The ultra-cold neutron facility at TRIUMF

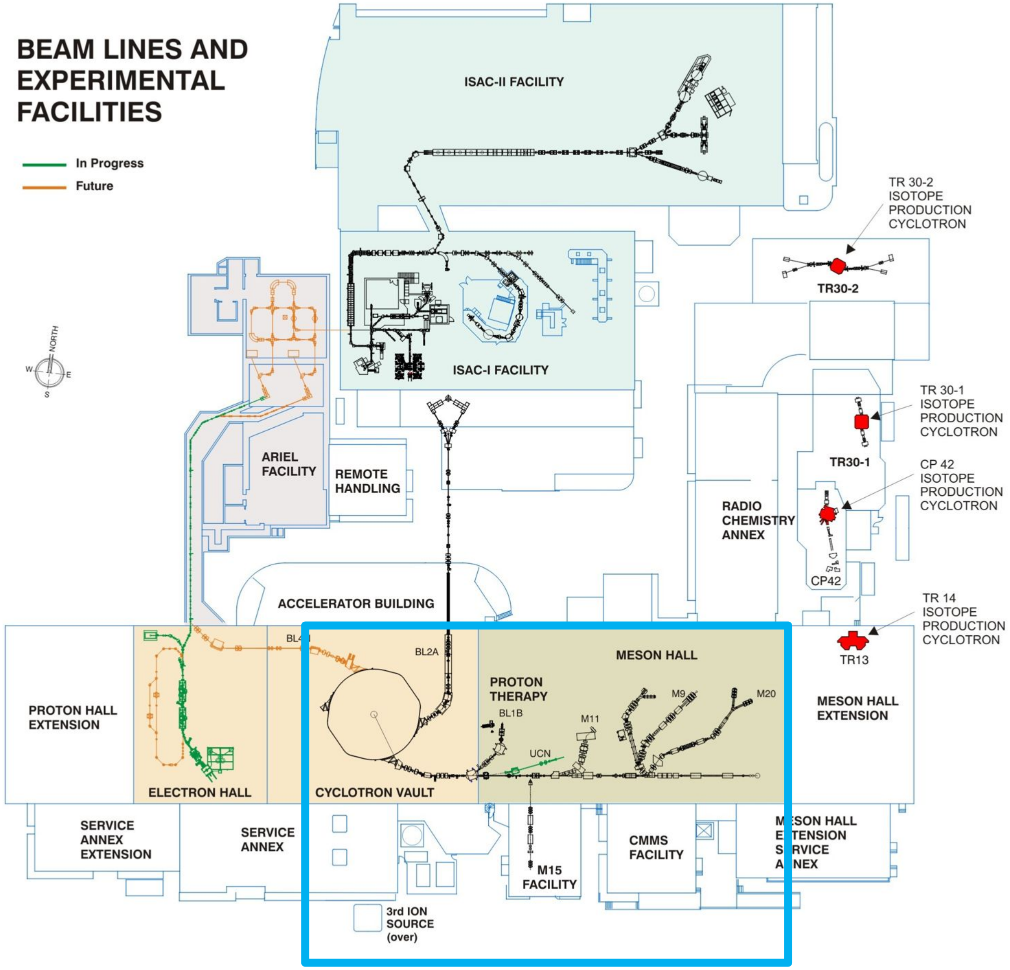
Florian Kuchler for the TUCAN collaboration

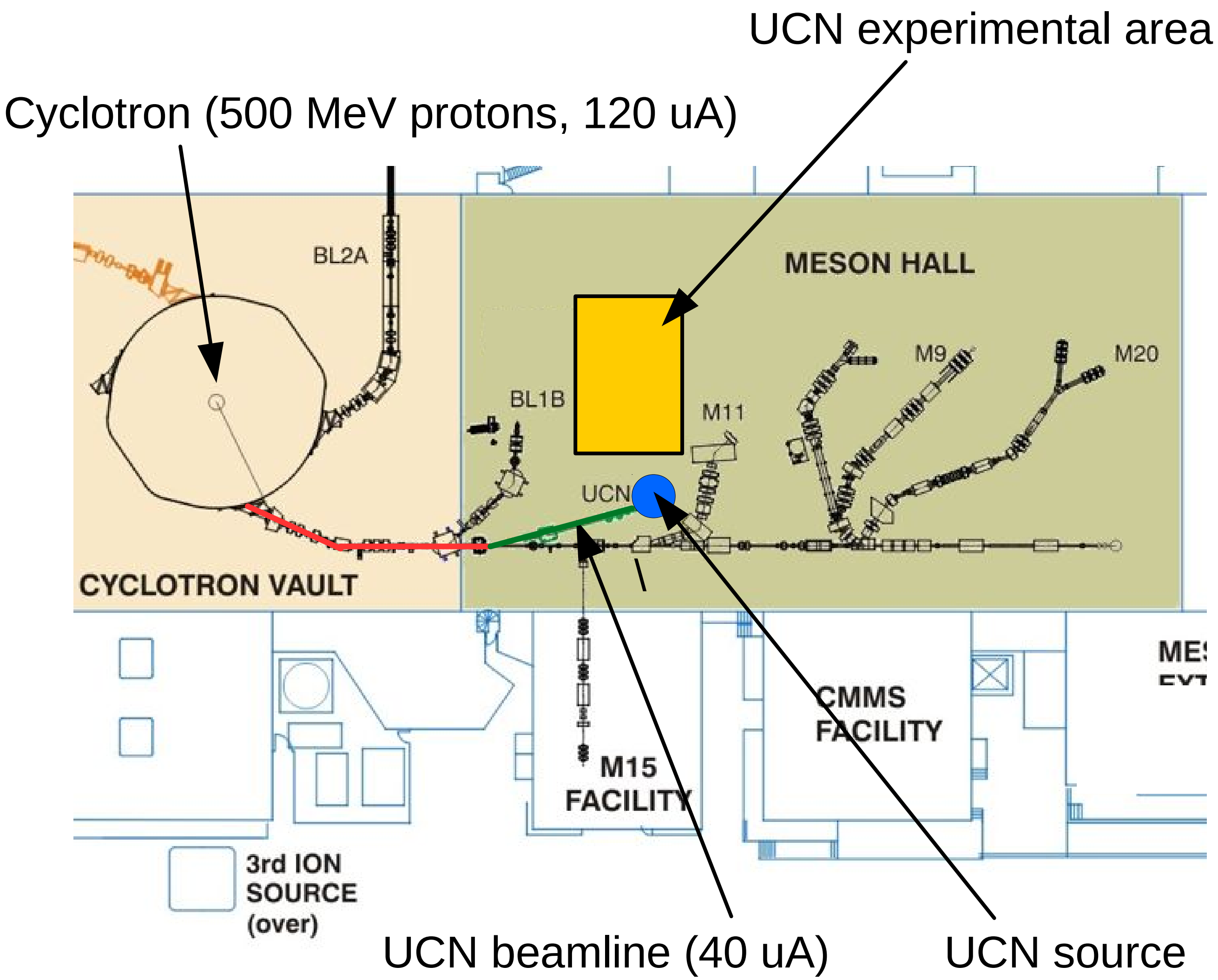
→ **T**RIUMF **U**ltra **C**old **A**dvanced **N**eutron Source

TRIUMF

TRIUMF location

TRIUMF site map

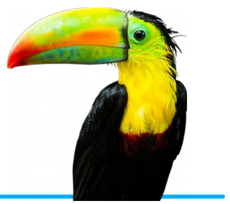




UCN project and TUCAN's goals

Search for an electric dipole moment (EDM) of the neutron with a sensitivity below 10^{-27} ecm

- Build world-leading UCN source
- Establish UCN user facility



Outline

Introduction on Electric Dipole Moments and Ultra Cold Neutrons

Neutron EDM experiment at TRIUMF

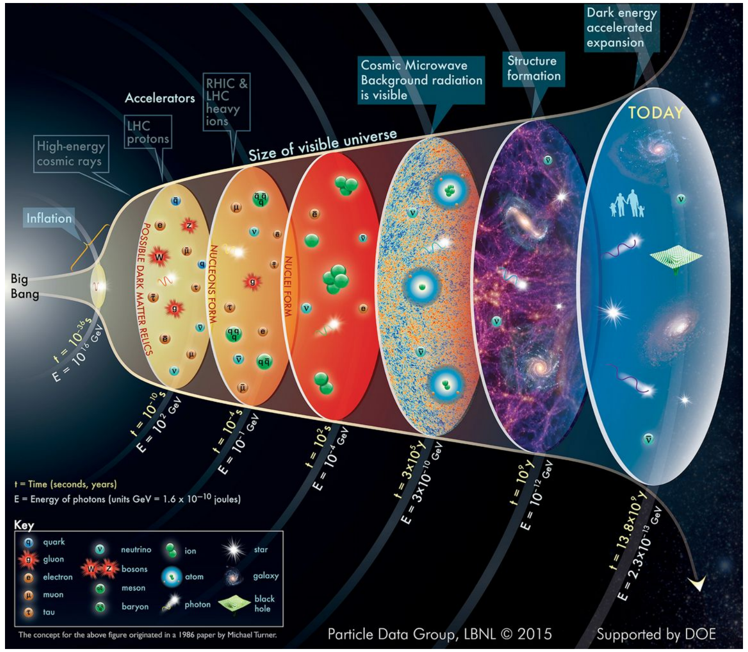
Status of UCN facility at TRIUMF

Preliminary results from first UCN production in Canada

Design of new world leading UCN source at TRIUMF

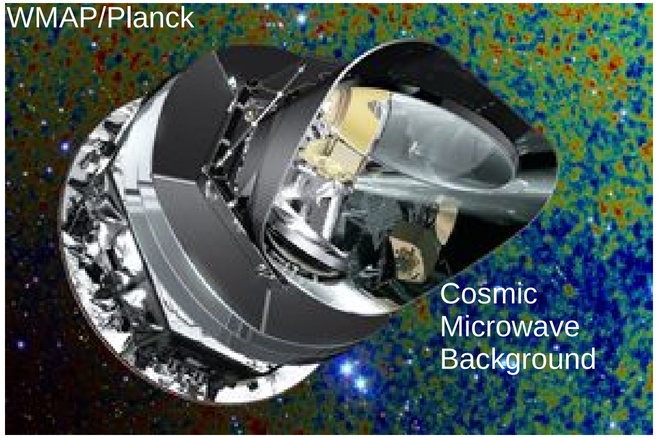
Summary

Why are we looking for **E**lectric **D**ipole **M**oments?



Observation (CMB and BBN) $\frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 10^{-10}$

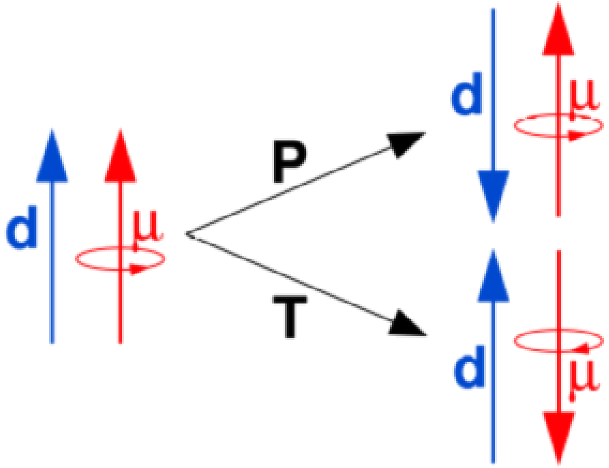
SM expectation $\frac{n_B - n_{\bar{B}}}{n_\gamma} \lesssim 10^{-18}$



Ade et al, Astronomy & Astrophysics 571, A16 (2014)

Iocco et al, Phys. Rep. 472, 1 (2009)

Sakharov's conditions
(i) departure from thermal equilibrium
(ii) Baryon number violation
(iii) $\mathcal{C}$ and $\mathcal{CP}$ violation



- non-zero EDM violates $\mathcal{T}$ and $\mathcal{CP}$ symmetries
- $\mathcal{CP}$ violation in the SM (CKM matrix, θ-term in QCD) not sufficient
- EDMs are a sensitive direct probe of new physics!

  (and constrain parameter space for new physics models)

EDMs of fundamental particles, atoms and molecules

- Typical approach is a sole-source analysis
- Additional limits on EDMs of various systems improve constraints in global analysis
- Neutron EDM limit from ^{199}Hg results: **d_n < 1.6e-26 ecm!**

	upper limit (95% CL) [10^{-28} ecm]	**SM pred.** [10^{-28} ecm]
neutron	360	~ 10^{-3} - 10^{-4}
^{199}Hg	0.074	~ 10^{-6}
^{129}Xe	6.6	~ 10^{-6}

Baker, PRL **97**, 131801 (2006)
[Pendlebury, Phys. Rev. D **92**, 092003 (2015)]
Graner, PRL **116**, 161601 (2017)
Rosenberry, PRL **86**, 22 (2001)

McKellar, Phys. Lett. B **197**, 556 (1987)
Donoghue, Phys. Lett. B **196**, 196 (1987)
Shushkov, Sov. Phys. JETP **60**, 873 (1984)

Example:

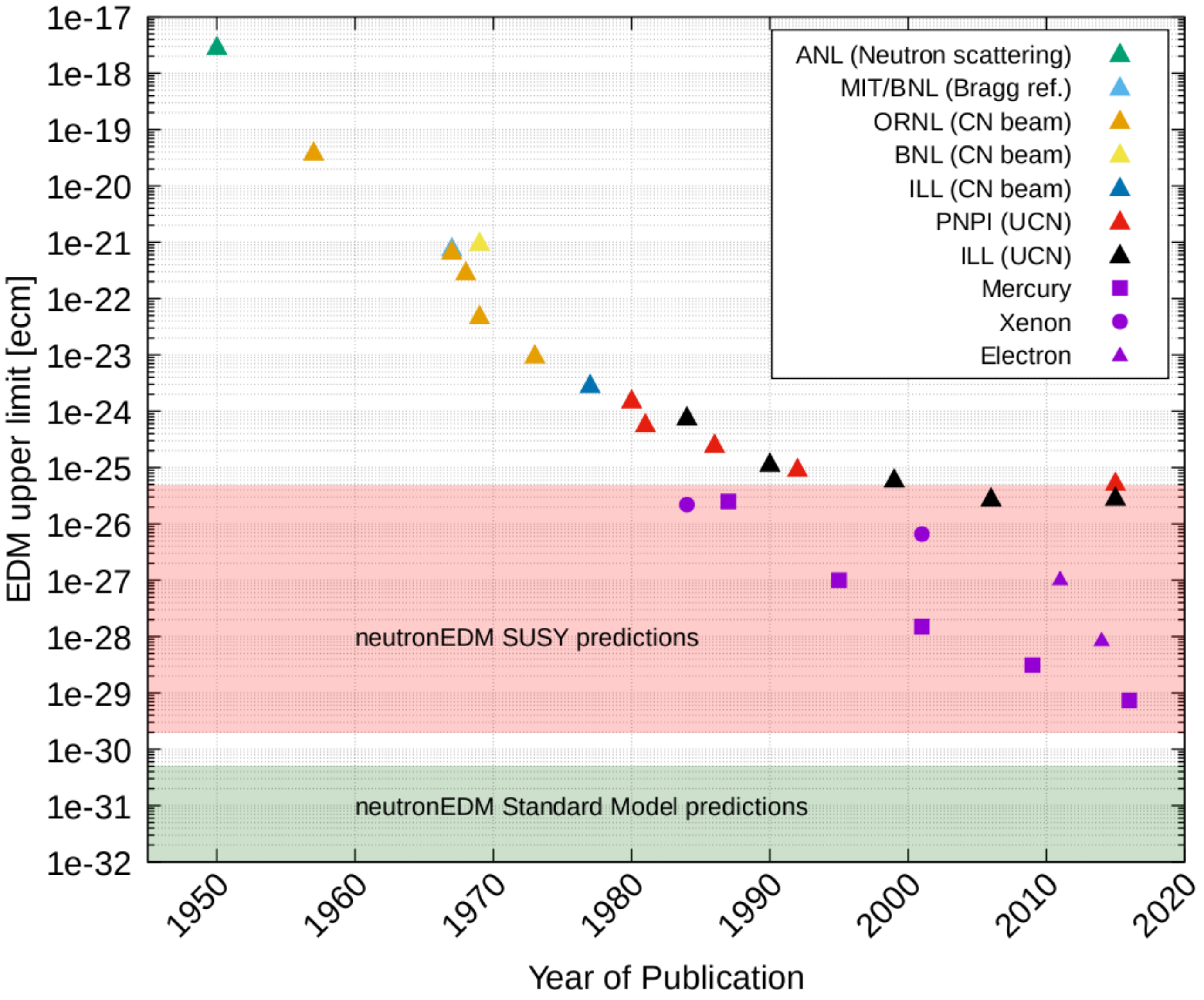
$$d_{\text{atom}} = \underline{\kappa_S} S + \underline{k_T} C_T + k_S C_S + \cancel{\eta_e d_e} + \cancel{\rho_p d_p} + \rho_n d_n + \text{h.o.}$$

$$S \approx a_0 \bar{g}_\pi^{(0)} + a_1 \bar{g}_\pi^{(1)}$$

	Current limits (95%)		d_e (e cm) 5.4×10^{-27}	C_S 4.5×10^{-7}	C_T 2×10^{-6}	$\bar{g}_\pi^{(0)}$ 8×10^{-9}	$\bar{g}_\pi^{(1)}$ 1.2×10^{-9}	$\bar{d}_n^{\text{sr}}$ (e cm) 12×10^{-23}
System	Current (e cm)	Projected	Projected sensitivity					
ThO	5×10^{-29}	5×10^{-30}	4.0×10^{-27}	3.2×10^{-7}				
Fr		$d_e < 10^{-28}$	2.4×10^{-27}	1.8×10^{-7}				
^{129}Xe	3×10^{-27}	3×10^{-29}			3×10^{-7}	3×10^{-9}	1×10^{-9}	5×10^{-23}
Neutron/Xe	2×10^{-26}	$10^{-28}/3 \times 10^{-29}$			1×10^{-7}	1×10^{-9}	4×10^{-10}	2×10^{-23}
Ra		10^{-25}			5×10^{-8}	4×10^{-9}	1×10^{-9}	6×10^{-23}
Ra		10^{-26}			1×10^{-8}	1×10^{-9}	3×10^{-10}	2×10^{-24}
Neutron/Xe/Ra		$10^{-28}/3 \times 10^{-29}/10^{-27}$			6×10^{-9}	9×10^{-10}	3×10^{-10}	1×10^{-24}

Chupp & Ramsey-Musolf, Phys. Rev. C, 91, 035502 (2015)

Neutron electric dipole moment – Experimental history

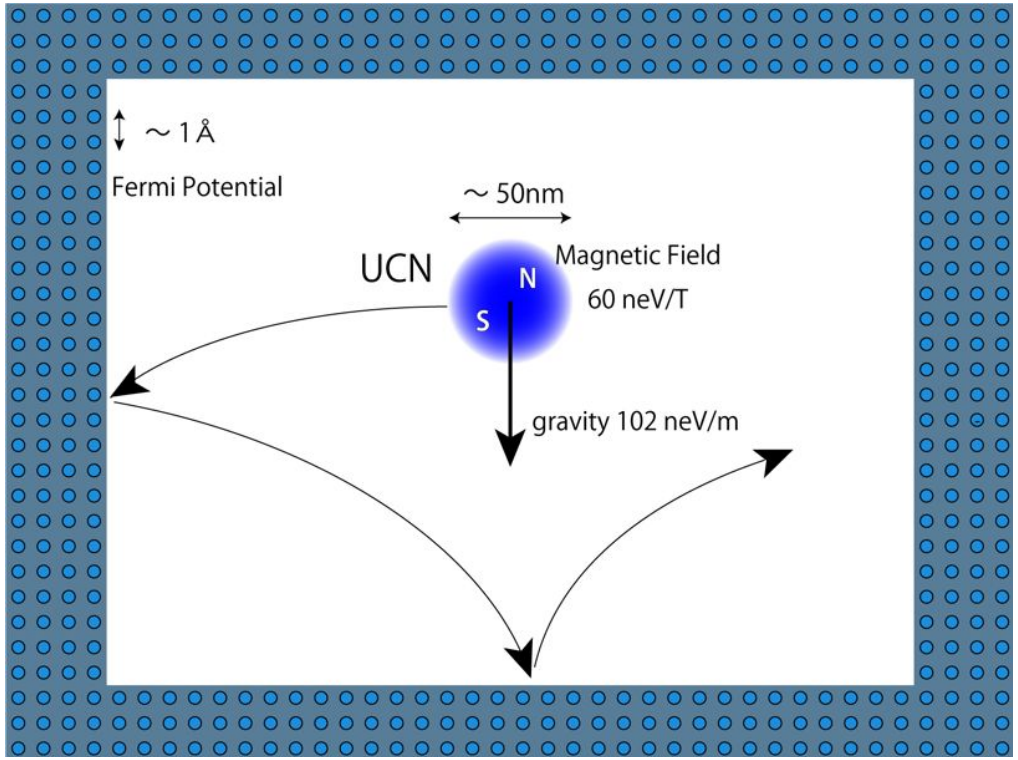


- Early measurements using neutron beams
- Revival of beam experiments?
  - Piegsa, Phys. Rev. C 88, 045502 (2013)
- State-of-the-art based on stored neutrons:
  - Ultra-Cold Neutrons

Ultra Cold Neutrons

Properties

- Kin. Energy < 300 neV
- Wavelength ~ 50 nm
- Velocity ~ 5 m/s



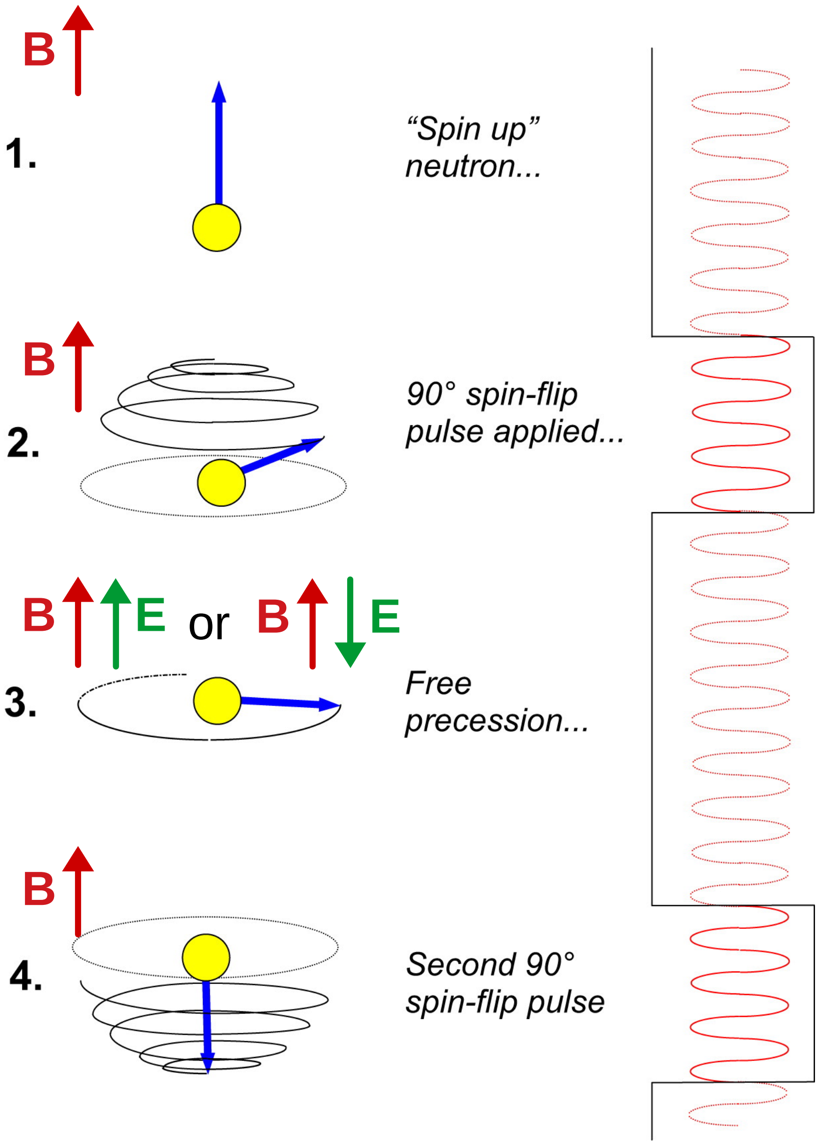
Interactions

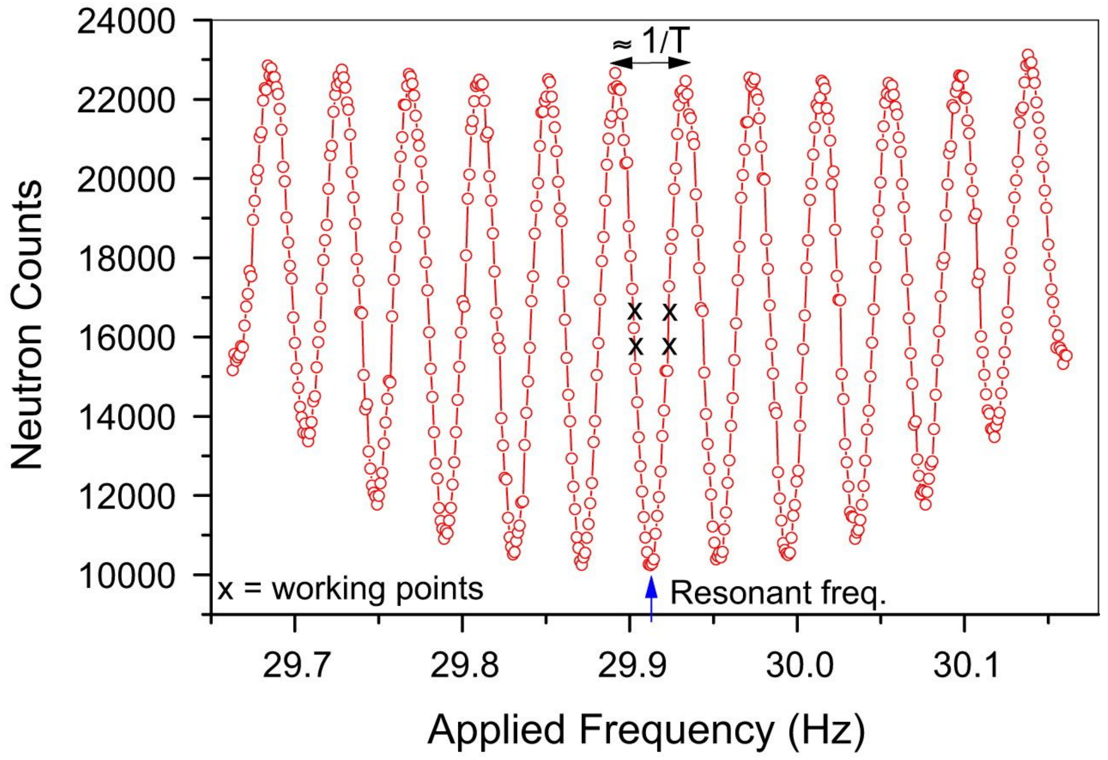
- Gravity 100 neV/m
- (Electro)Magnetic 60 neV/T
- Weak $n \longrightarrow p + e + \overline{\nu}_e$

  ➔ observation times of order τ ~ 880 s
- Strong $$V_F = \frac{2\pi\hbar^2}{m}\sum_i N_i b_i$$

Material	V_F [neV]
Aluminium	54
Copper	168
Stainless steel	188
^{58}Ni	350
SiO_2	90
Al_2O_3	146
Perfluoro Polyether (Fomblin Oil)	106

Measuring a neutron EDM - Ramsey's method of separated oscillating fields





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

α Visibility (spin polarization)
E Electric field
T Spin precession time
N Number of UCN

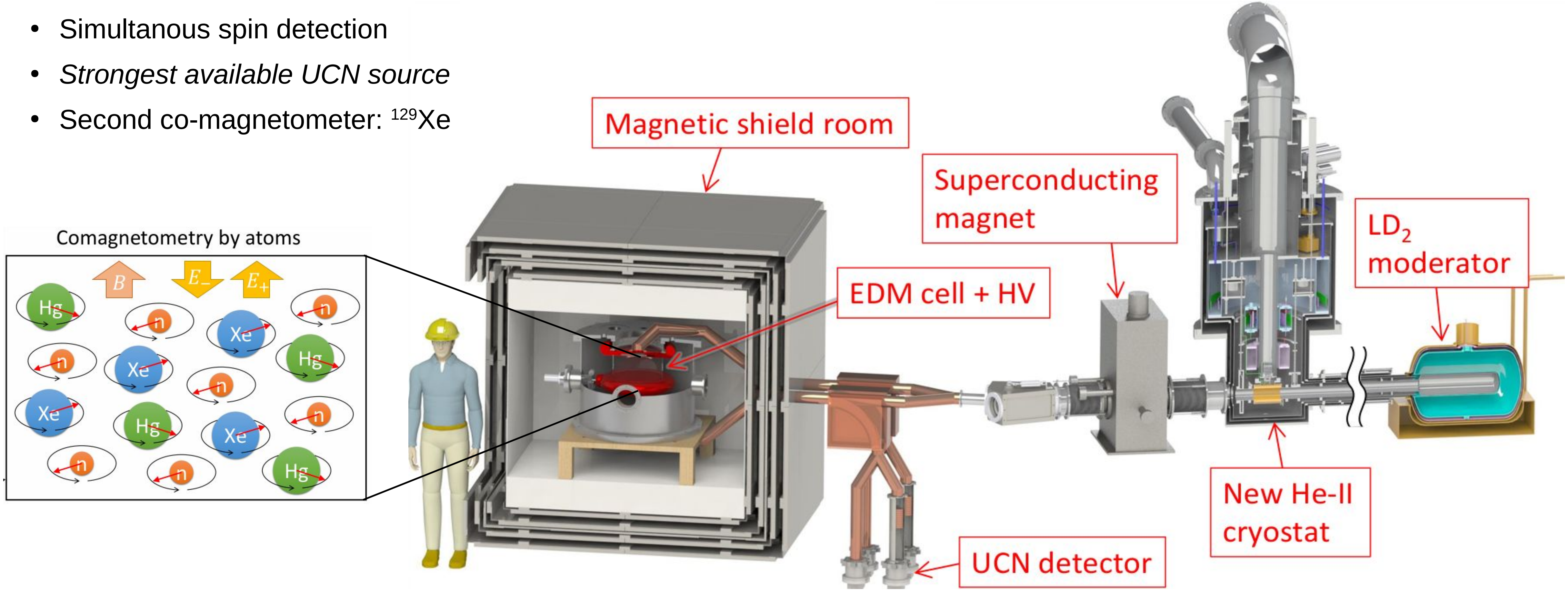
Status:	< 3.6 x 10^{-26} ecm	(4 yr, 95% CL)
TUCAN:	< 10^{-27} ecm	(400 d)

Baker et al, Phys. Rev. Lett. 97, 131801 (2006)
Baker et al, NIMA, 736, 184 (2014)
Pendlebury, Phys. Rev. D, 92, 092003 (2015)

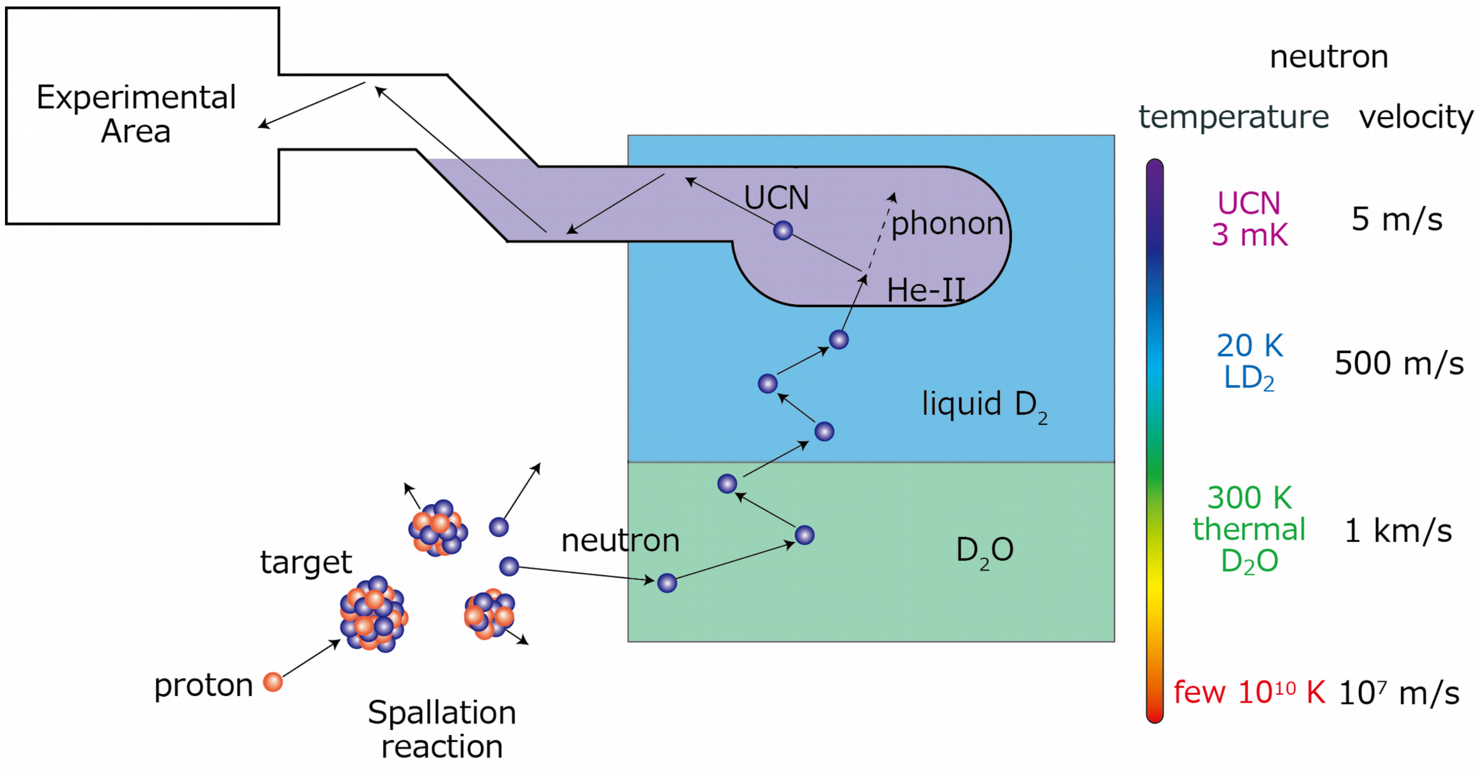
Neutron EDM experiment at TRIUMF

- State-of-the-art magnetic field: MSR and self-shielded coils, B_0 ~ 1 uT
- Double EDM cell
- SERF magnetometers
- Simultanous spin detection
- *Strongest available UCN source*
- Second co-magnetometer: ^{129}Xe

Magnetics and related systematic effects:
B. Franke's talk



UCN production at TRIUMF – Spallation neutrons & superfluid helium



Features

- Combination of spallation neutron source and superfluid helium converter
- Small distance btw target and He-II
- Long UCN storage lifetimes in He-II

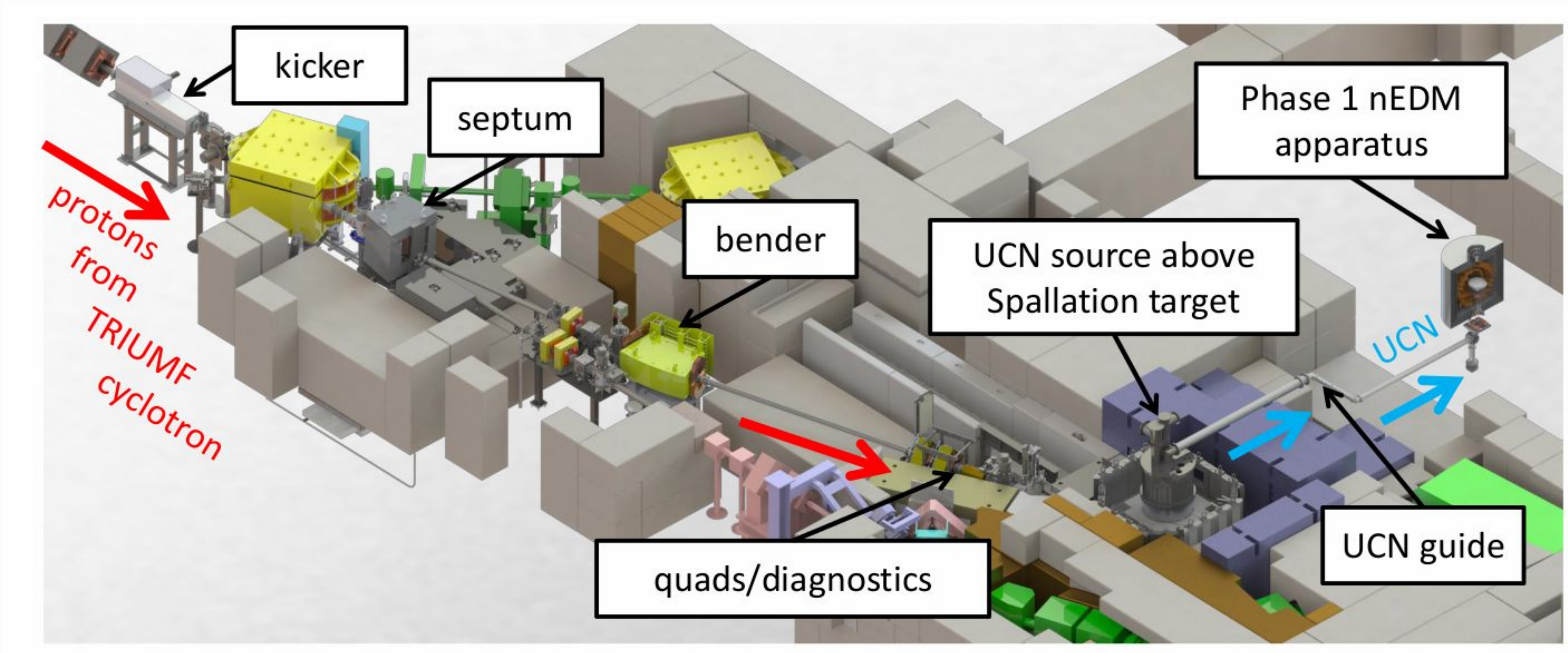
He-II temperature [K]	Storage time [s]
0.8	600
1.2	36

Golub & Pendlebury
Phys. Lett. A **53**, 133 (1975)
Phys. Lett. A **62**, 337 (1977)

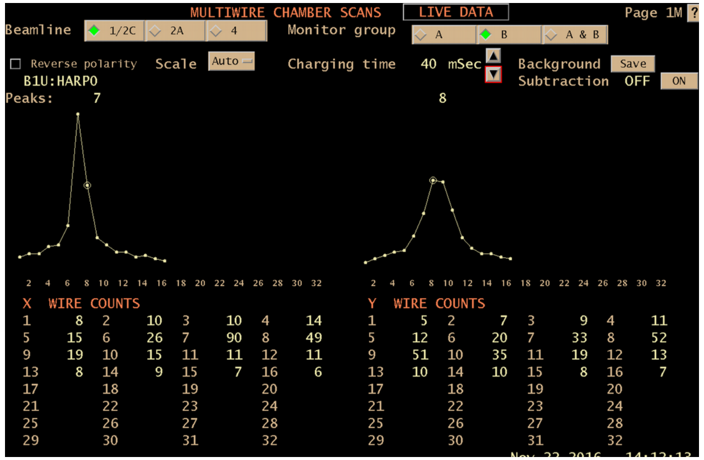
- Warm moderator D_2O 300 K
- Cold moderator ice D_2O, LD_2 20-80 K
- UCN converter superfluid He < 1.6 K

UCN production in superfluid helium and limitations: **J. Martin's talk**

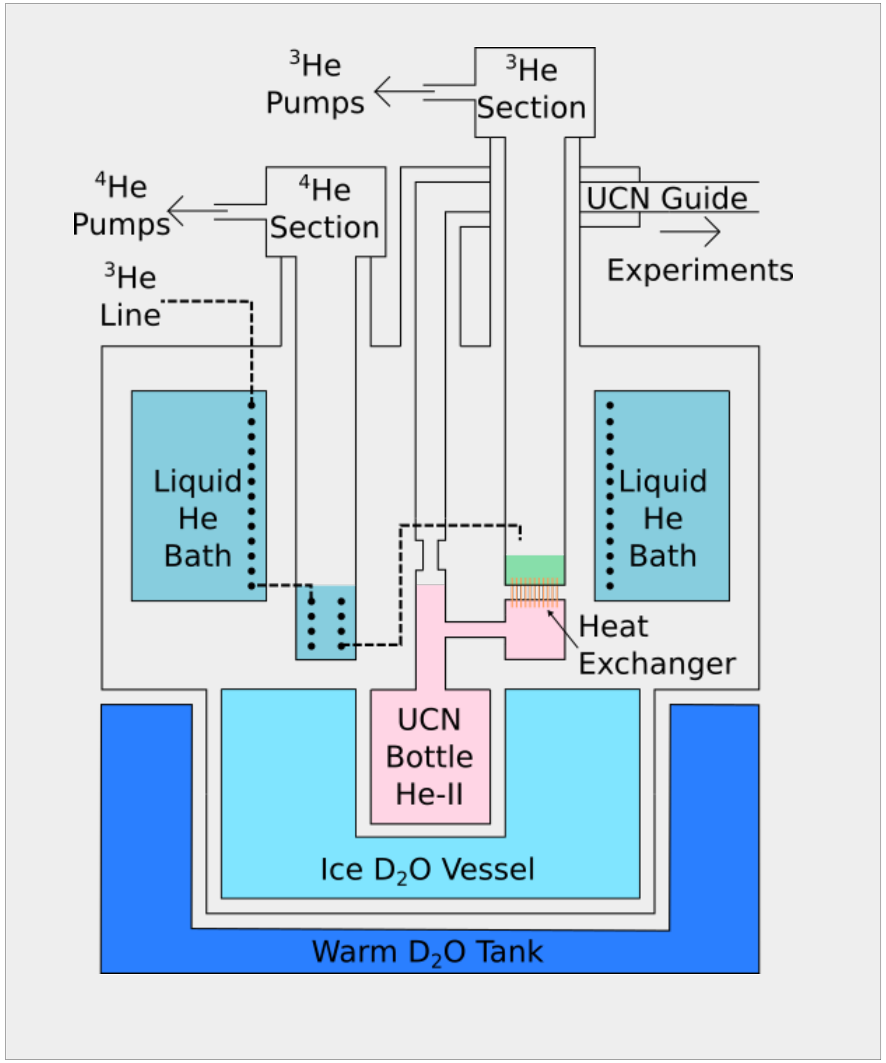
UCN beamline at TRIUMF



First beam on target on November 22nd 2016



Prototype UCN source



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

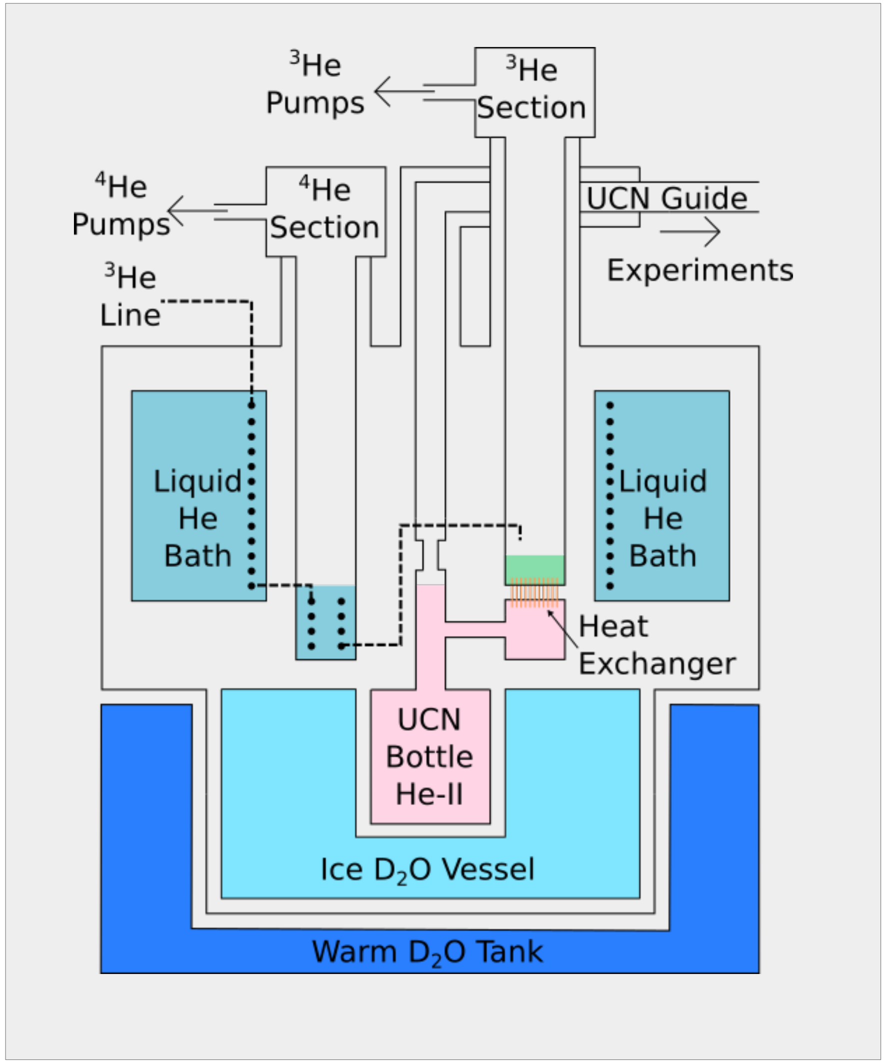
Vertical UCN source developed at RCNP

- 3He fridge with heat-exchanger
- Cooling stages:
  - 4 K 60 L liquid natural helium
  - 1 K ^{4}He pot (pumping natural helium)
  - 0.7 K ^{3}He pot and heat exchanger

- ➔ Superfluid helium temperature ~ 0.8 K
- ➔ UCN lifetime in source ~ 81 sec
- ➔ UCN detected ~ 280000 UCN
  (400 MeV, 1 uA, 8 L He-II, 240s irradiation)

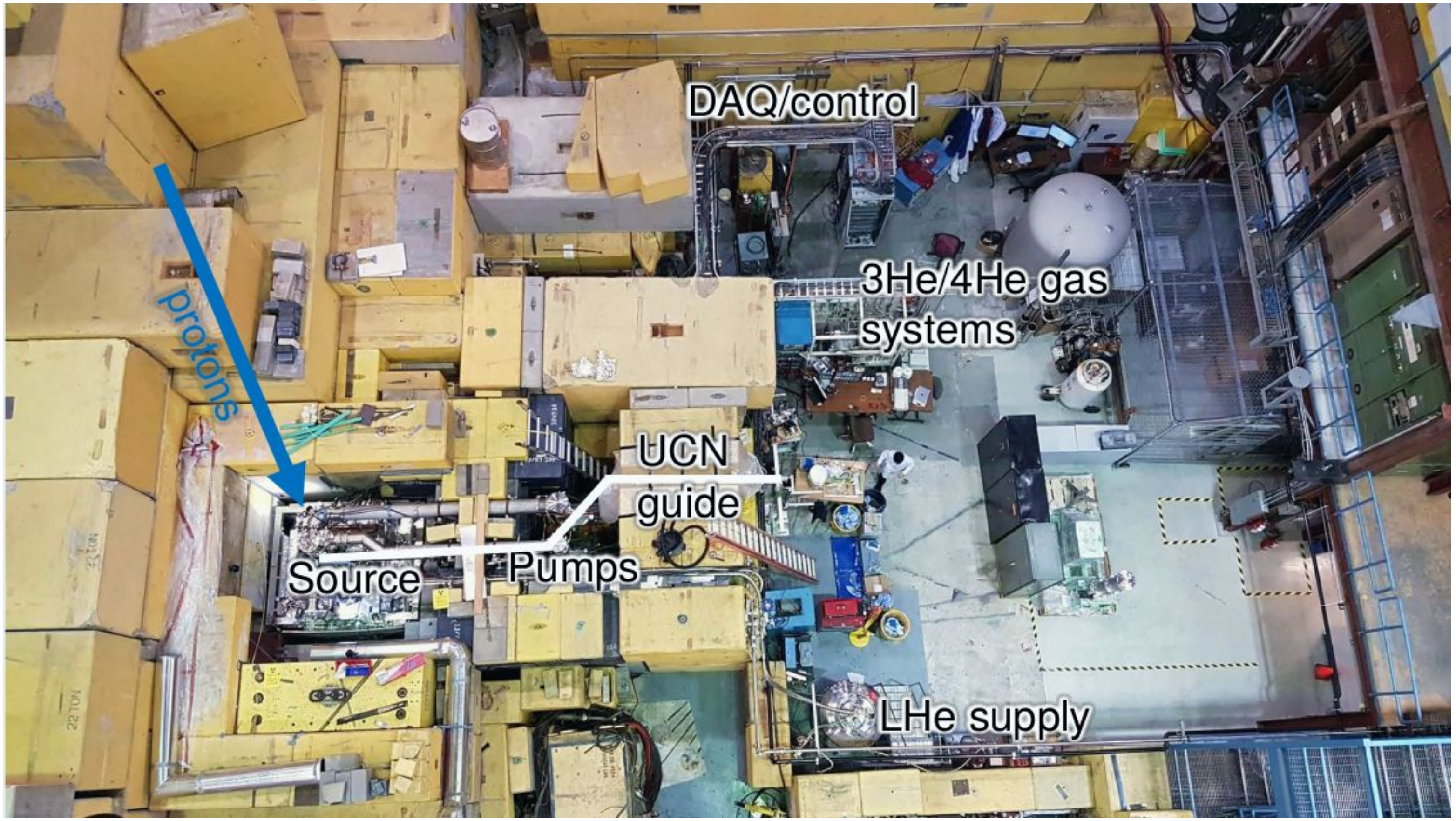
2016 Oct	Move to TRIUMF
2016 Nov-Jan	Safety modifications
2017 Jan–Apr	Installation

Prototype UCN source



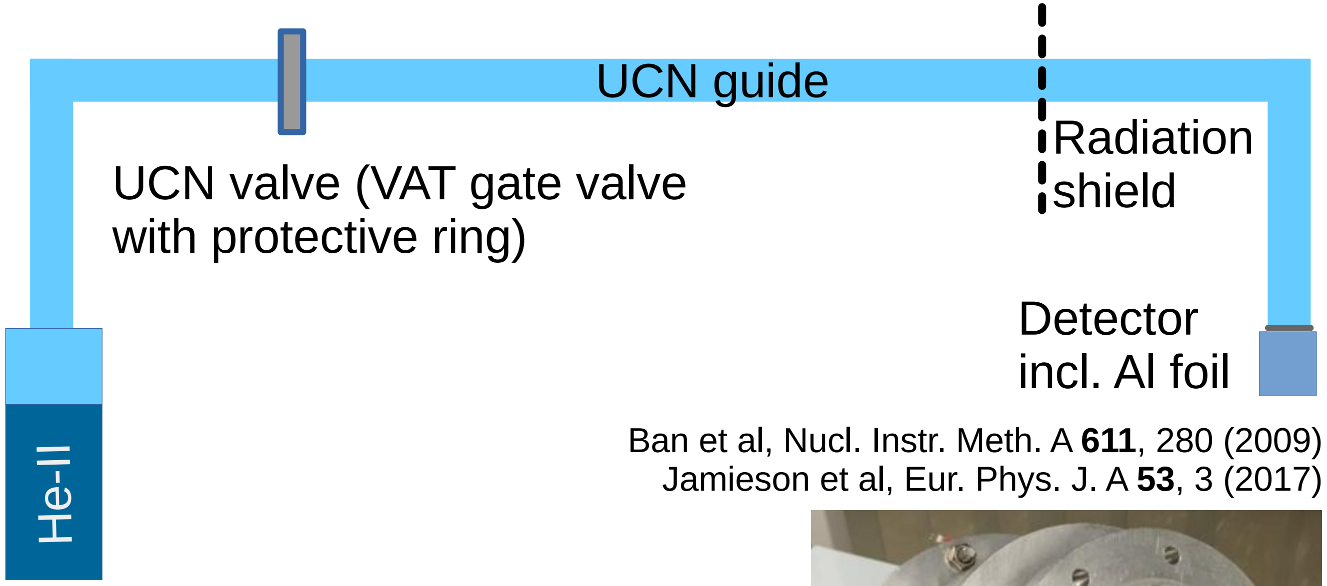
Masuda et. al., Phys. Rev. Lett. **108**, 134801 (2012)

UCN area top view

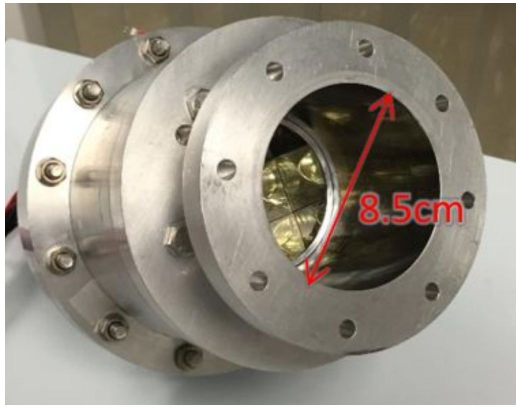


Installation of the prototype UCN source Jan-Mar 2017

November 13th 2017 - First UCN production in Canada

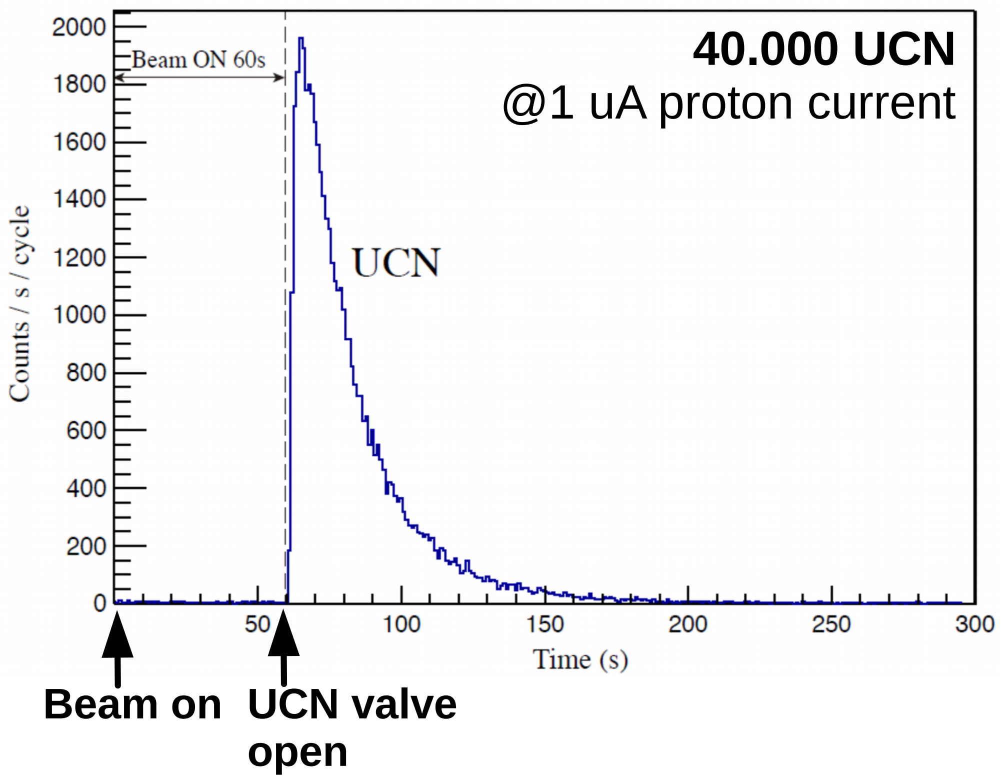


Ban et al, Nucl. Instr. Meth. A **611**, 280 (2009)
Jamieson et al, Eur. Phys. J. A **53**, 3 (2017)



Measurement program

- UCN source characterization
- Simulation benchmark (MCNP, PENTrack)
- UCN guide transmission
- Detector comparison

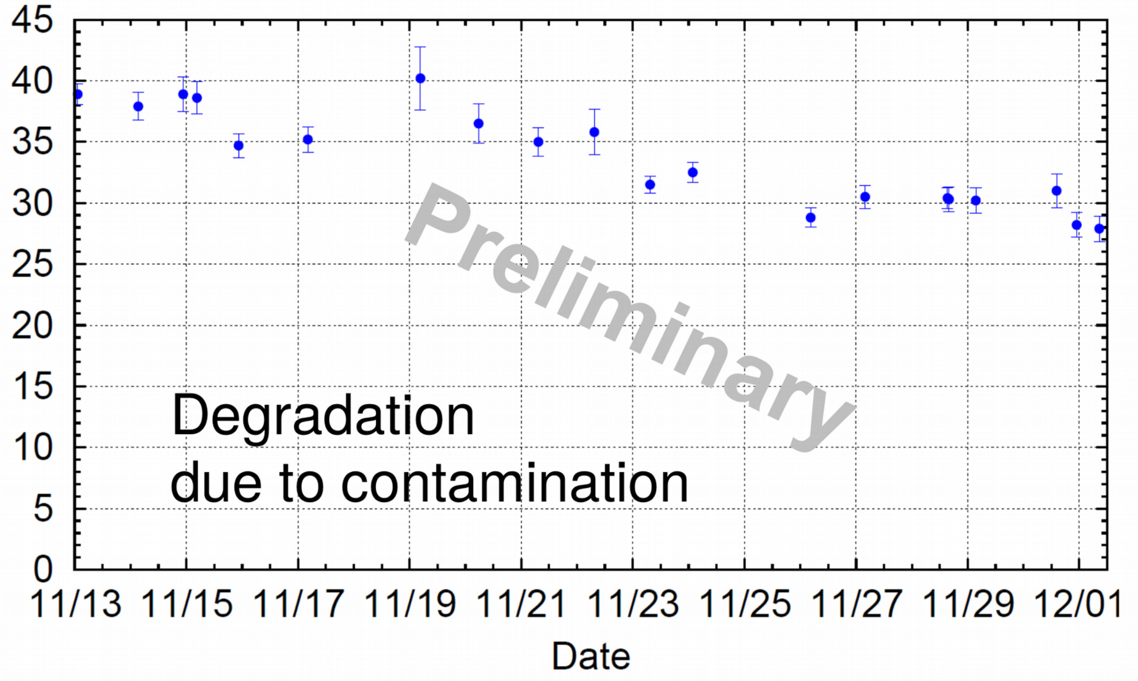


UCN Detectors

- ^{6}Li detector (UWinnipeg)
  - Suitable for high rates > 1MHz
  - Based on neutron capture in ^{6}Li layer
- ^{3}He detector (RCNP)

UCN production results

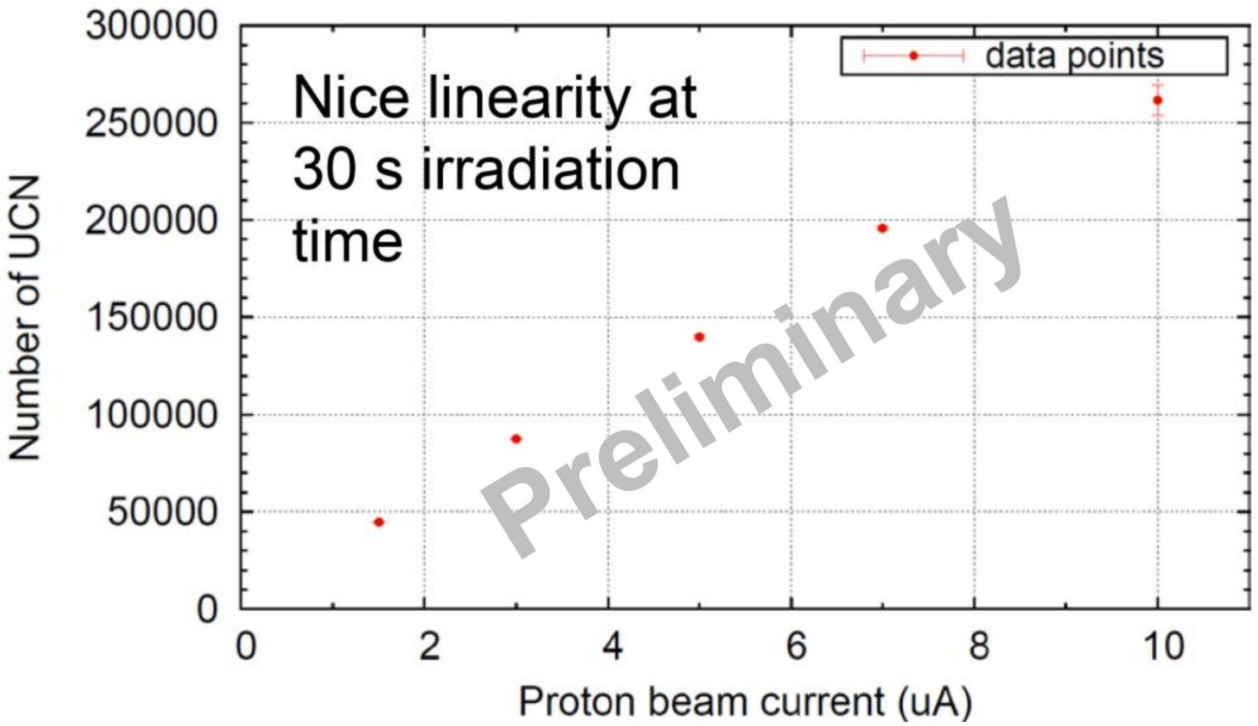
Production and UCN lifetime in source



- Initial UCN lifetime in source: 39 s (likely limited by UCN valve)
- UCN lifetime in source degraded to 28 s (18 days) (likely contamination due to measurements)

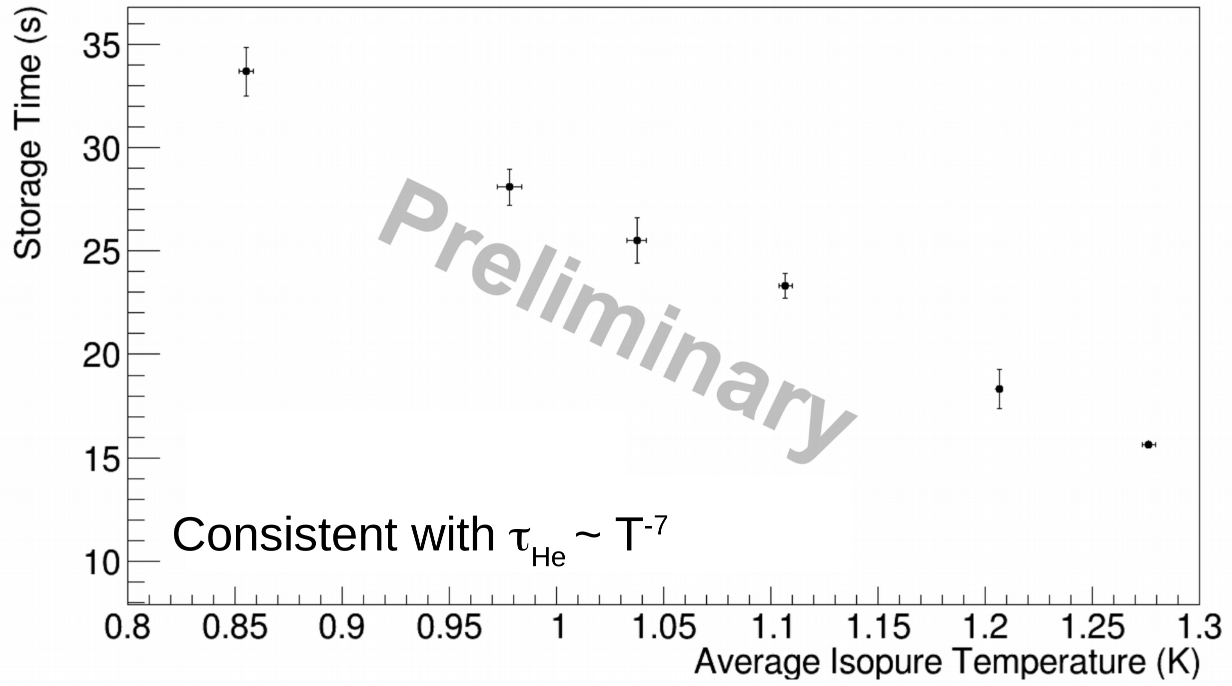
UCN production vs proton current

- Proton current on target: up to 10 uA
- 300.000 UCN @ 10 uA proton current, 60 s irradiation
- 30s irradiation time to avoid heating:
  - production increases linearly



UCN production results

Varying superfluid helium temperature



Ongoing analysis

- UCN transmission of components
- Detector comparison (^{3}He vs ^{6}Li)
- Characterize ^{3}He detector for normalization

Next run in fall 2018

- UCN transmission of components
- UCN storage properties of gate valves
- ...

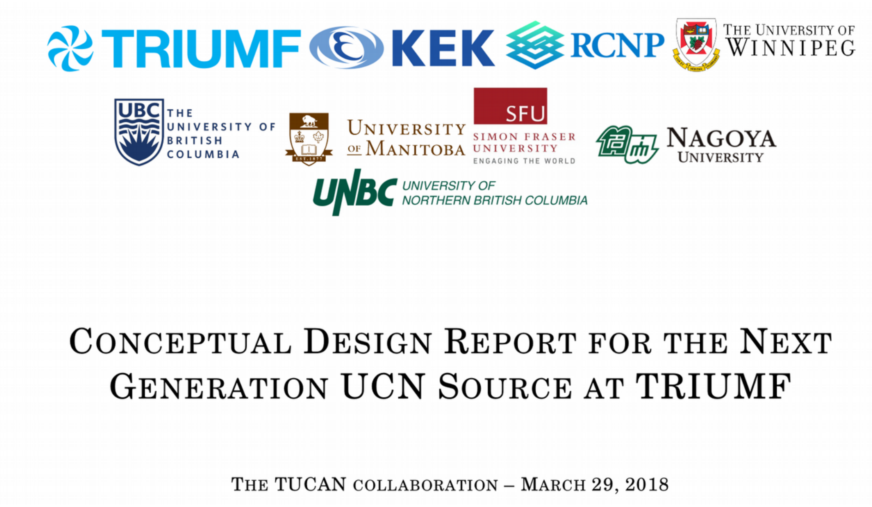
→ Successfully demonstrated UCN production with prototype source at TRIUMF
→ Testing of critical parts of the new UCN source
→ Benchmark for new source simulations

Design of a new world-leading UCN source

Improvements

- Cold moderator upgrade: LD_2
- Increased proton beam current (40 uA)
- Cooling power of 10 W @1.15 K
- UCN bottle materials
  (Be-Al alloys, Mg-Al alloys, Be)
- Optimized:
  - Geometry
  - LD_2 volume
  - Production vs heat load

Conceptual Design Report


TRIUMF KEK RCNP The University of Winnipeg
The University of British Columbia
University of Manitoba
SFU Simon Fraser University Engaging the World
Nagoya University
UNBC University of Northern British Columbia

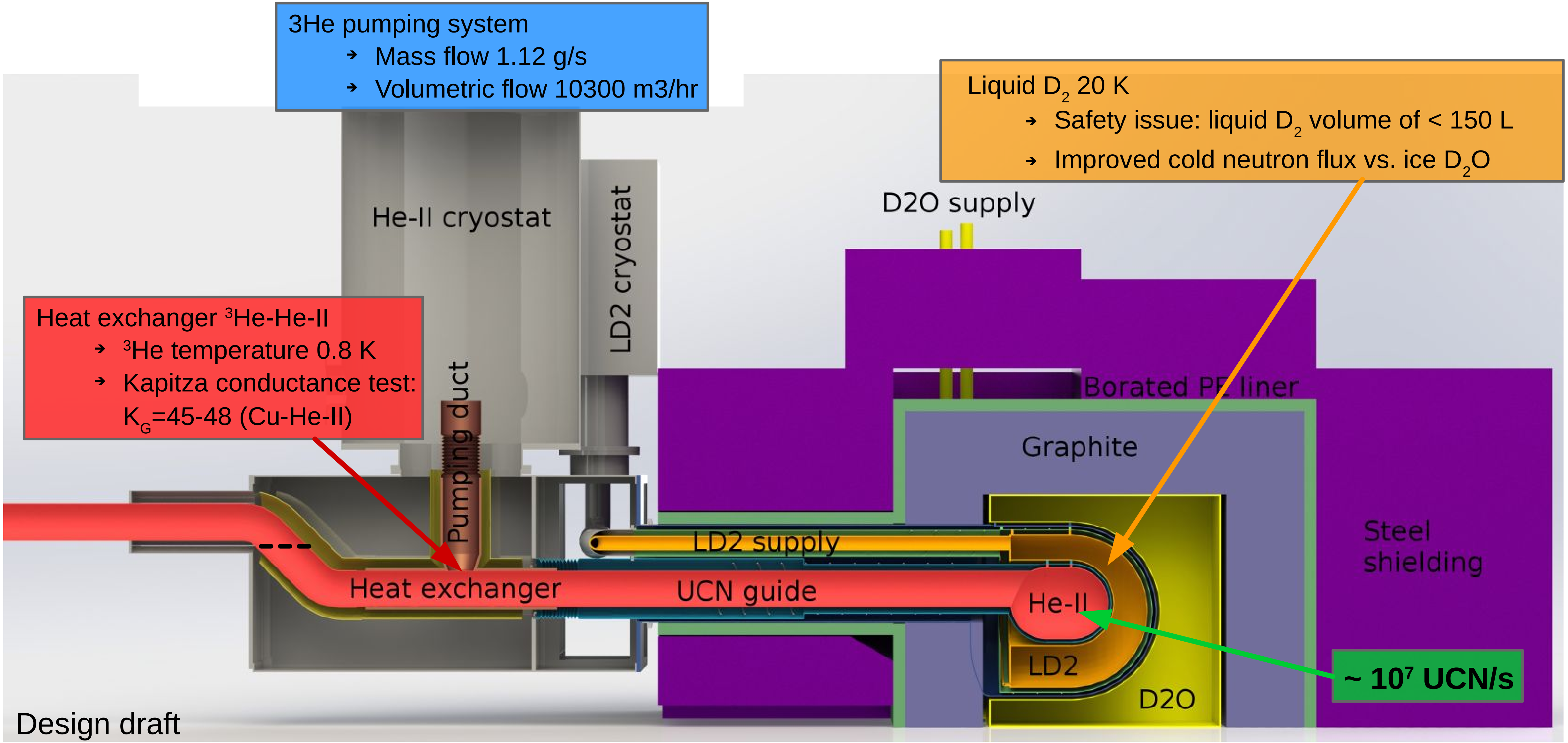
Conceptual Design Report for the Next Generation UCN Source at TRIUMF

The TUCAN collaboration – March 29, 2018

- Review at KEK April 2018
- Technical design started

→ Decision for ^{3}He fridge (vs direct pumping)
→ Expectation: 10^7 UCN/s
→ EDM sensitivity 10^{-27} ecm (400 days)

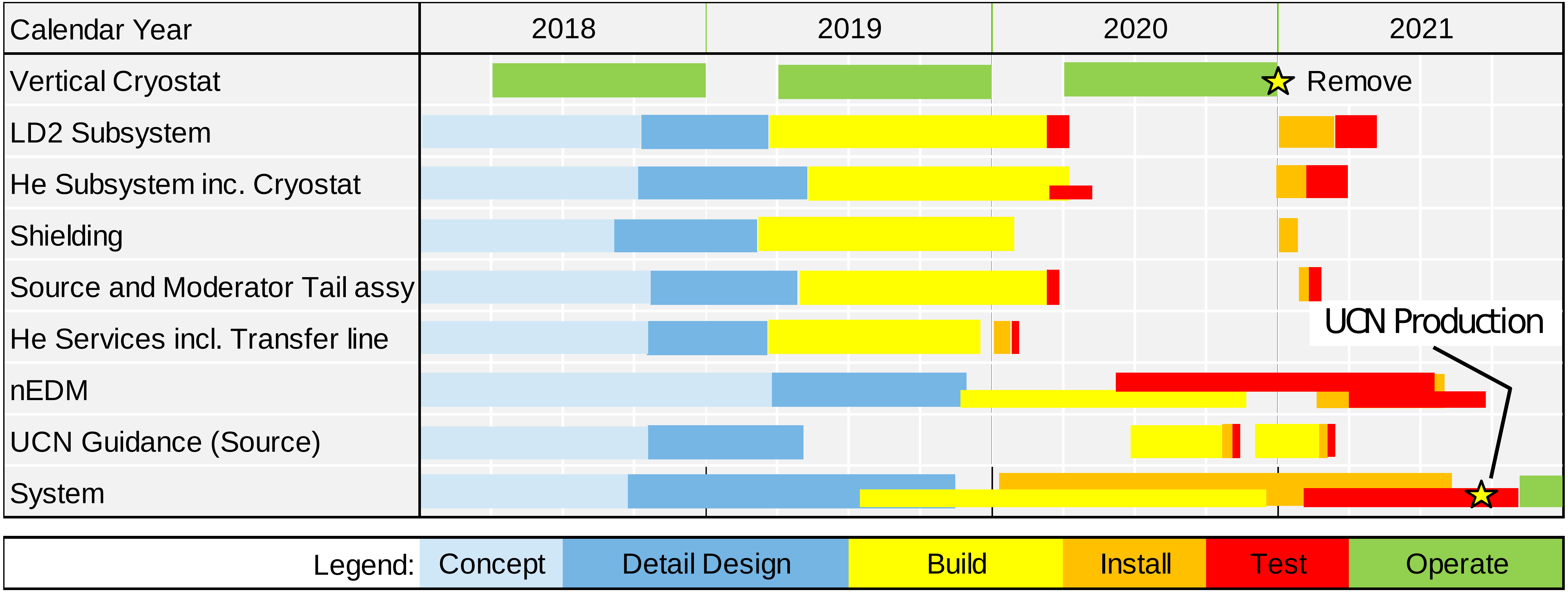
Draft design of a new world-leading UCN source



Design draft

UCN project schedule

New UCN source installation potentially shifted by one year due to shutdown



Ch. Gibson

Summary

- Installation of prototype UCN source in 2017 shutdown
- **UCN beamline** (and kicker) ready
- **First UCN production** - Nov. 2017
- Conceptual design report/review for new UCN source
- Neutron EDM project received CAD 15.7 million infrastructure funds (CFI)
- Neutron EDM conceptual design report by Spring 2019
  - Sensitivity goal of **10^{-27} ecm within 400 days**
- New UCN source commissioning in 2021

TUCAN collaboration

Thank you!
Merci!

S. Ahmed[3,4], E. Altiere[2], T. Andalib[3,4], C. Bidinosti[3,8], J. Birchall[4], M. Das[3,4], C. Davis[5], B. Franke[5], P. Giampa[5], M. Gericke[4], S. Hansen-Romu[3,4], K. Hatanaka[6], T. Hayamizu[2], B. Jamieson[3], D. Jones[2], S. Kawasaki[1], T. Kikawa[5,6,1], M. Kitaguchi[10], W. Klassen[3,4], A. Konaka[5,8], E. Korkmaz[7], F. Kuchler[5], M. Lang[3], T. Lindner[5,3], K. Madison[2], Y. Makida[1], J. Mammei[4], R. Mammei[3,5], J. Martin[3], R. Matsumiya[5], E. Miller[2], K. Mishima[1], T. Momose[2], T. Okamura[1], S. Page[4], R. Picker[5,9], E. Pierre[6,5], W. Ramsey[5], L. Rebenitsch[3,4], W. Schreyer[5], H. Shimizu[10], S. Sidhu[5,9], J. Sonier[9], I. Tanihata[6], S. Vanbergen[5], W.T.H. van Oers[4,5], Y. Watanabe[1]

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Spokespeople: J. Martin (Canada), K. Hatanaka (Japan

TRIUMF
KEK
RCNP
THE UNIVERSITY OF WINNIPEG
UNIVERSITY OF MANITOBA
UBC THE UNIVERSITY OF BRITISH COLUMBIA
SFU SIMON FRASER UNIVERSITY ENGAGING THE WORLD
UNBC UNIVERSITY OF NORTHERN BRITISH COLUMBIA
NAGOYA UNIVERSITY

Backup slides

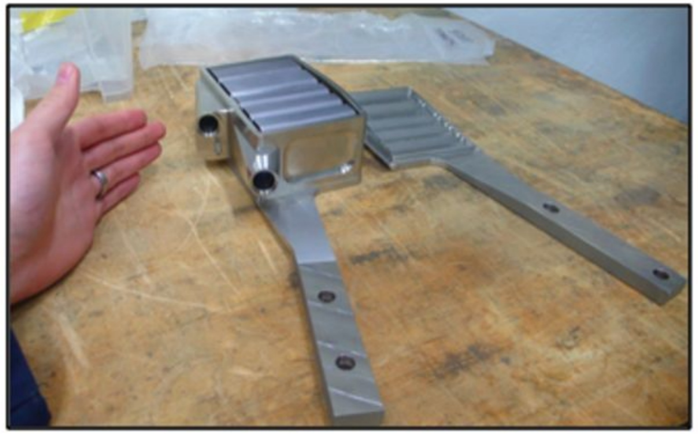
Neutron sources

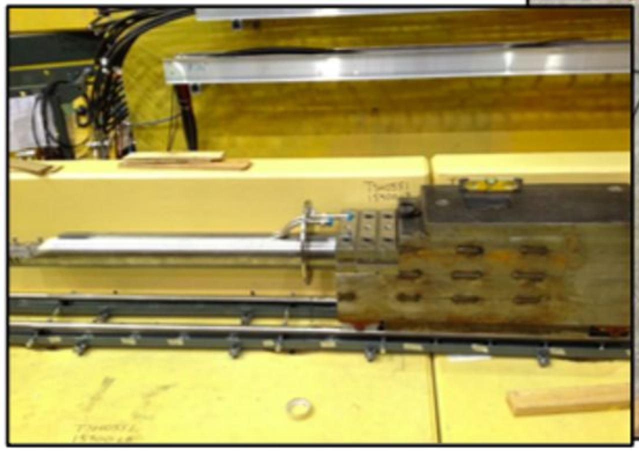
Place	Neutrons	UCN converter	Status
ILL	Reactor, CN	Turbine	Running
J-PARC	Spallation	Doppler shifter	Running
ILL SUN-2	Reactor, CN	Superfluid He	Running
ILL SuperSUN	Reactor, CN	Superfluid He	Future
RCNP/KEK/TRIUMF	Spallation	Superfluid He	Installing/Future
Gatchina WWR-M	Reactor	Superfluid He	Future
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

KEK-TRIUMF combination of spallation target and superfluid helium is unique.
Upgrade schedule is competitive with other leading sources of UCN.

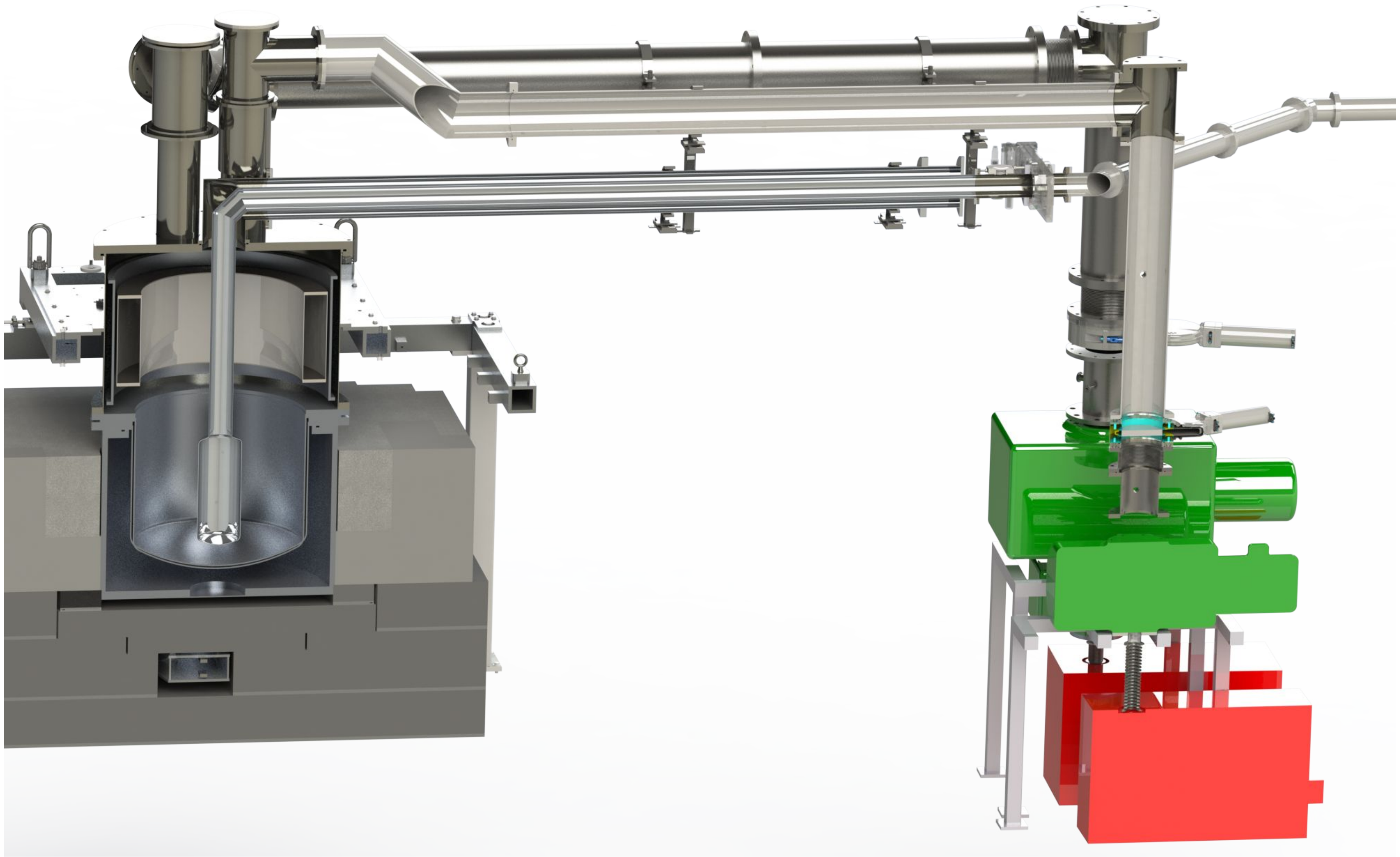
UCN target

- UCN target: tantalum-clad tungsten.
- Installed during Winter 2016.
- Water cooling; 14kW of heat to remove (at final power)
  - Need to deal with activated water. Finishing commissioning water package now.
- Have system for remotely removing UCN target

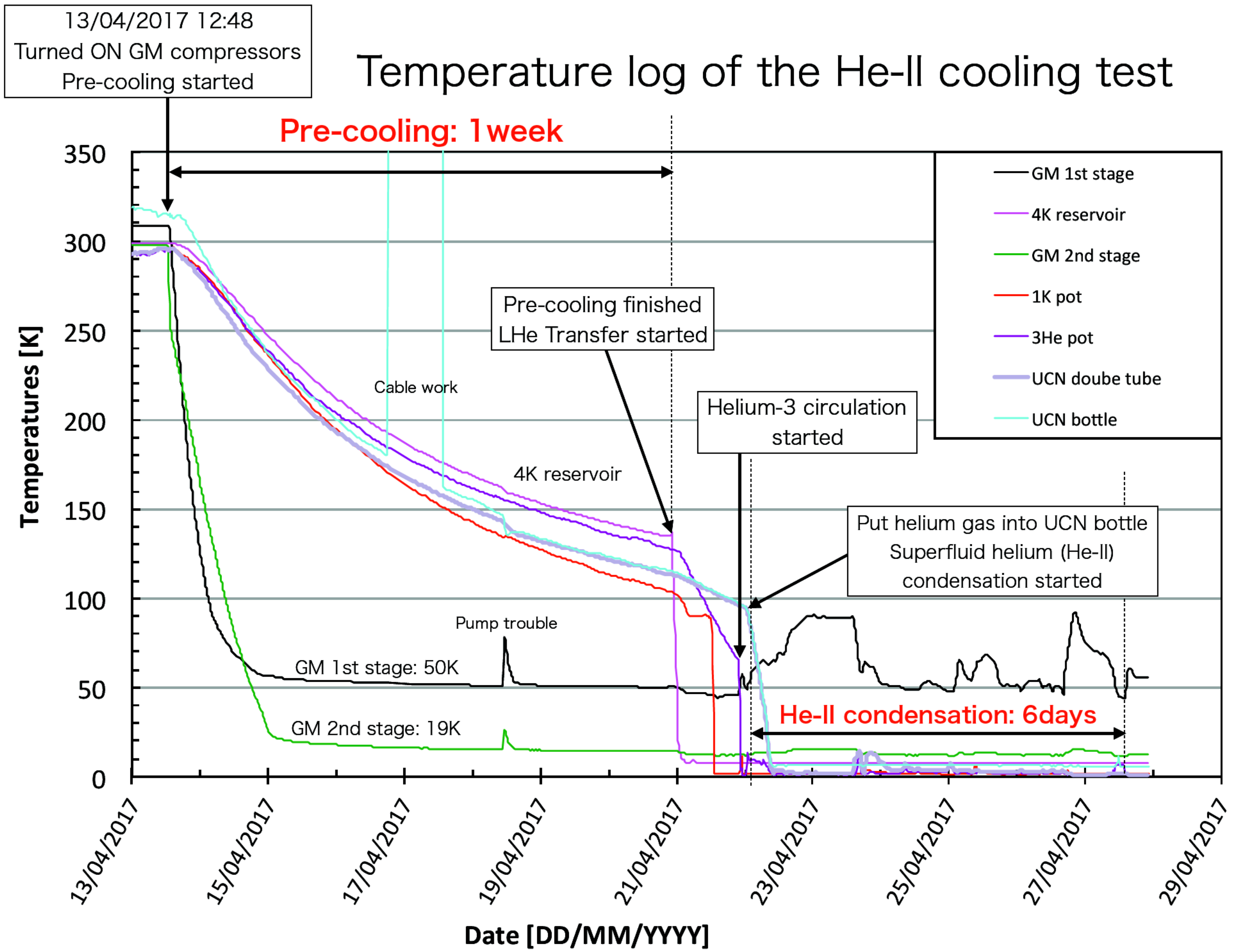





Prototype UCN source and pumps



Cooldown test of the prototype UCN source at TRIUMF



- Full cooling test in April 2017
- Final temperature 0.92 K
- 8 L of liquid He-II condensated

Shortage of liquid helium delayed condensation:

- ➔ TRIUMF helium liquefier plant now upgraded with liquid nitrogen
- ➔ Liquid helium supply of 50 L/hr

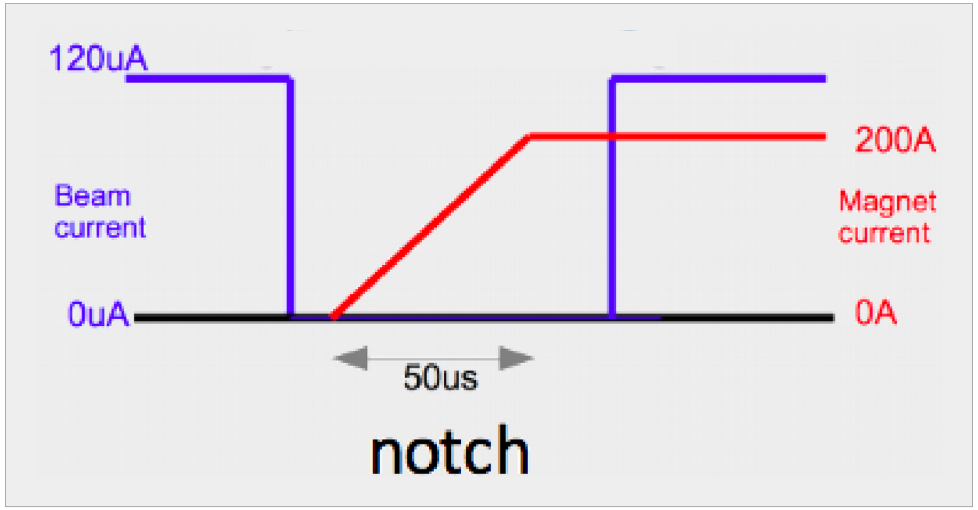
UCN kicker and beam timing structure

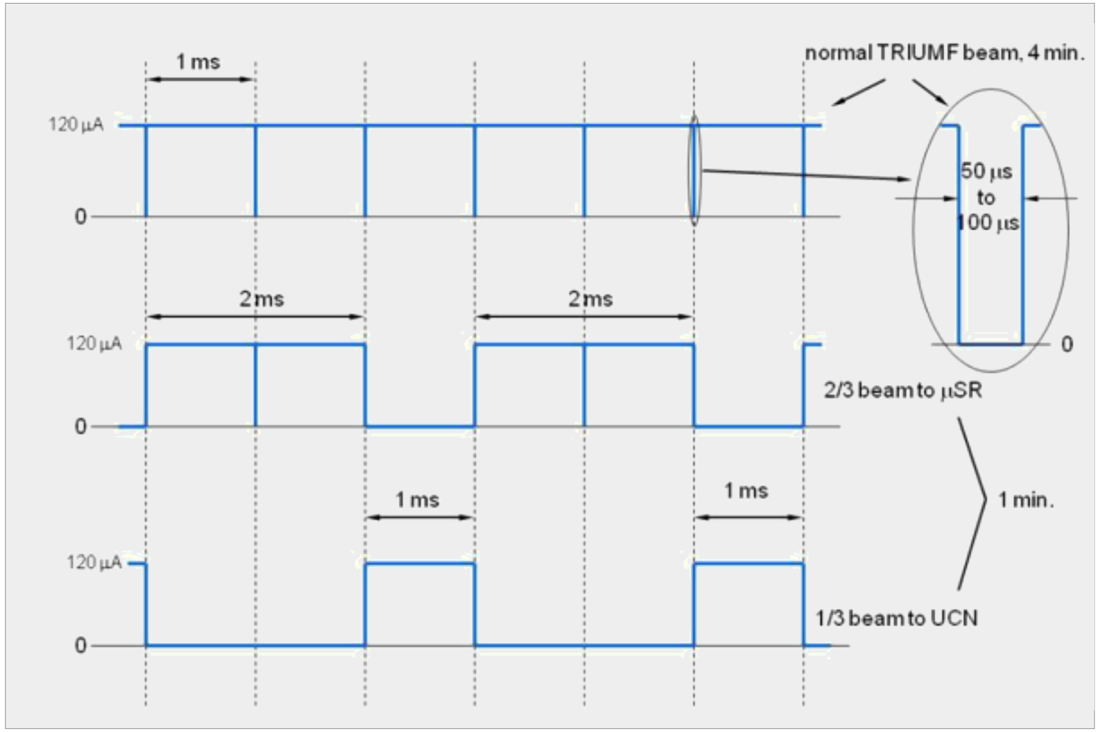
<u>TRIUMF beam structure:</u> 120 μA pulse for 1 ms
no beam for 50-100 μs

Kicker ramps up during beam notch (200 A/50 μs)

- kicks every 3rd pulse to BL1U (UCN)
- average of 40 μA for UCN

- currently limited to 1 μA (every 120th pulse)





Timing of target irradiations:

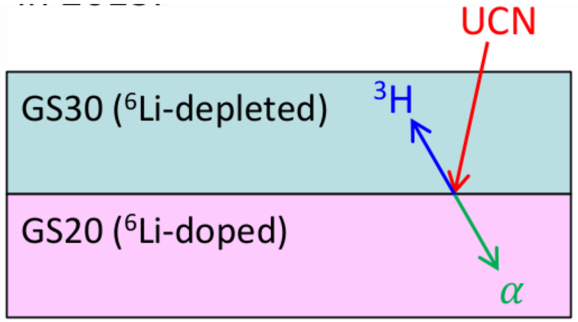
- Balance of UCN density accumulation and heat load
- Planning target irradiation time of ~ 60 s

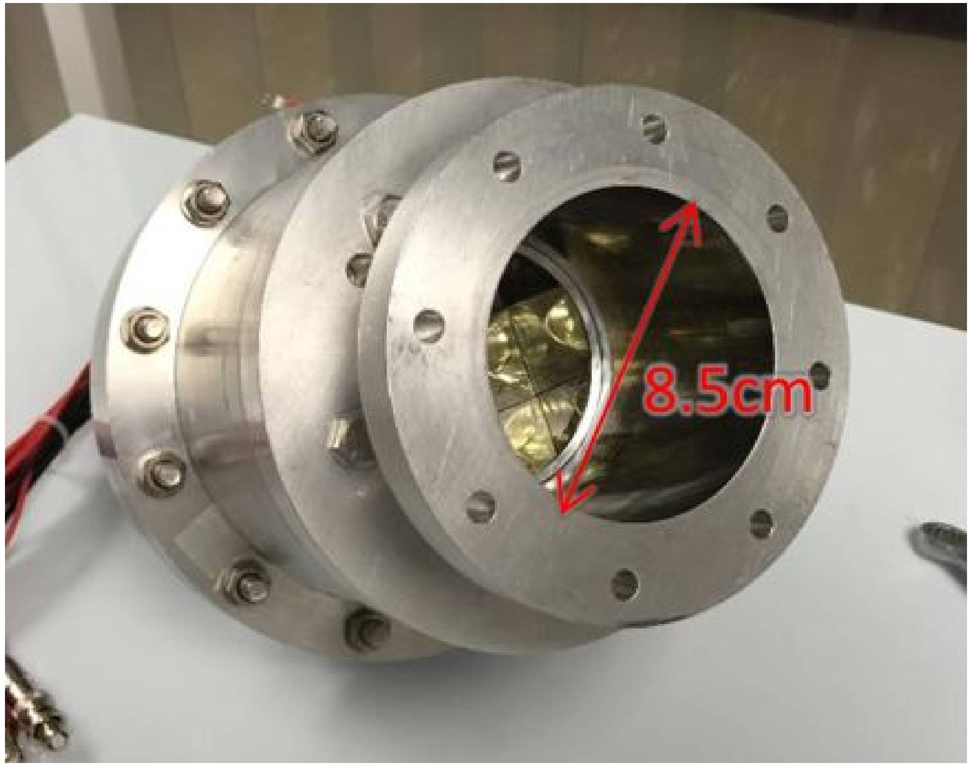
Installation of the prototype UCN source Jan-March 2017

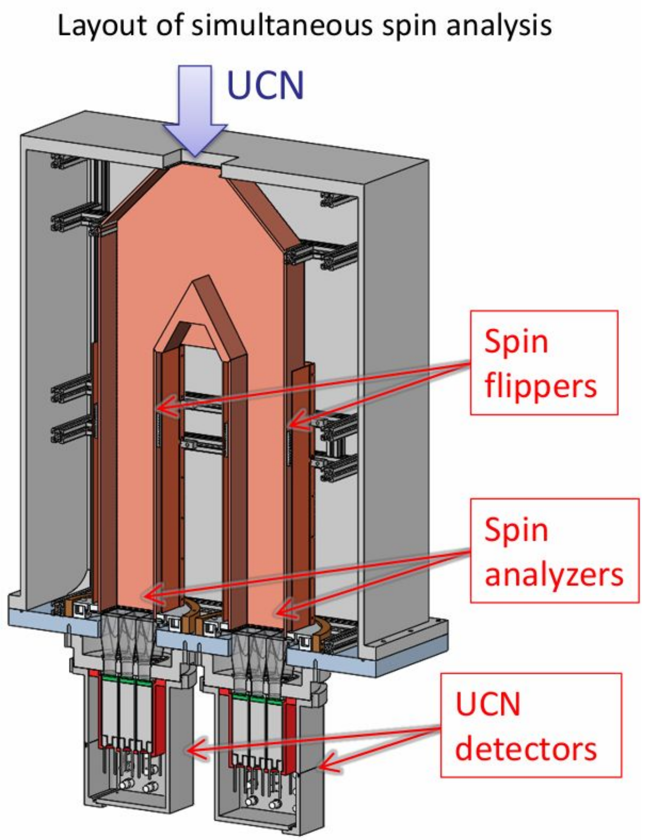
UCN detection for the neutron EDM experiment

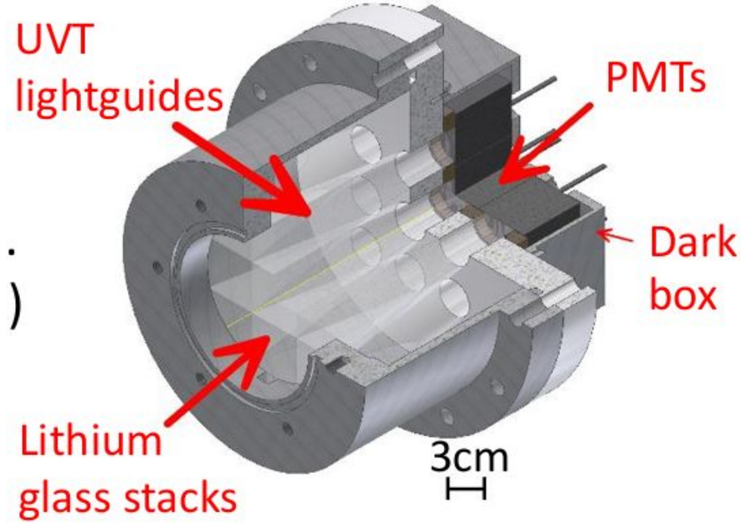
High rate counting (>1.3MHz) and UVT efficiency stability (0.05% / hour) lightguides are required

- Detection via neutron capture in 6Li: $^{6}Li + n \rightarrow {}^{3}H(2.73MeV) + \alpha(2.05MeV)$
- Detector was well characterized by beam test at PSI UCN beamline
- Increase the UCN statistics by measuring both spin state simultaneously
- Increase visibility due to less depolarization while storing above analyzer foil









New UCN source bottle materials

Material	Composition (wt.-%)	Wall thickness	Effect on P/Q
Aluminium	100 Al	2 mm	
Al6061	95.85 Al, 1.2 Mg, 0.8 Si, 0.7 Fe, 0.4 Cu 0.35 Cr, 0.25 Zn, 0.15 Mn, 0.15 Ti	2 mm	-5 %
Beryllium	100 Be	1.5 mm	+90 %
Magnox AL80	99.2 Mg, 0.8 Al, 0.004 Be	4 mm	+15 %
AZ80	90.85 Mg, 8.5 Al, 0.5 Zn, 0.15 Mn	2.5 mm	+40 %
AlBeCast 910	57 Be, 38 Al, 3.4 Ni, 0.5 Si, 0.3 Fe, 0.24 O	3 mm	+5 %
BerAlCast 310	60 Be, 36 Al, 2.5 Ag, 0.25 Si, 0.2 Co, 0.2 Ge, 0.2 Fe	1.5 mm	-5 %
AlBeMet 162	62 Be, 38 Al	2 mm	+50 %