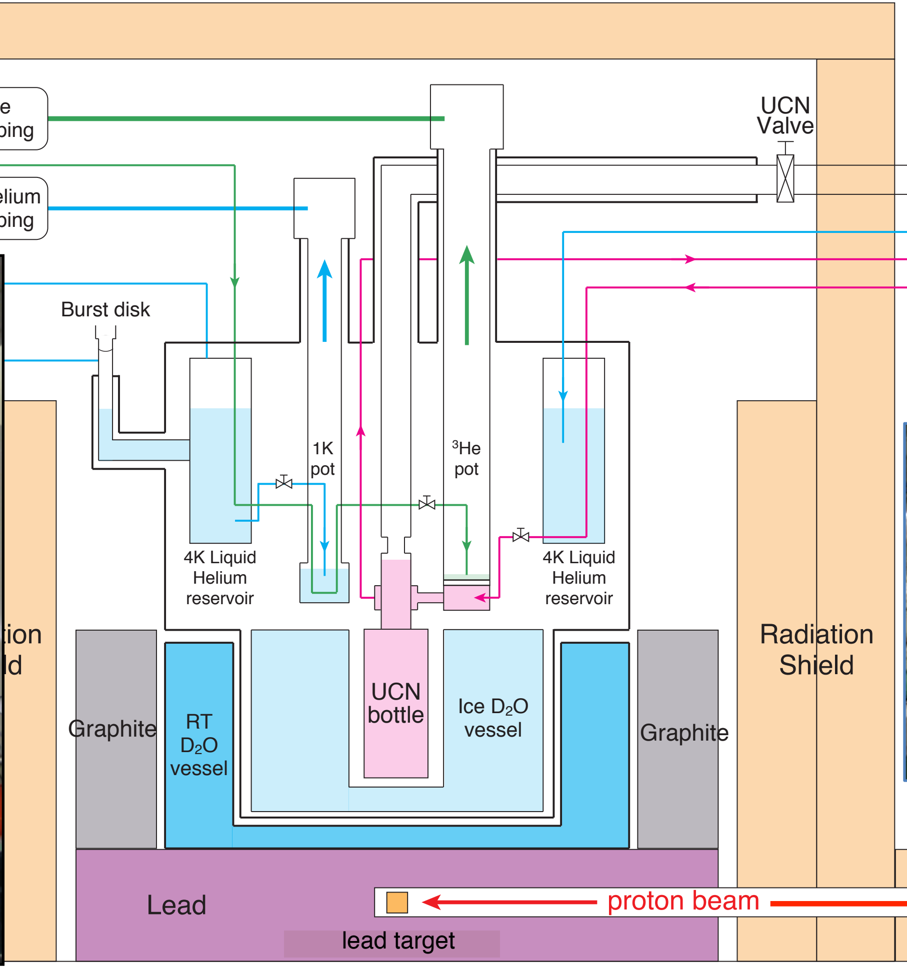
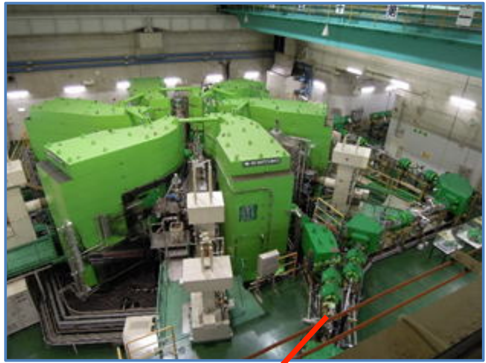


UCN cryostat



RCNP
ring cyclotron
p 400MeV, 1uA

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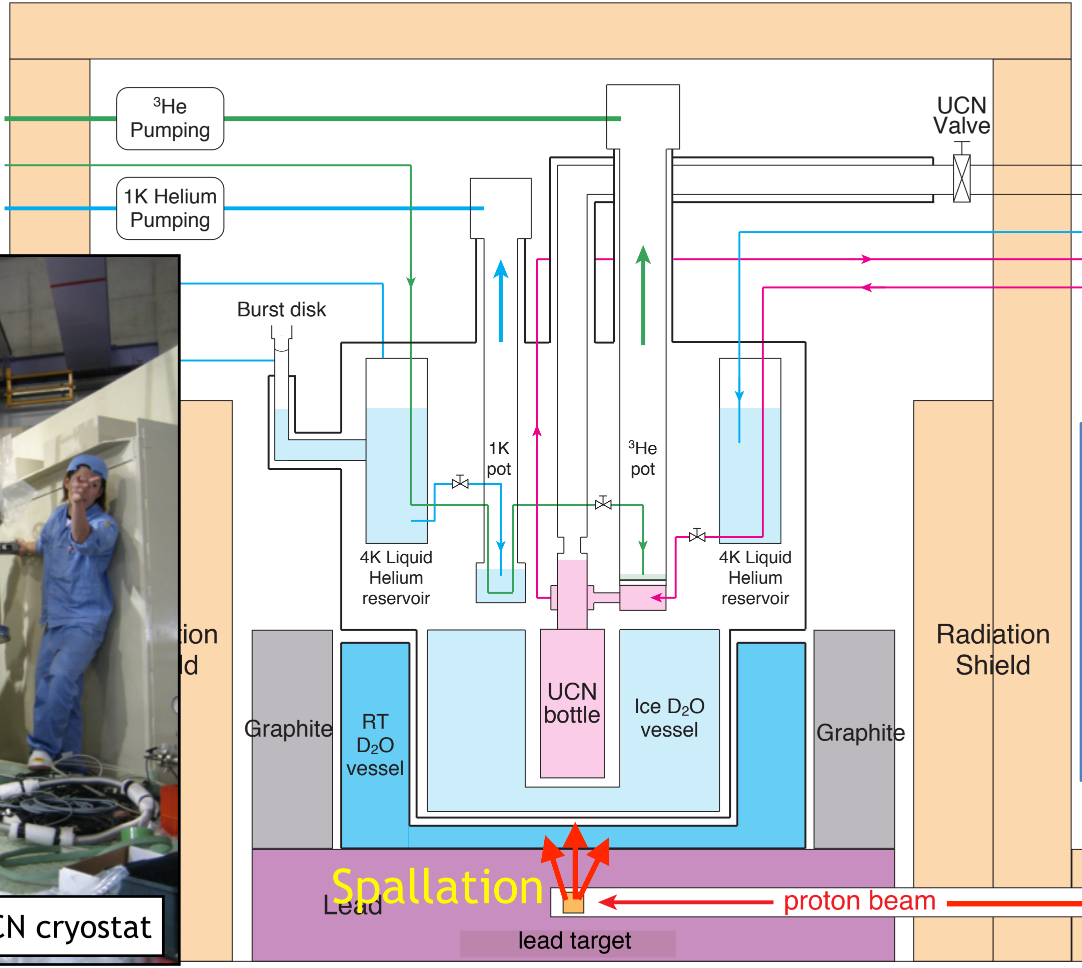

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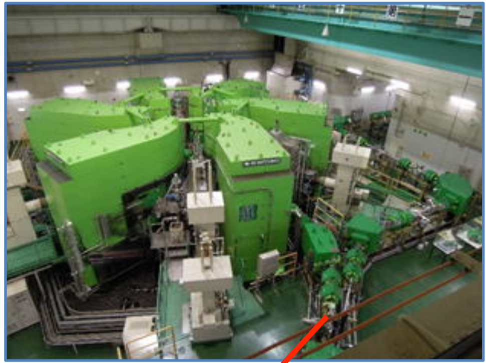

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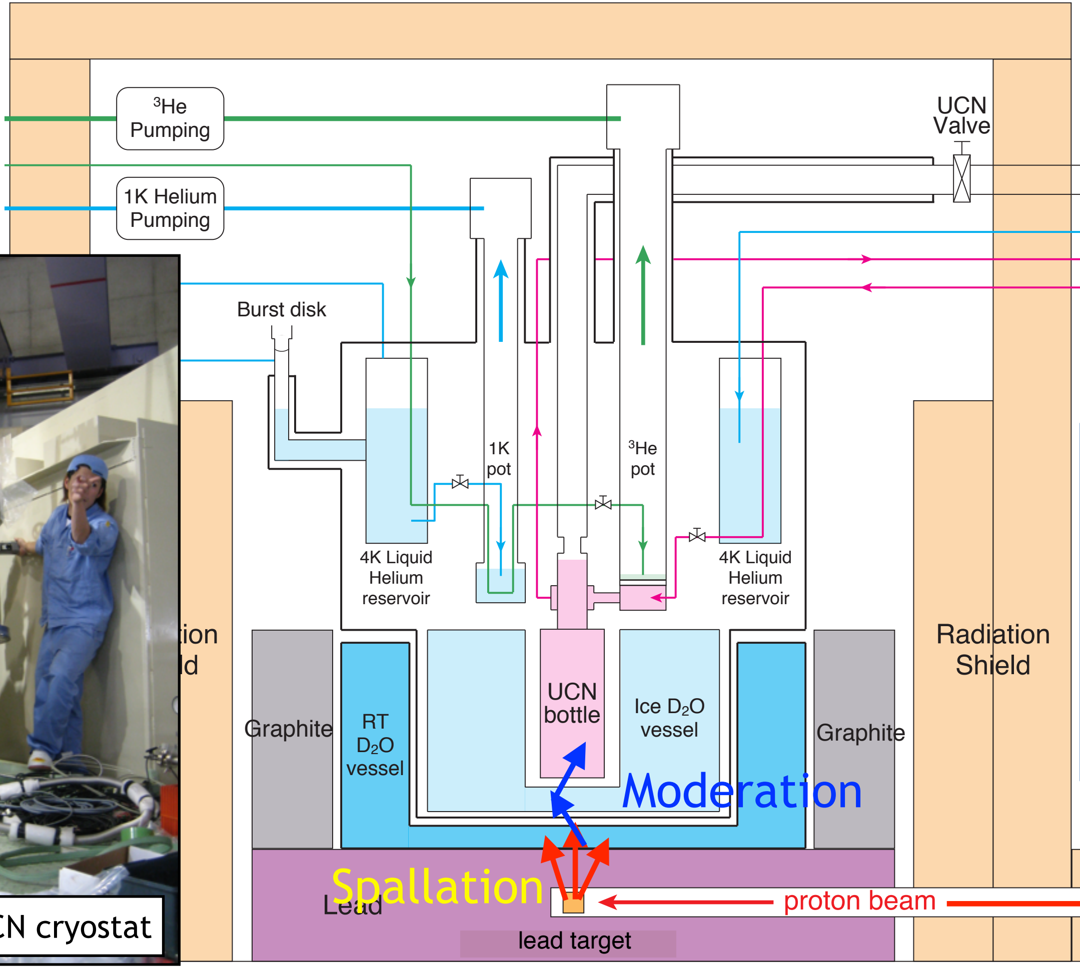

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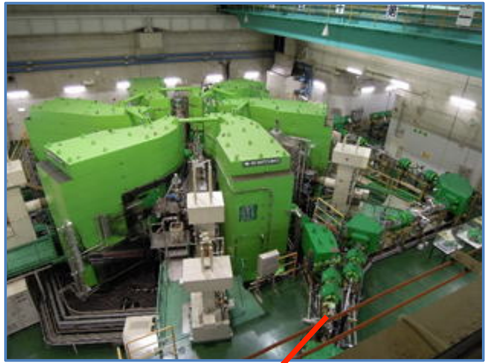

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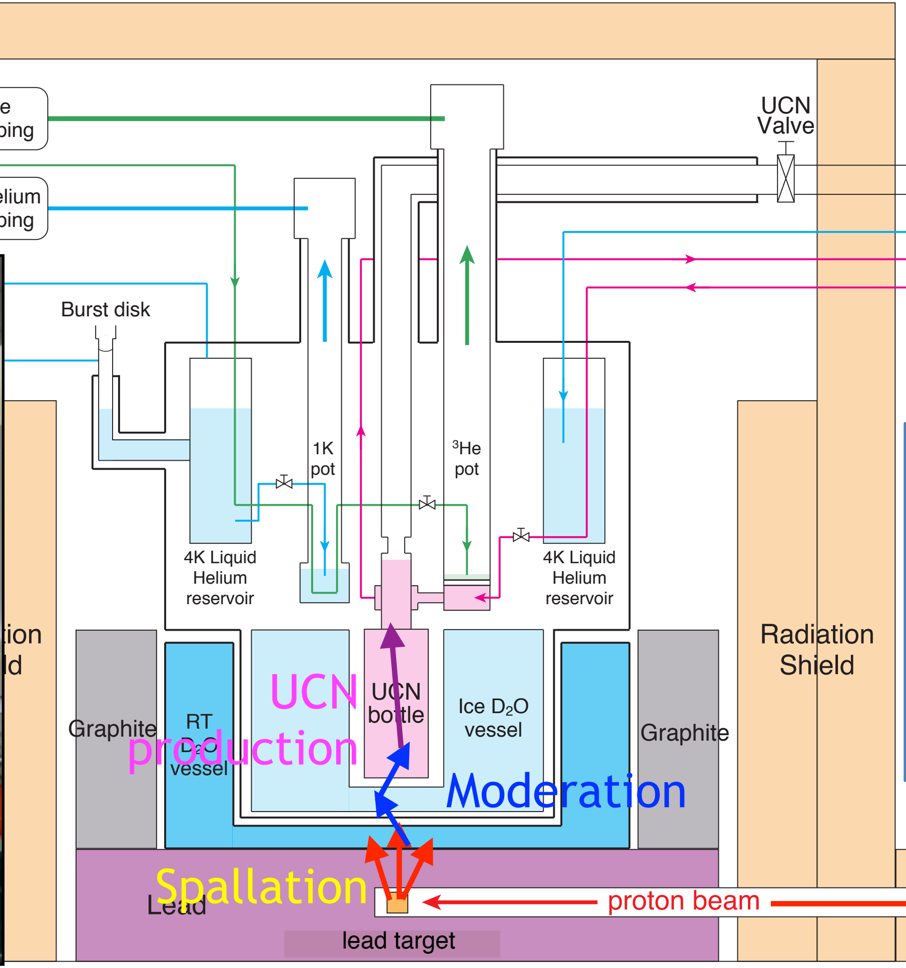

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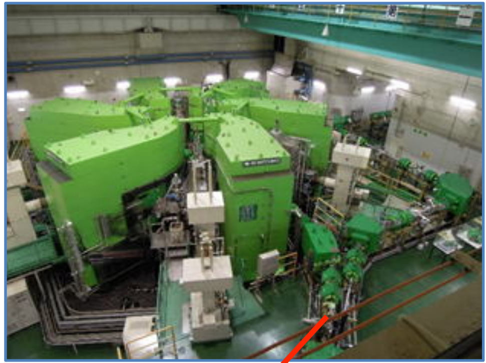

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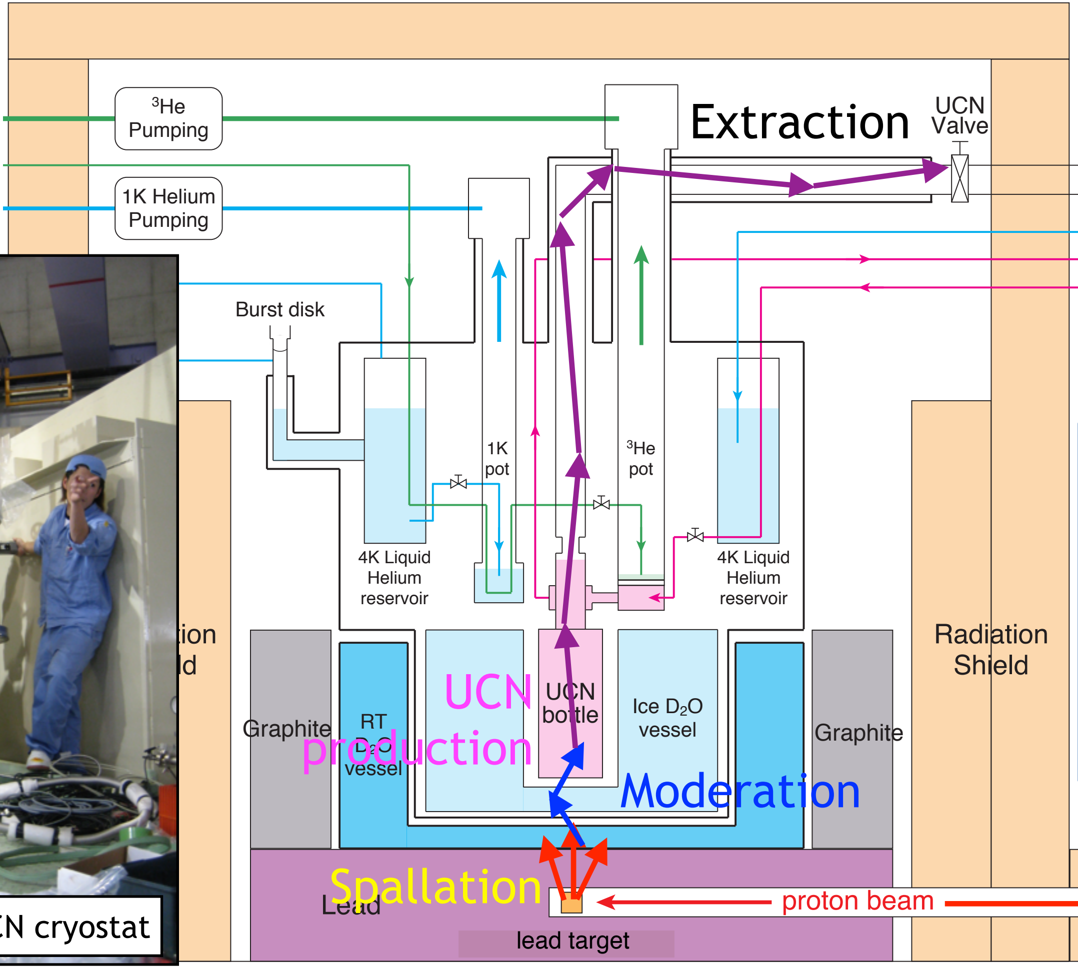

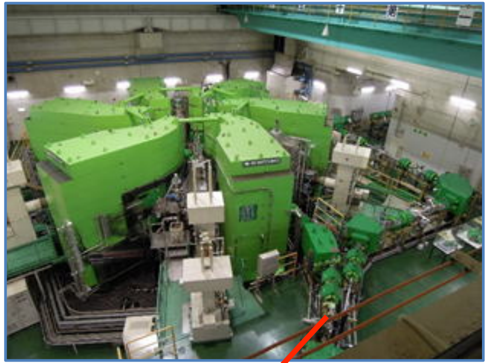

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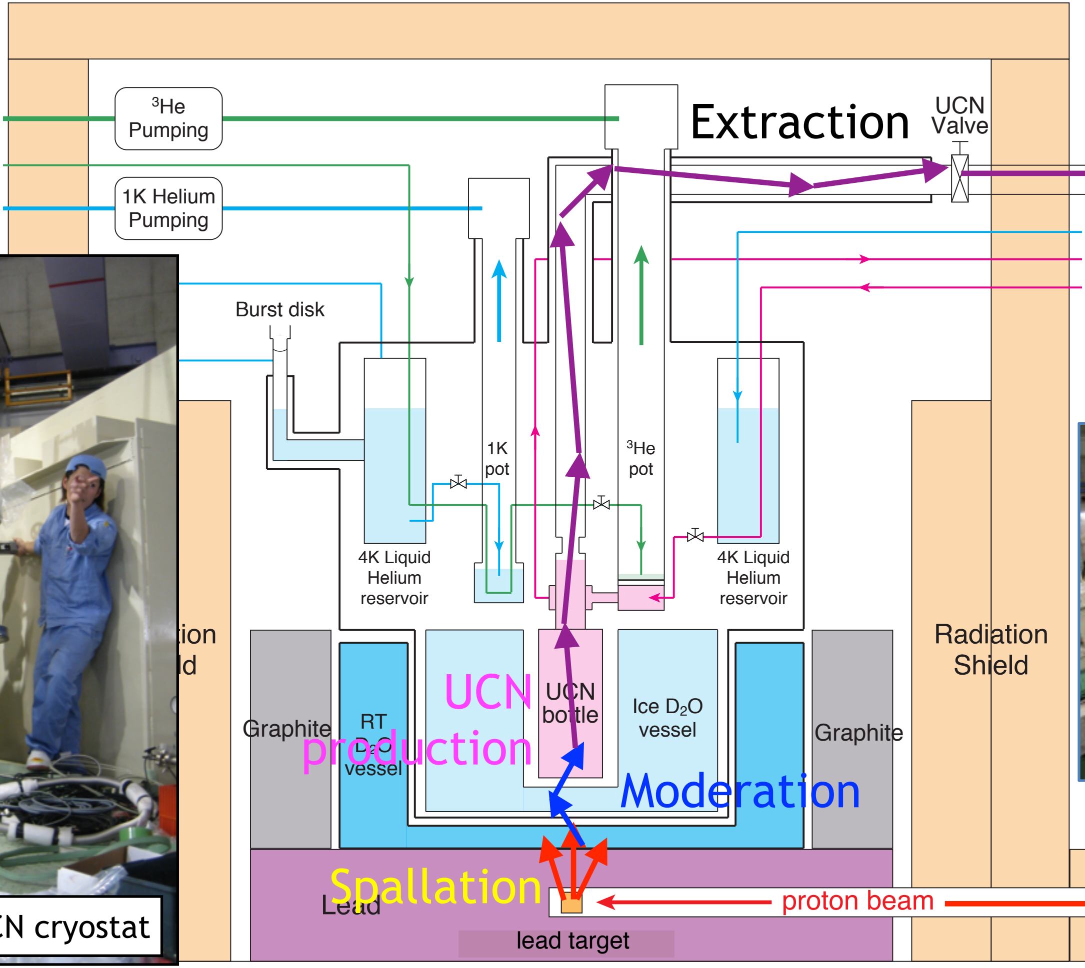
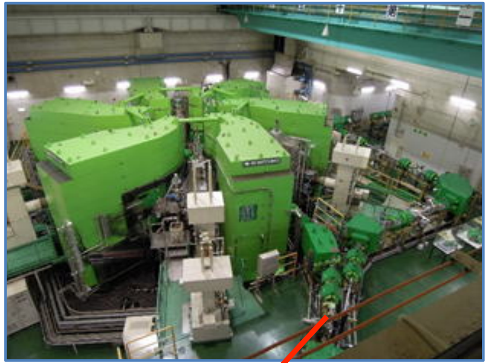


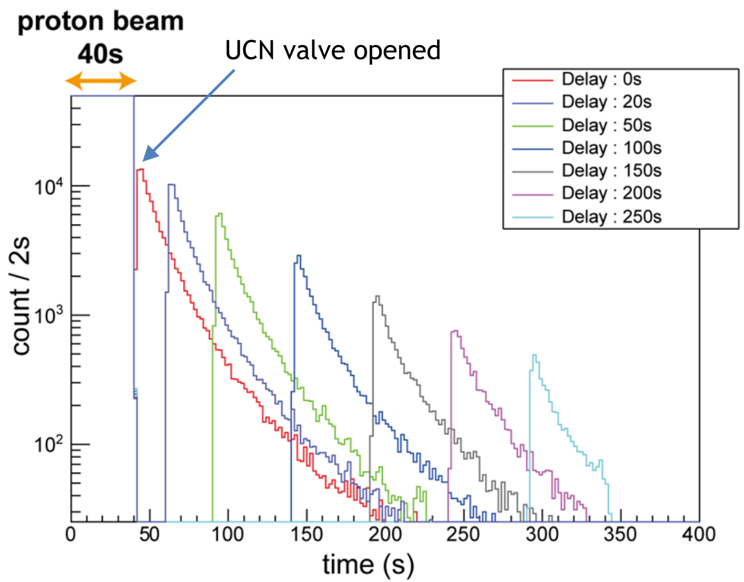
UCN cryostat

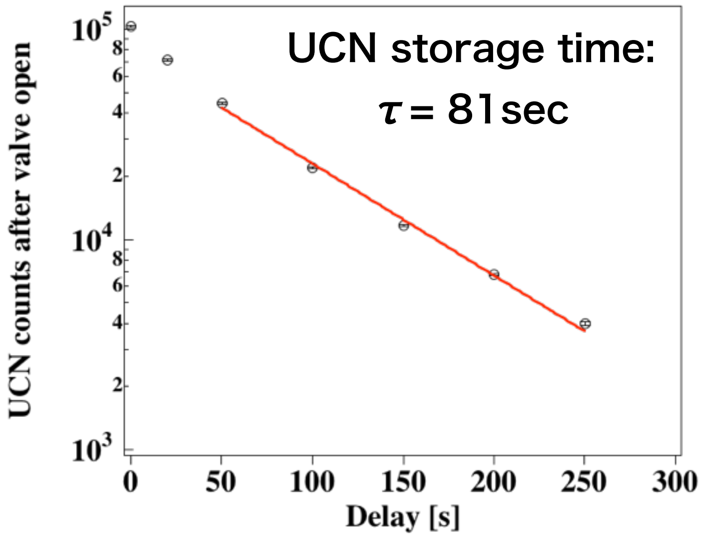
UCN equipment



RCNP ring cyclotron p 400MeV, 1uA

R&D at RCNP





Best record (2011)

- p-beam: 400W (1μA×400MeV)
- UCN counts: 10^5 UCN for 40s p-beam
- 260,000 UCN for 240s p-beam
- ~9UCN/cm^3 (E_c=90neV)in the UCN source

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

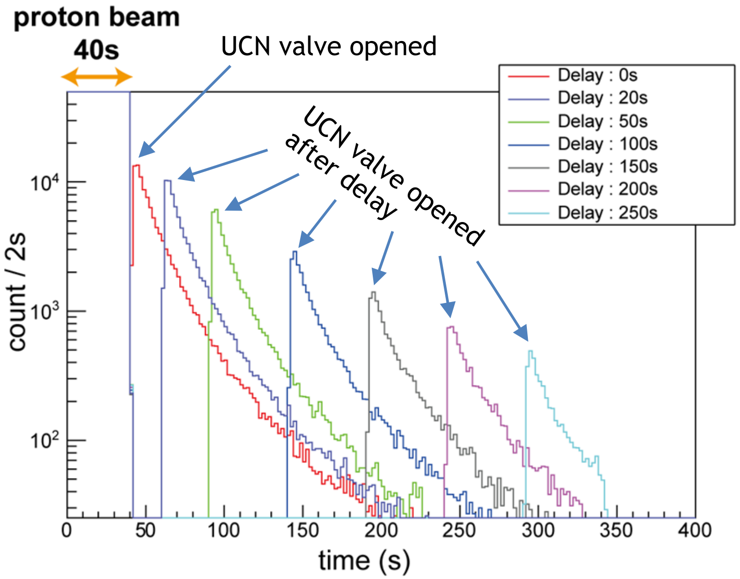
- UCN storage time $\frac{1}{\tau} = \frac{1}{\tau_{phonon}} + \frac{1}{\tau_{gas}} + \frac{1}{\tau_{wall}} + \frac{1}{\tau_{\beta}}$

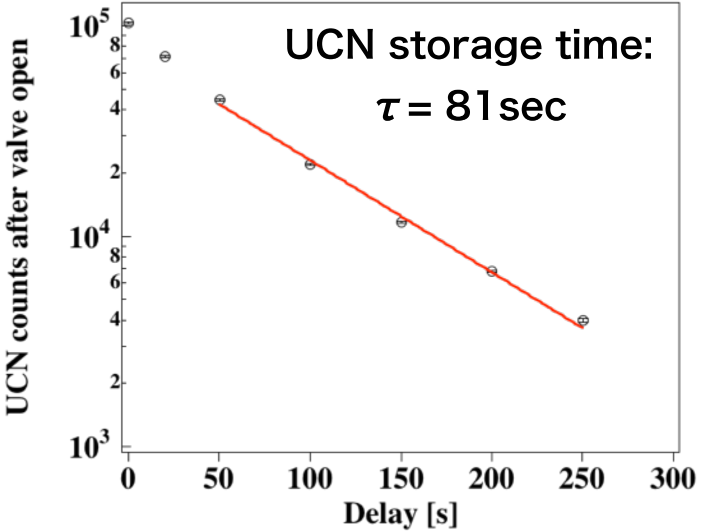
✓ In addition to β-decay (~15min), UCN is lost by phonon up-scattering, collision with helium gas, absorption by wall material.

✓ Longer UCN storage time leads to higher UCN density

- Lowering He-II temperature (Cooling system improvement)
- Cleaning UCN bottle & guide (Baking & Alkali degreasing)

R&D at RCNP





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Transport from Japan to Canada

- The prototype UCN source was transported from RCNP to TRIUMF in 2016 ~ 2017.

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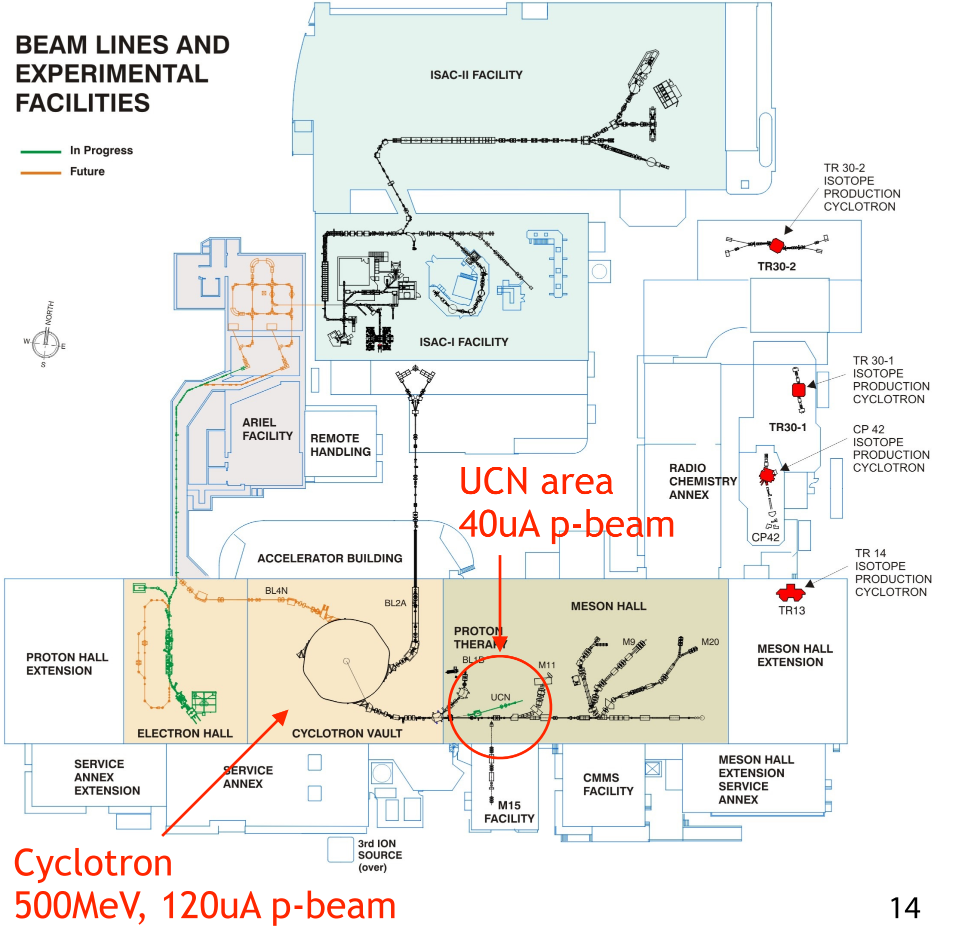
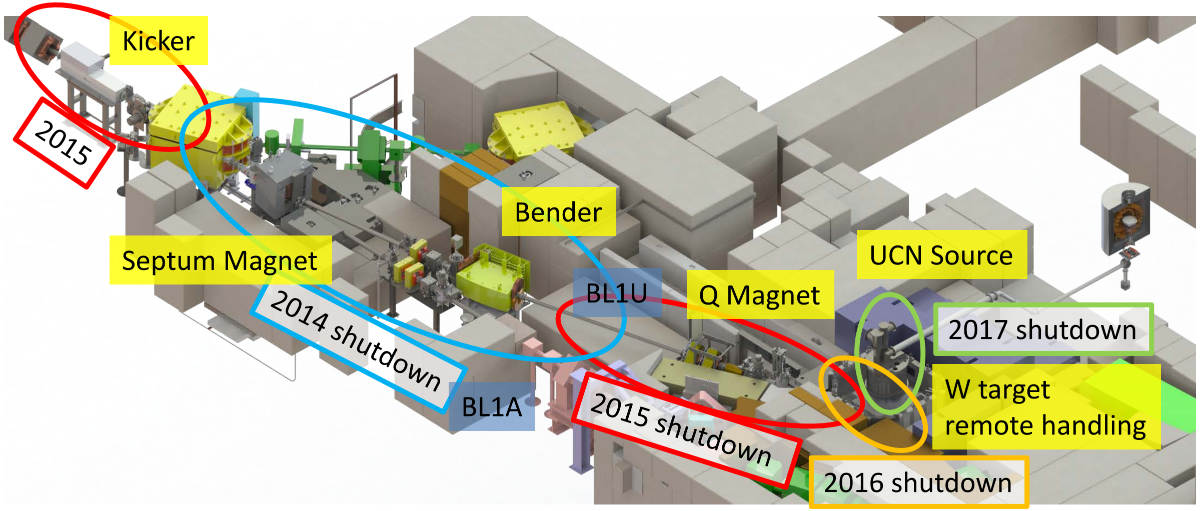
CANADA V6T 2A3


BEAM LINES AND EXPERIMENTAL FACILITIES
In Progress
Future
ISAC-II FACILITY
ISAC-I FACILITY
ARIEL FACILITY
REMOTE HANDLING
ACCELERATOR BUILDING
RADIO CHEMISTRY ANNEX
TR 30-2 ISOTOPE PRODUCTION CYCLOTRON
TR30-2
TR 30-1 ISOTOPE PRODUCTION CYCLOTRON
TR30-1
CP 42 ISOTOPE PRODUCTION CYCLOTRON
CP42
TR 14 ISOTOPE PRODUCTION CYCLOTRON
TR13
PROTON HALL EXTENSION
ELECTRON HALL
CYCLOTRON VAULT
BL4N
BL2A
MESON HALL
PROTON THERAPY
BL1B
M11
M9
M20
UCN
MESON HALL EXTENSION
SERVICE ANNEX EXTENSION
SERVICE ANNEX
M15 FACILITY
CMMS FACILITY
MESON HALL EXTENSION SERVICE ANNEX
3rd ION SOURCE (over)
UCN area
40uA p-beam
Cyclotron
500MeV, 120uA p-beam

TRIUMF Proton Beam Line (BL1U)

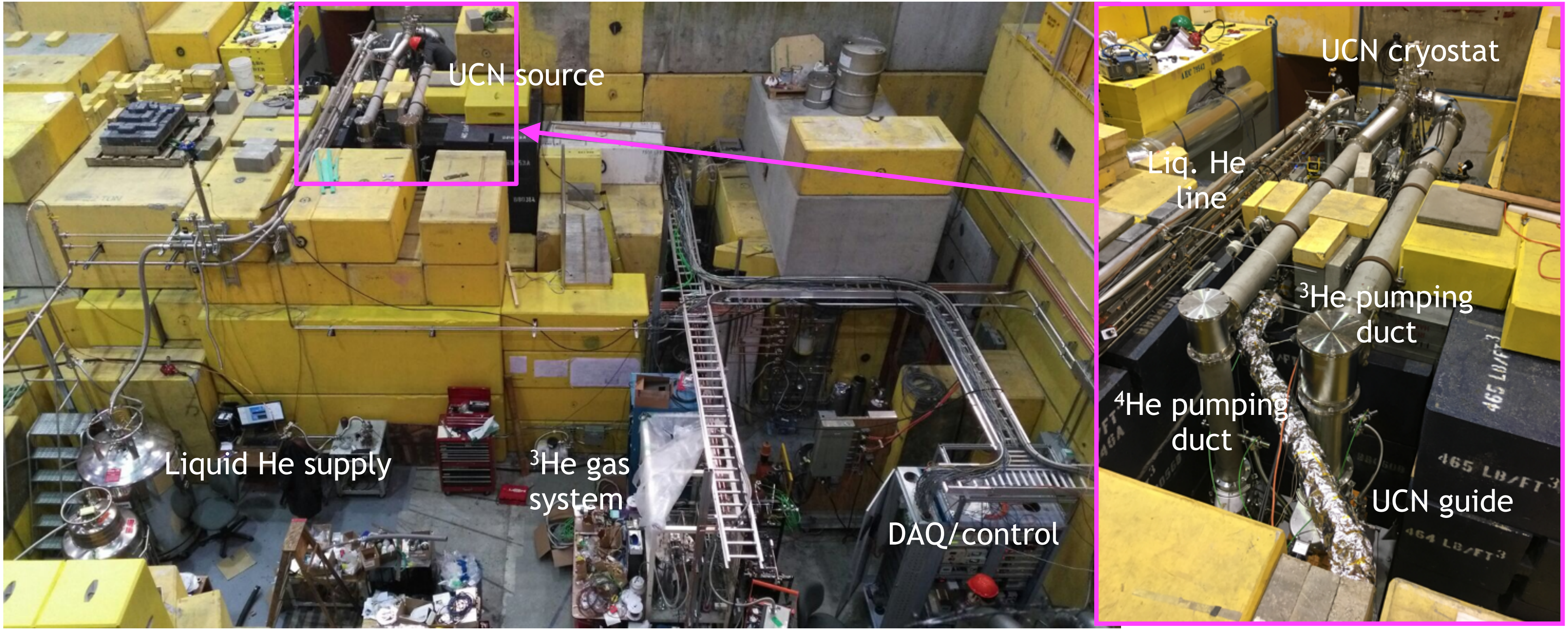


First beam on target on Nov 22, 2016

Major milestones

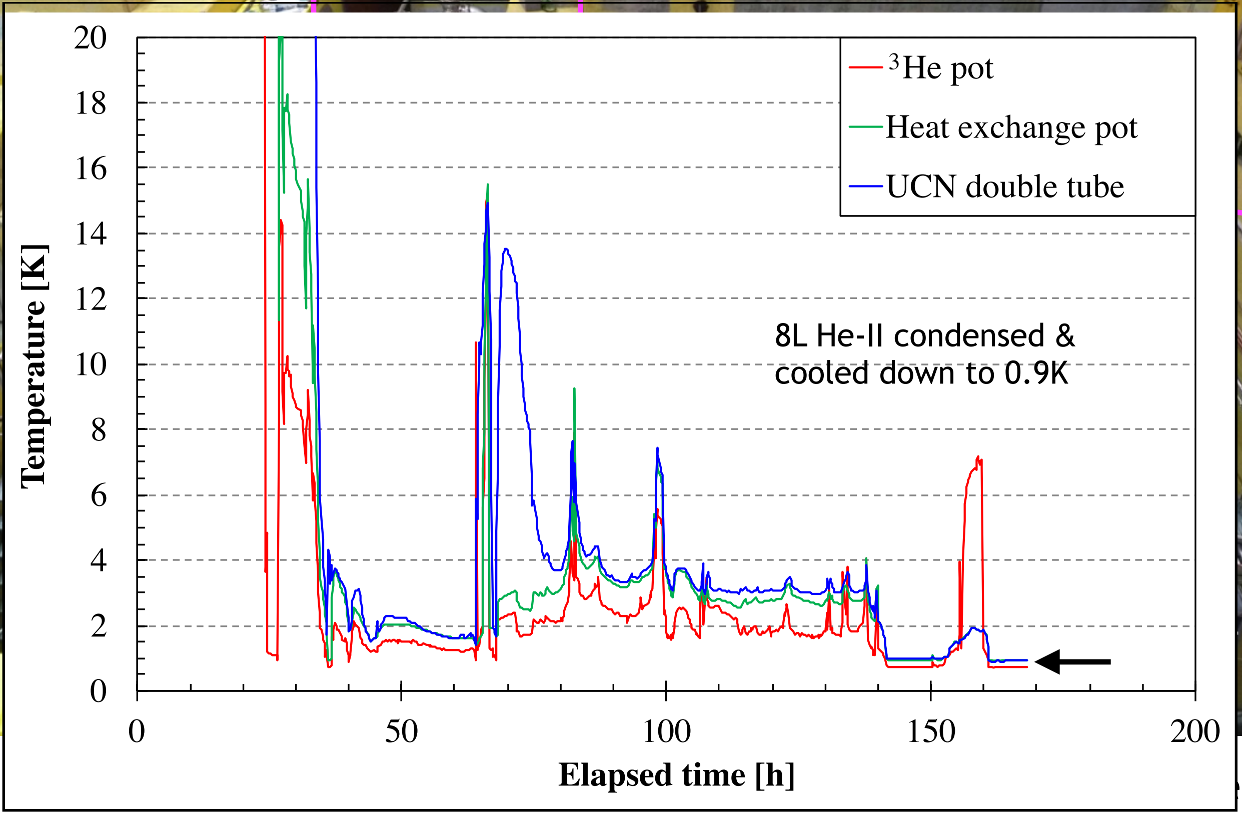
☆ 2014~2016	Construction of Beam line 1U
☆ 2016 Fall	Commissioning of the proton beam and CN production
☆ 2017 Spring	Prototype UCN Source Installation & Cooling test
☆ 2017 Nov.	UCN Production with the Prototype UCN Source
2021-	Next Generation UCN Source

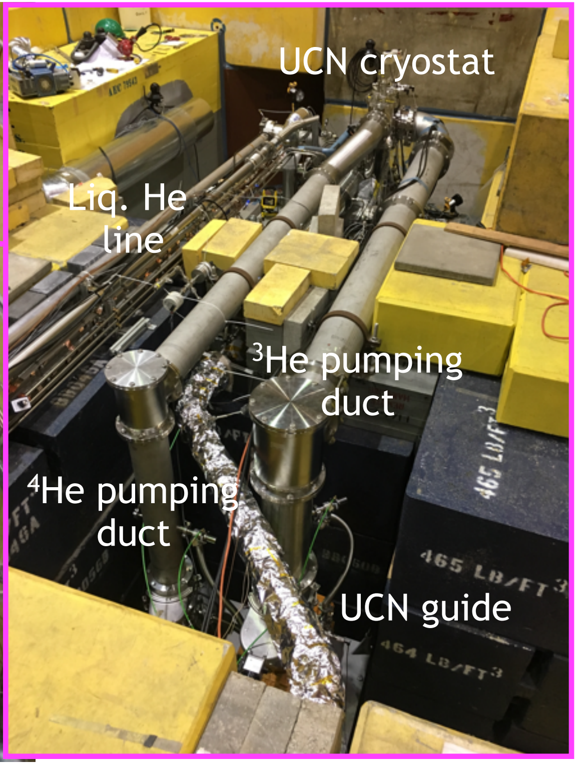
Installation at TRIUMF



- The prototype UCN source and equipments were installed on the beam line in 2017.
- He-II cooling test was performed in April, 2017. He-II temperature 0.9K was achieved.

Installation at TRIUMF



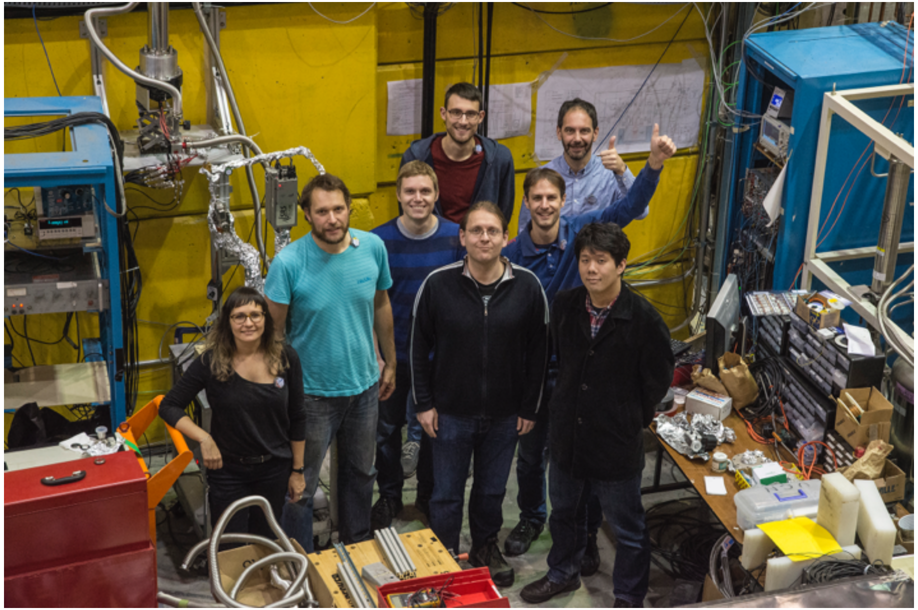


beam line in 2017.

- He-II cooling test was performed in April, 2017. He-II temperature 0.9K was achieved.

First UCN Production at TRIUMF

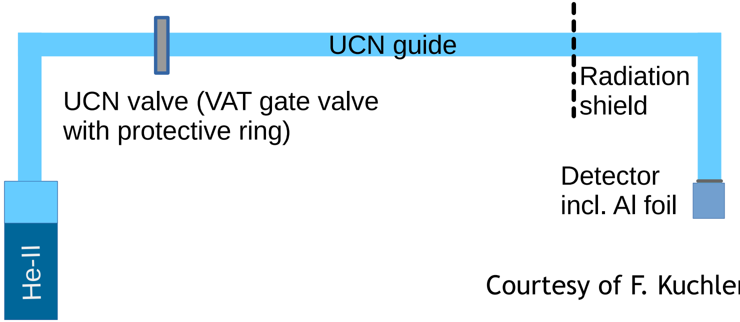
- TUCAN collaboration achieved First UCN production on November 13, 2017



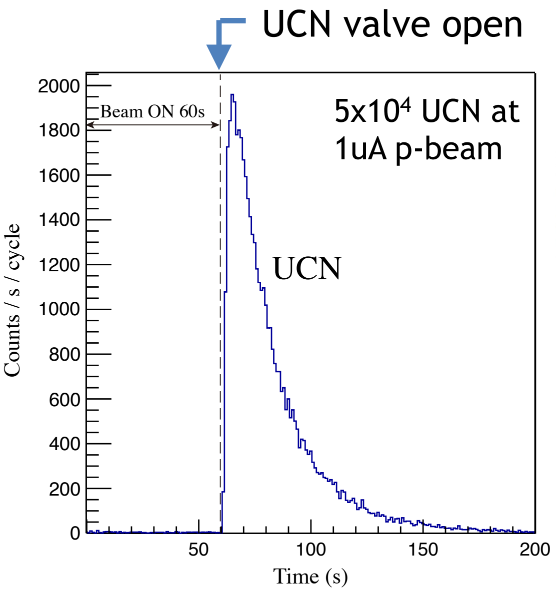
(Part of) TUCAN comrades

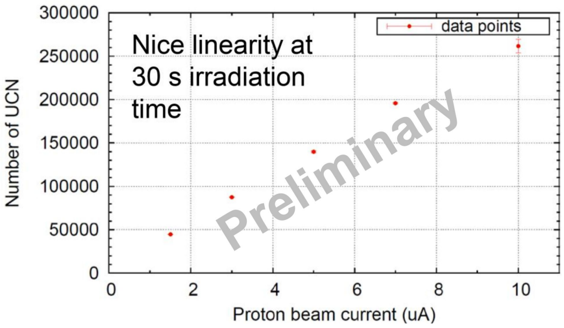
First UCN Production at TRIUMF

- November 13, 2017 - First UCN production
  - 5×10^{4} UCN at 500MeV & 1uA p-beam, 60sec
  - UCN storage time: 38 sec (81sec at RCNP)
  - 3×10^{5} UCN at 10uA p-beam, 60sec irradiation



Courtesy of F. Kuchler

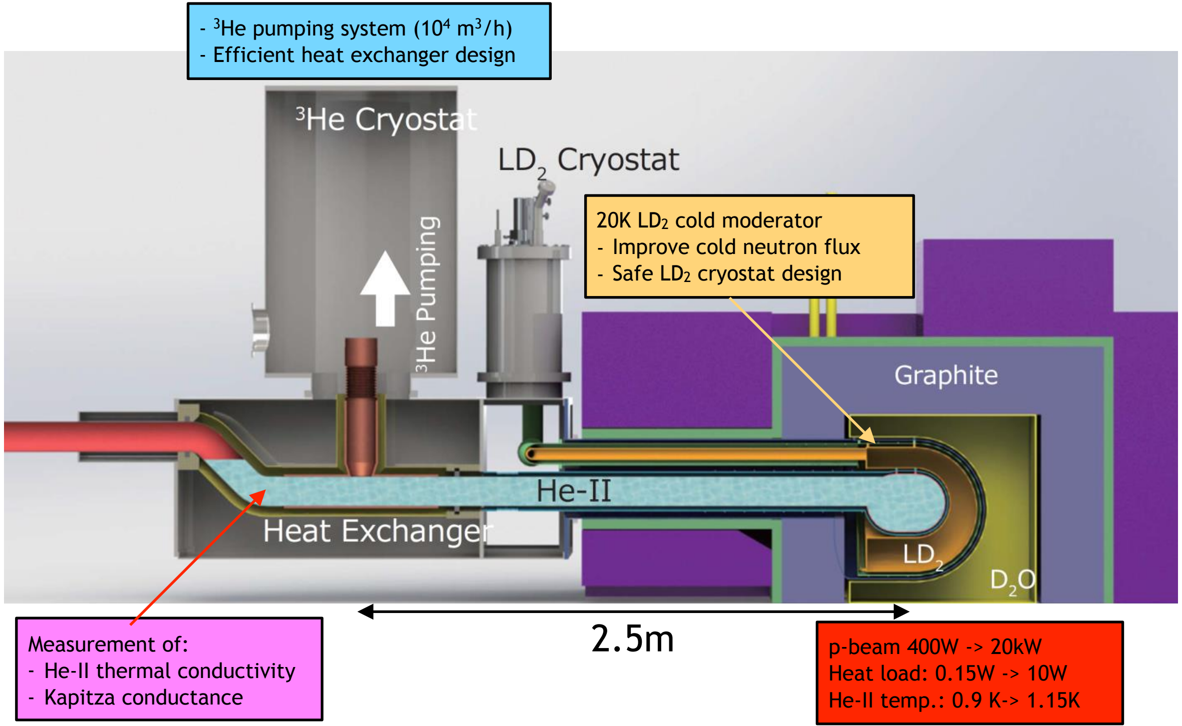




This UCN source is not designed for 40uA p-beam. For nEDM experiment, we need a new source!

New World-leading UCN Source

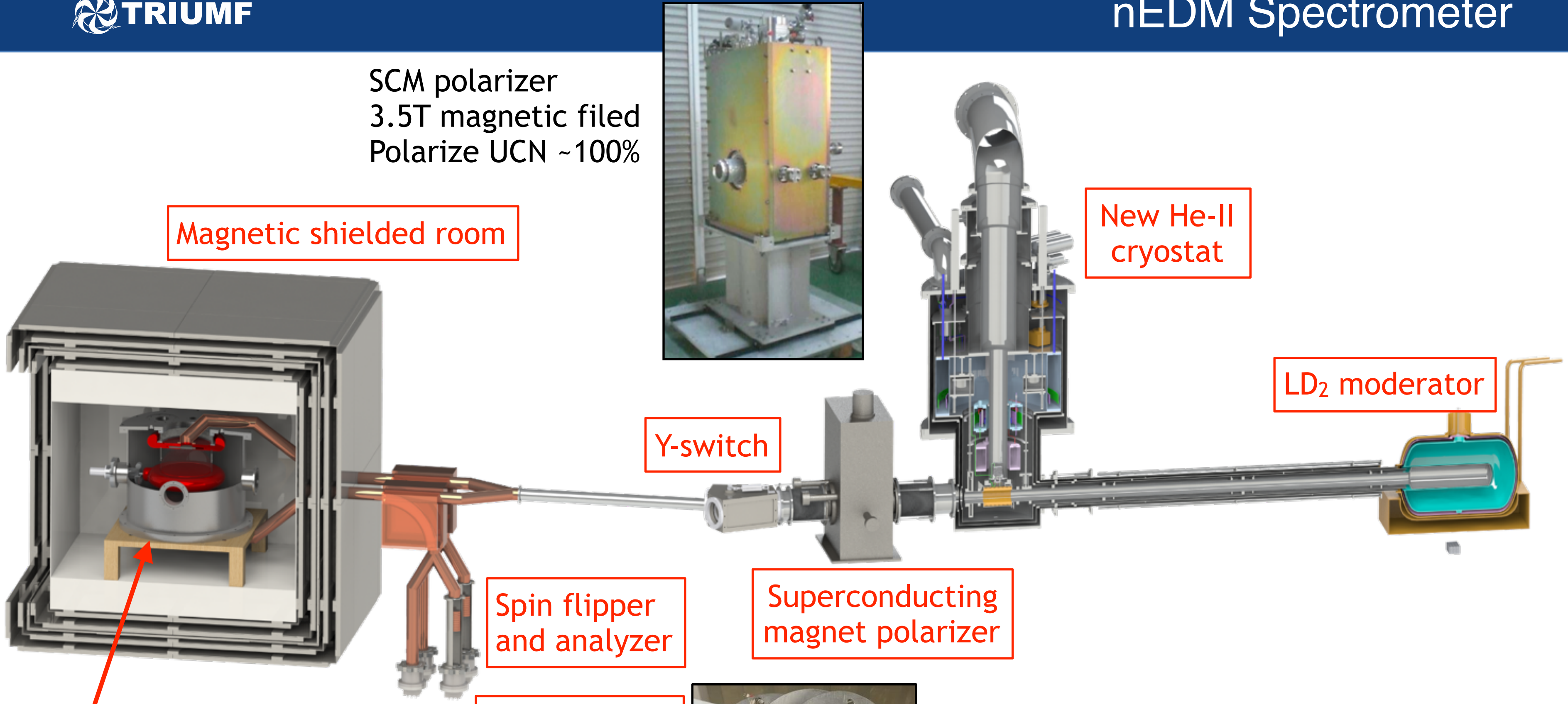
- TUCAN is designing a new world-leading UCN source.
  - CDR was written and reviewed in April 2018.
  - Technical design started.
  - 2020-2021 install and start operation

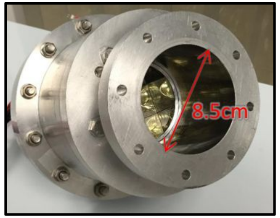


	Prototype UCN source	New UCN source	Factor
Beam power	400W (400MeV×1uA)	20kW (500MeV ×40uA)	×50
Cold moderator	20K Ice D_2O	20K Liquid D_2	×2.5
UCN production volume	8L	34L	×4.3
UCN production rate [UCN/s]	3.2×10^4	2×10^7	×540 (50×2.5×4.3)
UCN density [UCN/cm^3]	9	5.6×10^3	×630

nEDM Spectrometer

SCM polarizer
3.5T magnetic filed
Polarize UCN ~100%





Ban et al., NIM A611, 280 (2009)
Jamieson et al,, EPJ A53,3 (2017)

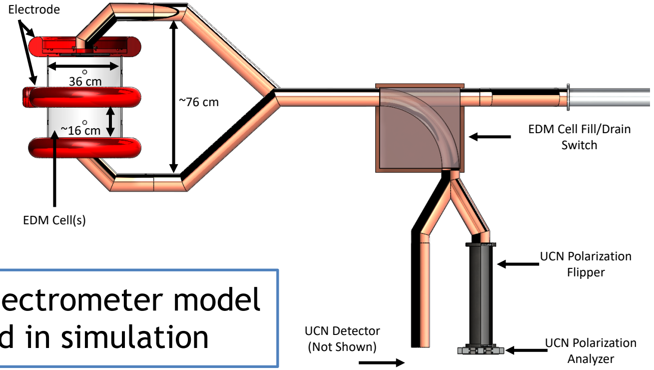
nEDM Spectrometer

Statistical error:

$$\sigma(d_n) = \frac{\hbar}{2\alpha T_c E\sqrt{N}}$$

- $\alpha_0 = 0.95$
- $T_c = 120$ s
- $E = 12$ kV/cm
- $N_0 = (6\sim7)\times10^6$
- UCN density ~ 200 UCN/cm^3
- 10^{-27} $e$cm reached after ~400 beam days

- UCN guides
  - ✓ Low UCN loss and depolarization
  - ✓ Test at available UCN facilities (PSI, Prototype UCN source)
  - ✓ Coating facility at U Winnipeg
- EDM vessel
  - ✓ Low UCN loss and depolarization
  - ✓ Applying high voltage (~200kV), good insulation wall
- Magnetic field
  - ✓ High homogeneity and stability / active field control
  - ✓ Field monitoring with magnetometers & co-magnetometer
- Systematic effects
  - ✓ Simulation studies



EDM spectrometer model used in simulation

Summary & Future Outlook

- The prototype UCN source developed at RCNP was transported to TRIUMF, then installed on the dedicated proton beam line.
- First UCN production at TRIUMF was achieved in Nov, 2017.
- Designing a new world-leading UCN source.
  - Aiming at 10^{-27} *e*cm sensitivity nEDM measurement
  - Will be operational in 2021
- nEDM spectrometer
  - Being developed in parallel with the new UCN source
- UCN from the prototype source is available until 2020.

TRIUMF

Canada’s national laboratory
for particle and nuclear physics
and accelerator-based science

Thank you!
Merci!
谢谢！

TRIUMF: Alberta | British Columbia | Calgary | Carleton | Guelph | Manitoba | McGill | McMaster | Montréal | Northern British Columbia | Queen’s | Regina | Saint Mary’s | Simon Fraser | Toronto | Victoria | Western | Winnipeg | York

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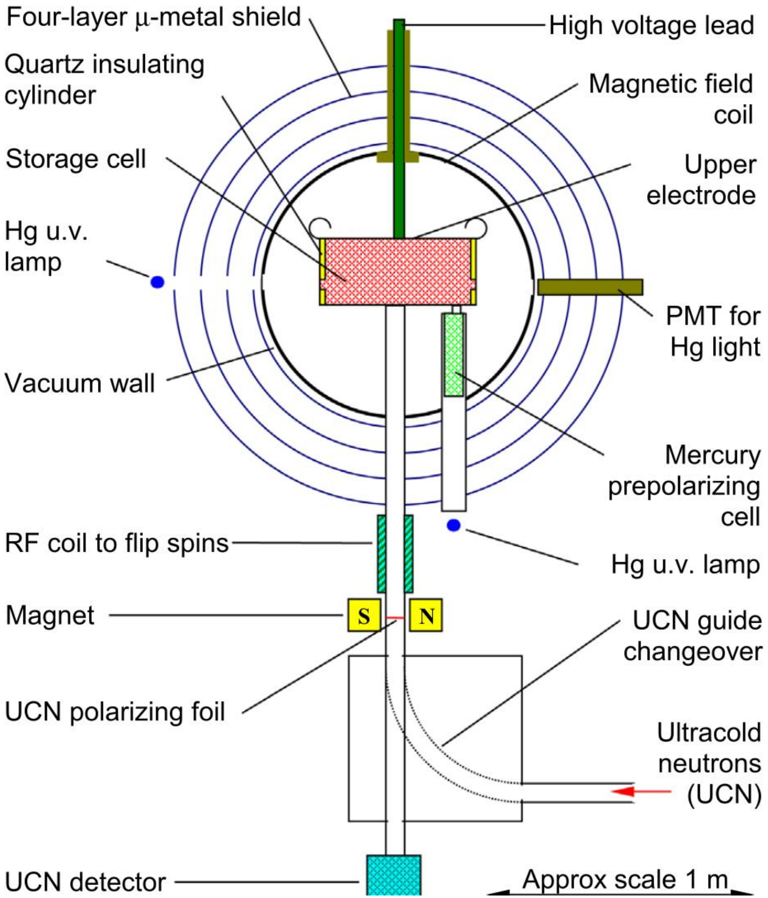
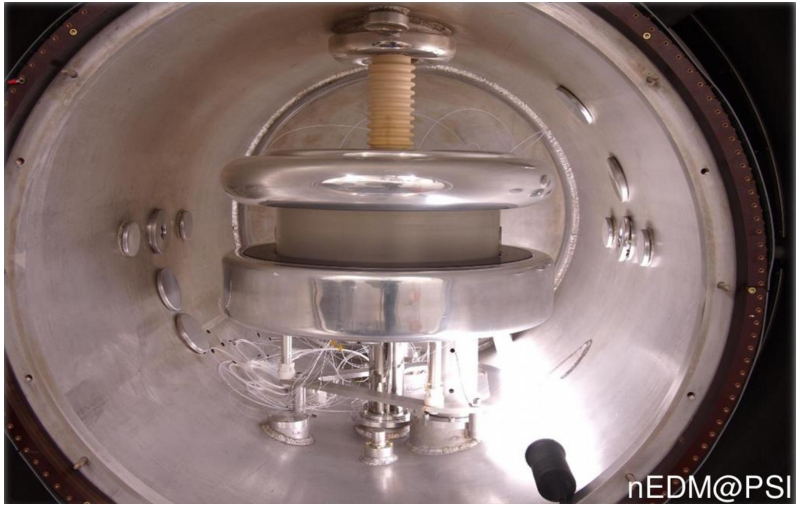
Backup slides

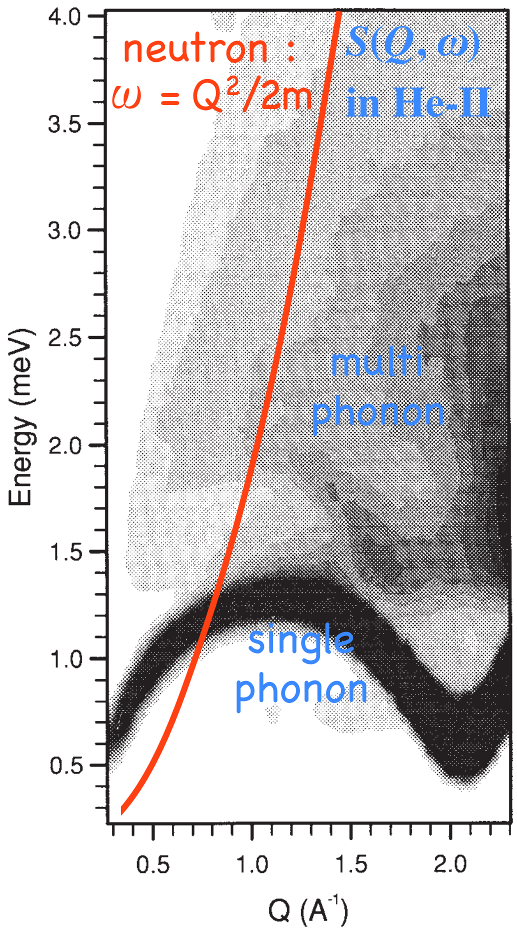
nEDM Spectrometer @ILL/PSI



- ILL/RAL/Sussex setup
- nEDM uper limit: 3×10^{-26} $e$cm (90%C.L)
- Moved to PSI



Neutron-phonon scattering in He-II



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

UCN Production rate in He-II

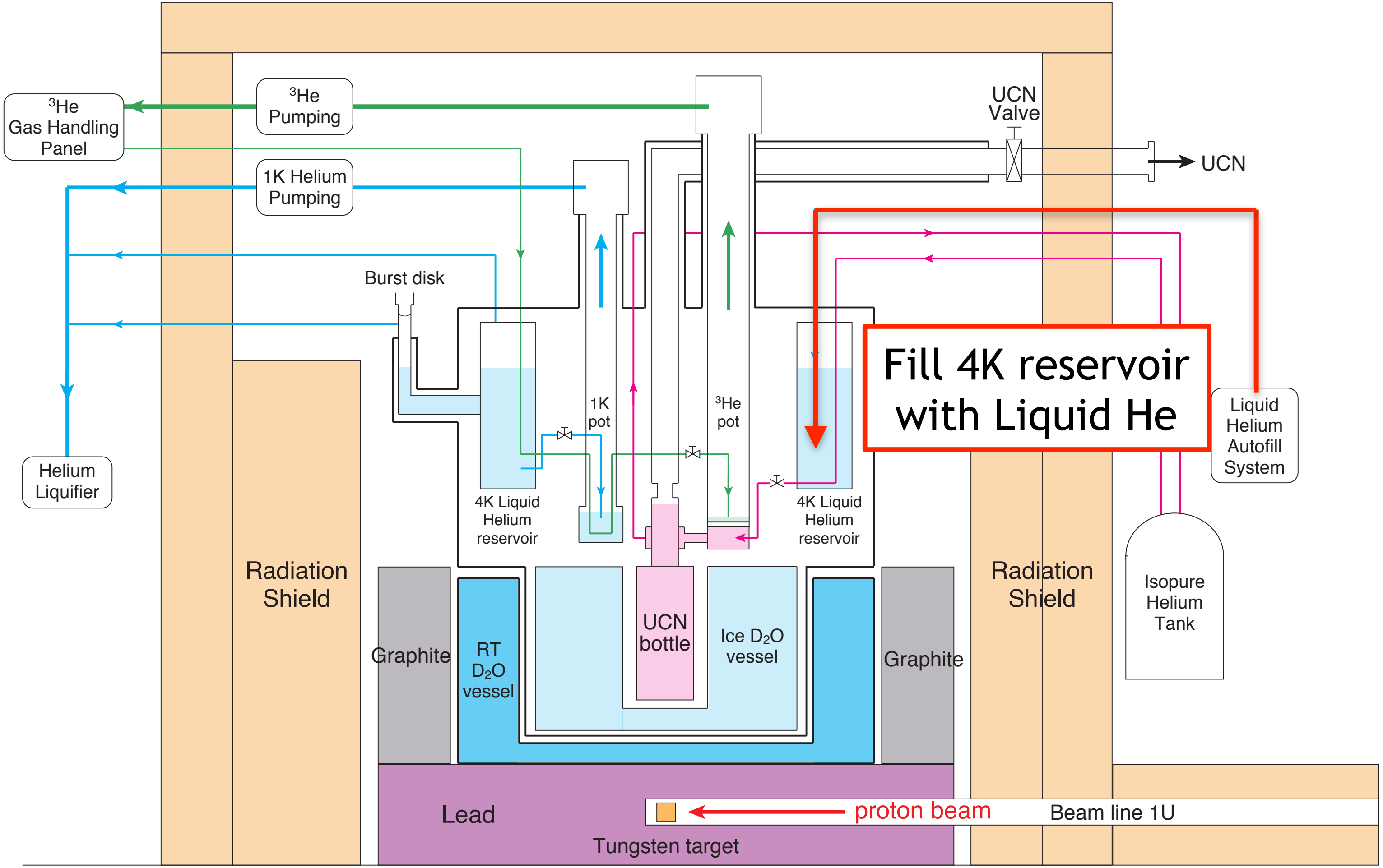
$$P = \int dE_{ucn} \int dE_{in} \; N_{4He} \; d\sigma(E_{in} \rightarrow E_{ucn})/d\omega \; d\Phi_n(E_i)/dE$$

N_{4He}: He-II density; $d\sigma(E_{in} \rightarrow E_{ucn})/d\omega$: cross section; $d\Phi_n(E_i)/dE$: cold n flux

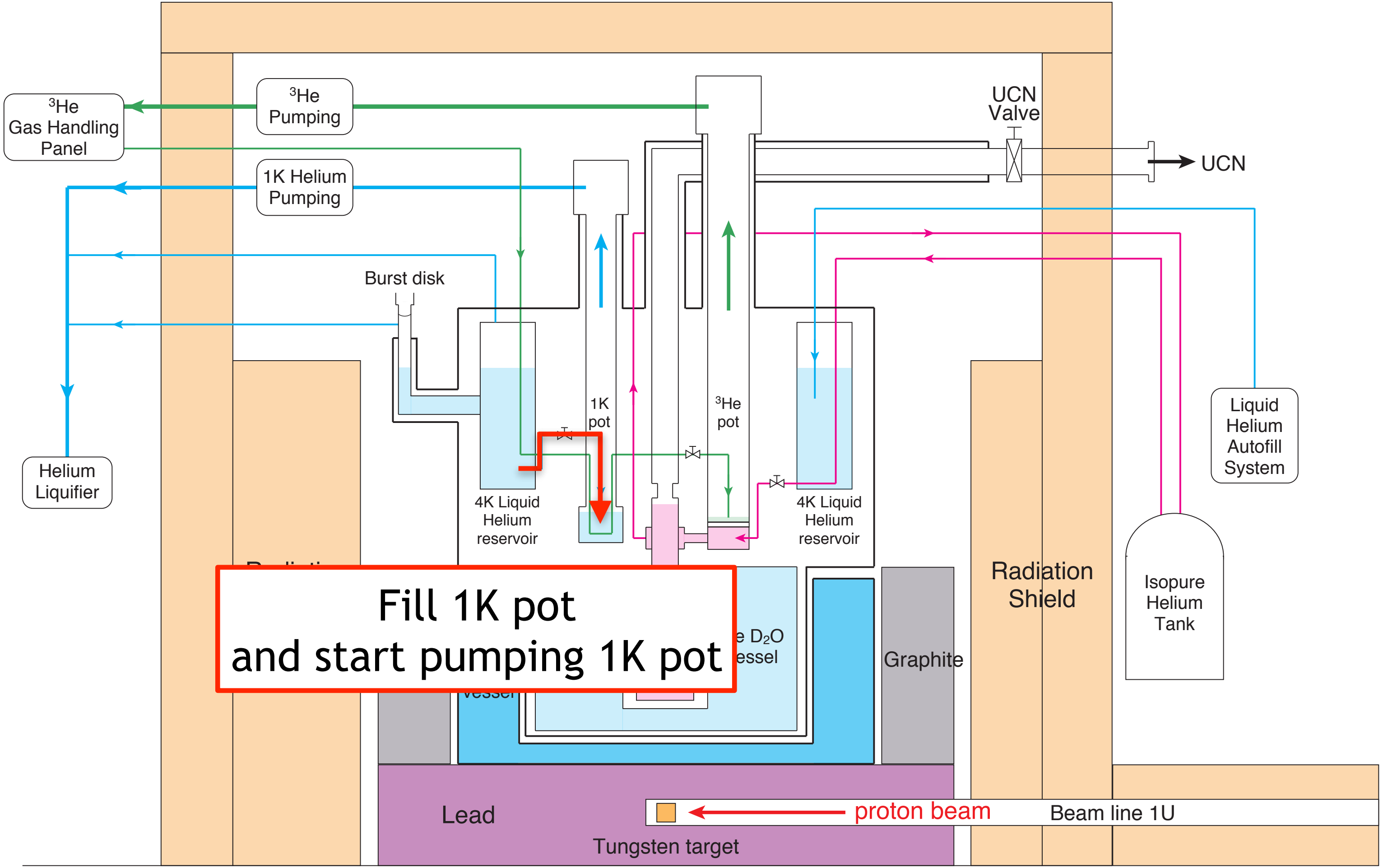
$$\frac{d\sigma}{d\omega} = 4\pi \, b_{coh}^2 \, \frac{k_f}{k_i} \, S(Q, \omega)$$

- b_{coh}: scattering length
- k_f: wave number of scattered n
- k_i: wave number of incident n
- $S(Q, \omega)$: Scattering function

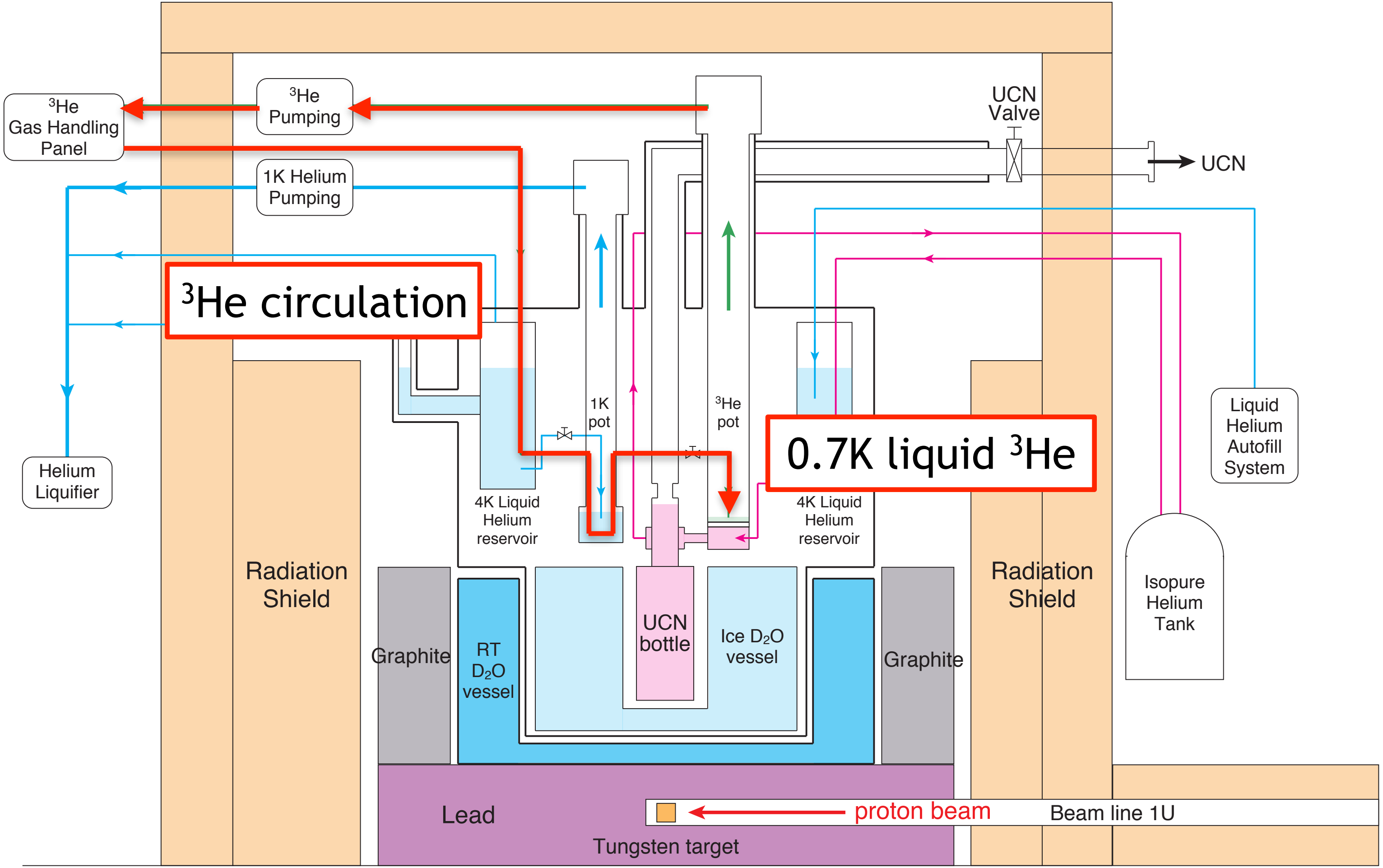
Cooling UCN Cryostat



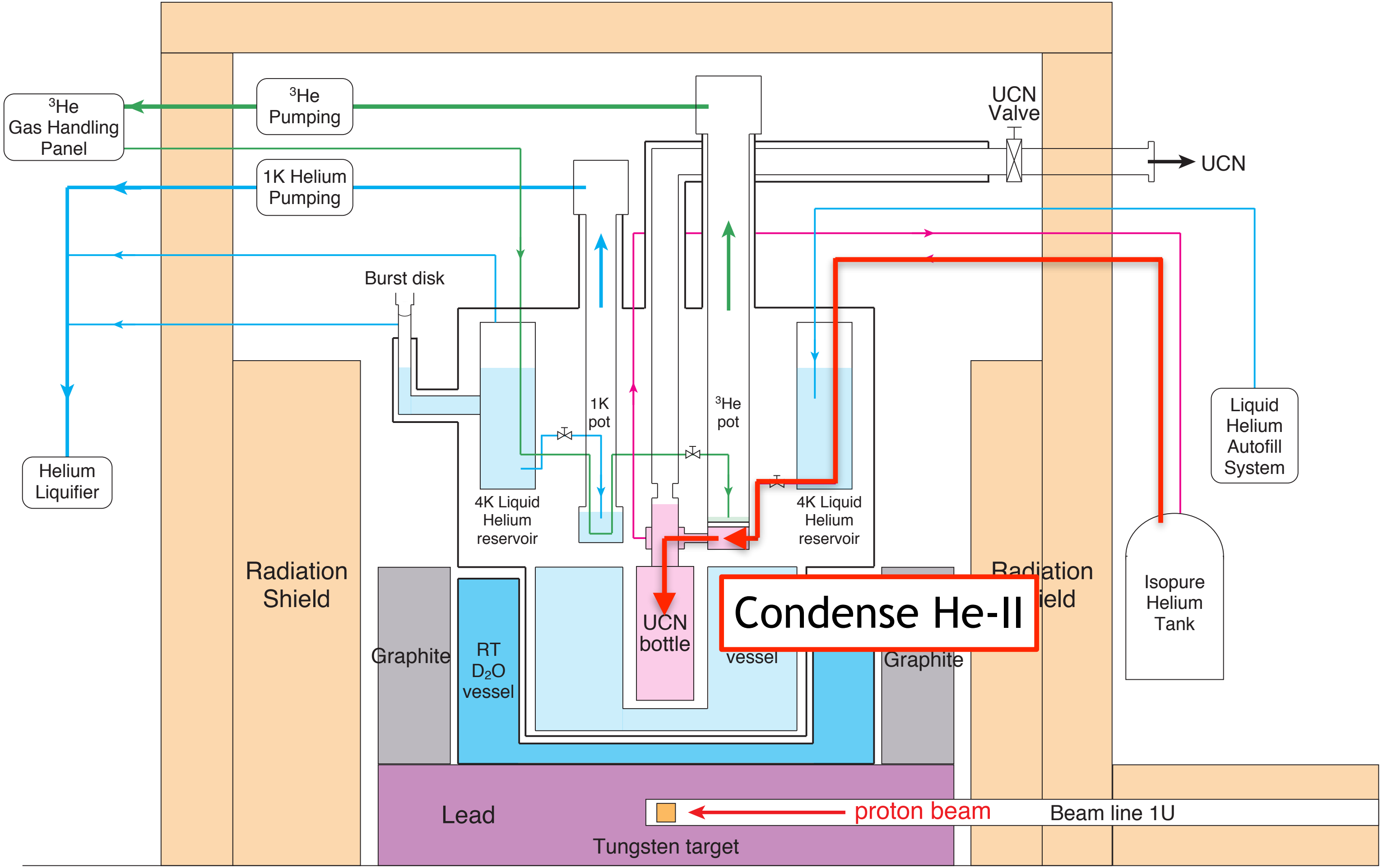
Cooling UCN Cryostat



Cooling UCN Cryostat



He-II condensation



World Status

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

Courtesy of J.W. Martin

Spin polarization with SCM

Magnetic potential

$V = -\boldsymbol{\mu_n} \cdot \boldsymbol{B}$

Potential is spin dependent.

$B = 3.5\text{T} \rightarrow -\boldsymbol{\mu_n} \cdot \boldsymbol{B} = \pm 210$ neV

$E_C \sim 200$ neV from our UCN source

Only one state can pass.