TRIUMF

Commissioning of the UCN Facility at TRIUMF – a first step towards a neutron electric dipole moment search

Beatrice Franke
TRIUMF Research Scientist

Brief introduction to Ultracold Neutrons (UCN) and nEDM
The TUCAN Collaboration and Source
Status update, first UCN results, other progress

Introduction to ultracold neutrons

$E_{\mathrm{UCN}} \leq 300\,\mathrm{neV} \,\hat{=}\, 3.5\,\mathrm{mK}$ ("ultracold")

- Strong interaction results in pseudopotential $\hat{=}$ "optical" Fermi potential V_{F}
  - UCN undergo total reflection *under all angles of incidence*

    if $E_{\mathrm{UCN}} \leq V_{\mathrm{F}}(\mathrm{material})$

    $\Rightarrow$ UCN are storable, like a gas
  - $V_{\mathrm{F}}(\mathrm{BeO}) \approx 300\,\mathrm{neV}$,
    $V_{\mathrm{F}}(\mathrm{SUS}) \approx 180\,\mathrm{neV}$,
    $V_{\mathrm{F}}(\mathrm{Quartz}) \approx 90\,\mathrm{neV}$
- Gravitational interaction: $E_{\mathrm{UCN}}(1\,\mathrm{m}) \approx 100\,\mathrm{neV}$
- Magnetic interaction depicts a spin-dependent potential: $E_{\mathrm{UCN}}(1\,\mathrm{T}) \approx \pm 60\,\mathrm{neV}$
- Weak interaction: $\tau_{\mathrm{n}} \approx 900\,\mathrm{s}$

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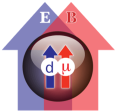
What to do with UCN?

- Search for the neutron electric dipole moment
- Measure the neutron lifetime
- Investigate beta decay correlations
- Sensitivity to energies of down to peV allows to search for exotic interactions, fifth forces, axions, dark matter, quantized states in gravitational potential, etc.

The neutron electric dipole moment d_n

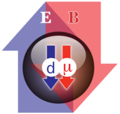
Does the spin of the neutron couple to an electric field?
Hamiltonian of a neutron in a magnetic field and an electric field

$$\mathcal{H} = -\mu_n \frac{\vec{\sigma}}{|\vec{\sigma}|}\vec{B} - d_n \frac{\vec{\sigma}}{|\vec{\sigma}|}\vec{E}$$



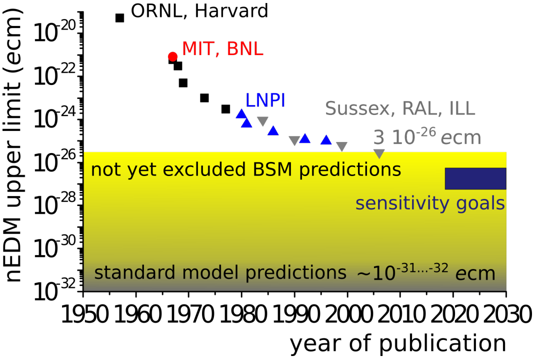
Time reversal symmetry T is not conserved:

$$\mathrm{T}\mathcal{H} = -\mu_n \frac{-\vec{\sigma}}{|\vec{\sigma}|}(-\vec{B}) - d_n \frac{-\vec{\sigma}}{|\vec{\sigma}|}\vec{E} \neq \mathcal{H}$$



CPT theorem: T-violation ⇔ CP-violation.

⇒ CP-violating processes are needed to understand the Baryon Asymmetry of our Universe (BAU)



Beyond Standard Model (BSM) physics shall fix BAU and predict
more CP-violation ⇔ larger nEDM

The TUCAN collaboration

TRIUMF's UltraCold Advanced Neutron Source

KEK	T. Adachi, S. Jeong, S. Kawasaki, Y. Makida, K. Mishima, T. Okamura, Y. Watanabe
U Nagoya	M. Kitaguchi, H. Shimizu
RCNP Osaka	K. Hatanaka, I. Tanihata, E. Pierre (E.P. also TRIUMF), J. Ong Hooi
UBC	E. Altiere, D. Jones, K. Madison, E. Miller, T. Momose, T. Hayamizu
U Winnipeg	C. Bidinosti, B. Jamieson, R. Mammei (also TRIUMF), J. Martin
U Manitoba	T. Andalib, J. Birchall, M. Gericke, M. Lang, J. Mammei, S.. Page, L. Rebenitsch, S. Hansen-Romu, S. Ahmed
TRIUMF	C. Davis, B. Franke, K. Katsika, T. Kikawa, A. Konaka (also UVic and Osaka U.), F. Kuchler, L. Lee, R. Matsumiya, R. Picker (also SFU), W. Ramsay, , W. Schreyer, W. van Oers (also U. Manitoba), T. Lindner (also UW)
UNBC	E. Korkmaz
SFU	S. Sidhu, J. Sonier

The TUCAN collaboration

TUCAN's Objective

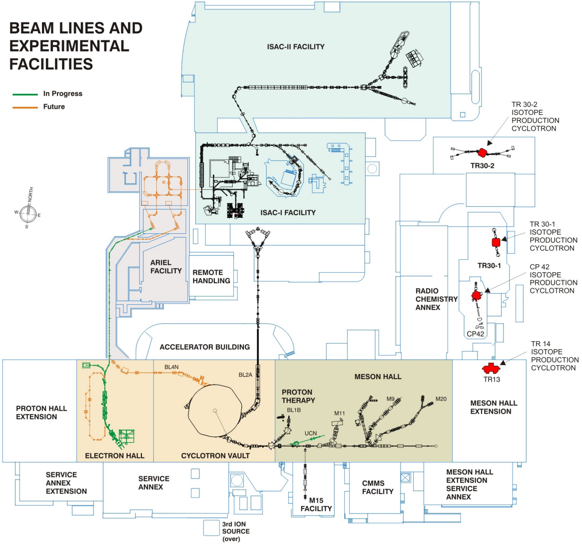
- Operate world's strongest intensity ultracold neutron (UCN) source at TRIUMF: combination of spallation neutron source and superfluid He converter

- Search for the neutron electric dipole moment (nEDM) to a precision of $10^{-27}\,e$cm
- Establish UCN user facility with a second port & and attract international scientific community

Current activities of the collaboration

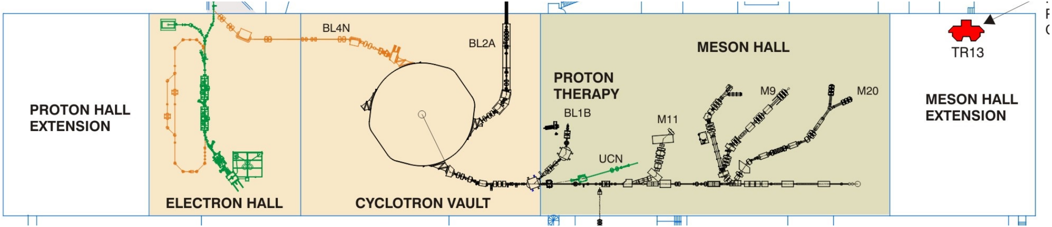
- Operate prototype ultracold neutron (UCN) source at TRIUMF
  ($\sim$1 month a year, 2017 – approximately2020)
- Design a next generation, high intensity UCN source (technical design stage)
- Design a next generation nEDM spectrometer (conceptual design stage)

TRIUMF (Vancouver, Canada)

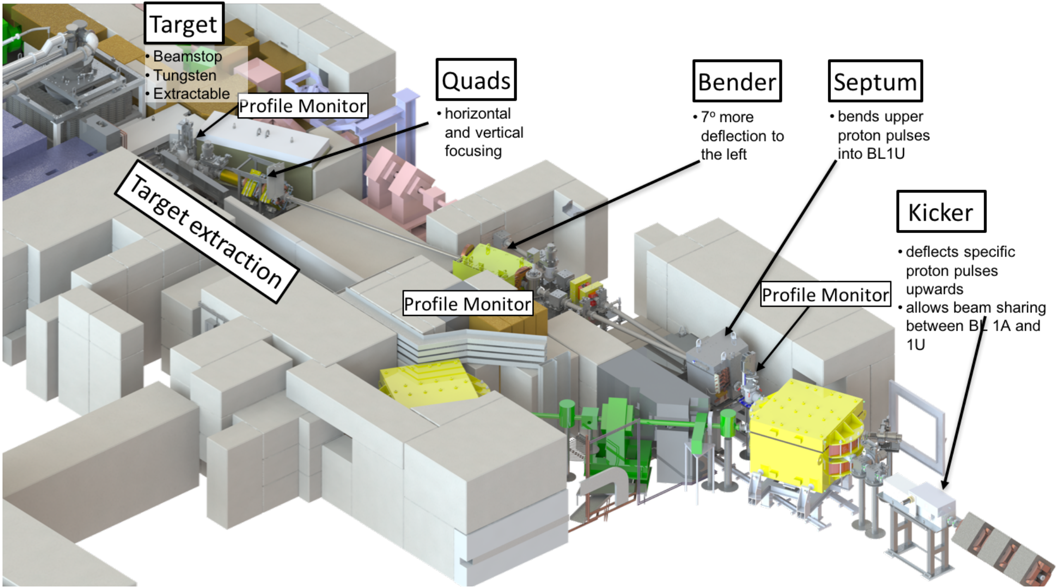


The Cyclotron (needed for spallation process)

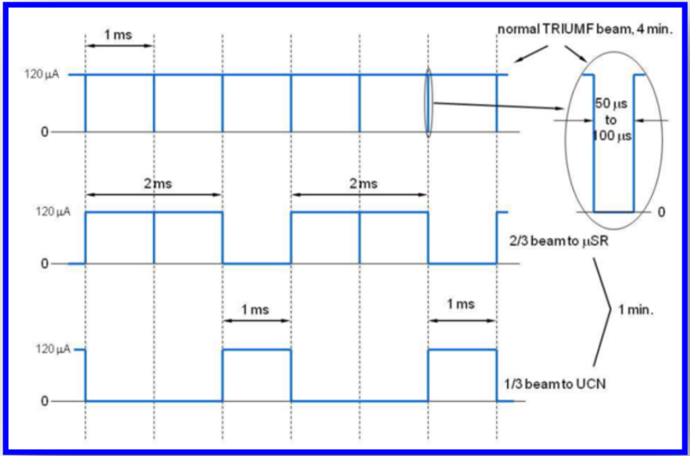
- H- ions are accelerated, and p^+ extracted through stripper foil at $\sim$500 MeV
- Three beamlines can be fed with 120 μA at a time – simultaneous operation of different facilities
- Nuclear Physics, Particle Physics, Life Sciences, Material and Molecular Science, Eye Cancer Treatment via Proton Therapy



Beamline 1U, Meson hall



Beam Structure and Kicker Magnet



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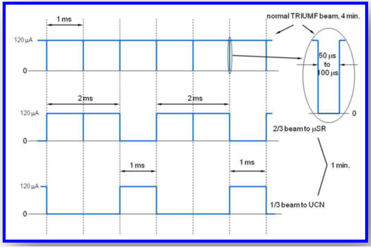
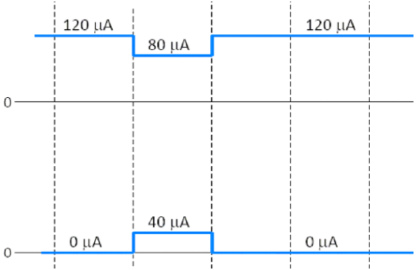
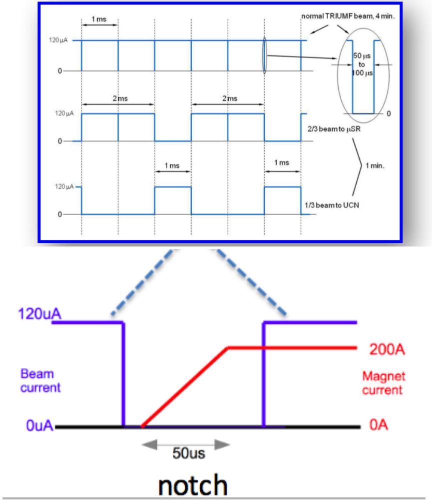




- We need to share the beam with other BL1A users (Center for Materials and Molecular Science, CMMS)
- TRIUMF's beam structure has a 'notch' of zero beam between the 120 μA pulses

  (pulse: 1 ms; notch: 50-100 μs)
- Directing every third pulse to BL1U results in an average of 40 μA

Beam Structure and Kicker Magnet



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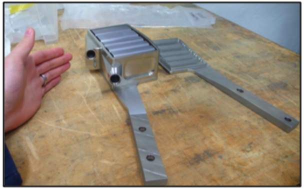
  (pulse: 1 ms; notch: 50-100 μs)
- Directing every third pulse to BL1U results in an average of 40 μA
- Kicker magnet has to ramp within notch!
- Timing of target irradiation:

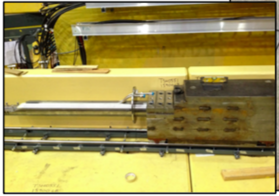
  find optimum between UCN density accumulation, and heat load on cryostat
- difference between sD2 and He-II: UCN lifetime inside converter medium!

  $\sim$200 ms vs tens/hundreds of seconds
- We aim at an irradiation time of $\sim$ one minute

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





Superthermal UCN production

(RCNP prototype source at TRIUMF as example)

- Free n via spallation
- Moderation to thermal and cold neutron energies:

$$E_{\text{kin}} \propto T_{\text{mod}} \xrightarrow{\text{works down to}} \sim 10\,\text{K}$$

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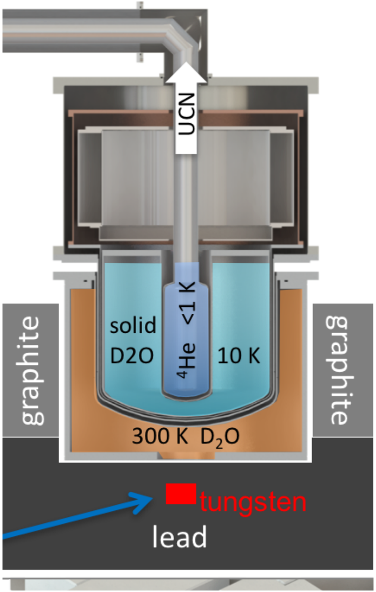
- Free n via spallation
- Moderation to thermal and cold neutron energies:
  $E_{\text{kin}} \propto T_{\text{mod}} \xrightarrow{\text{works down to}} \sim 10\,\text{K}$
- 'Superthermal' conversion process in superfluid He:
  $E_{\text{kin}}(\text{cold n}) \rightarrow$ phonon/roton excitation
  $\underbrace{T_{\text{He-II}}}_{=0.8\,\text{K}} \neq \underbrace{T_{\text{UCN}}}_{\leq 3.5\,\text{mK}}$

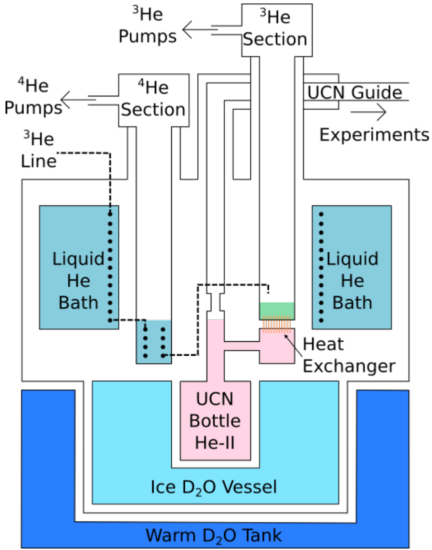


RCNP prototype source, cryogenics

How to get to superfluid helium (He-II) at 0.8 K?

- Four stages:

  4 K Liquid helium-4 bath
  1.4 K ^{4}He pumping section
  0.8 K ^{3}He pumping section
  0.8 K Heat exchanger for cooling isopure ^{4}He



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4 K	Liquid helium-4 bath
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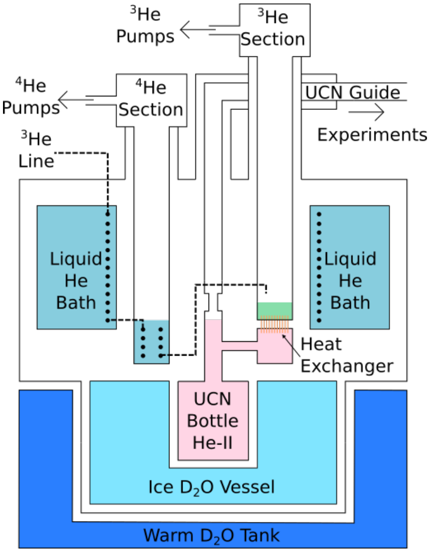
UCN production:

- Spallation Neutrons 'precooled' in moderators
- Superthermal conversion process in superfluid He
- Due to their low kinetic energies, neutrons can't overcome the potential of the wall material anymore

⇒ UCN accumulate within the He-II and in the vacuum above it

- Upon opening a valve, the accumulated density will diffuse towards the experiment



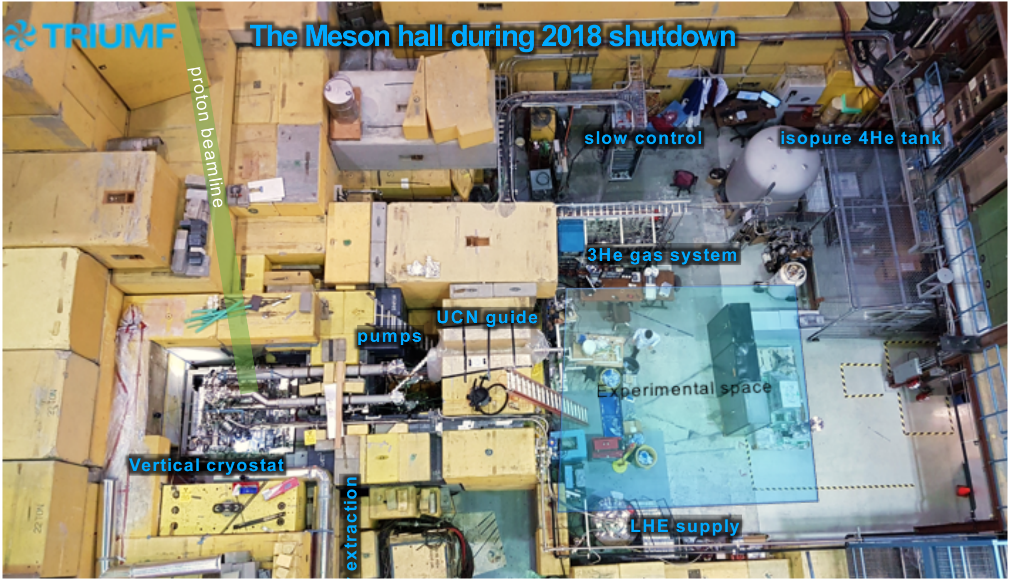
TUCAN status update

- Analyzing our first UCN data (from 2017) to understand source performance
- We are planning and preparing for another UCN data taking run for November 2018 (continue source characterization/simulation benchmarking, test equipment for new source)
- We are heavily working on a technical design for a new UCN source cryostat, after successfully passing a thorough conceptual design review by international cryo- and UCN experts
- Started working on a design report for the nEDM spectrometer

First UCN at TRIUMF

- During November 2017 we successfully produced the first UCN at TRIUMF!
- This major milestone (within TRIUMF and the neutron physics community) is a consequence of many earlier achievements coming together:
  - Beamline (installation work started in 2013)
  - Target (Commissioned in 2016)
  - Kicker Magnet which allows beam sharing between BL1A and BL1U
  - Vertical UCN source cryostat installed during 2017 shutdown
  - Experimental UCN infrastructure: guides, detectors, etc
- Are we ready for a neutron electric dipole moment measurement? Not quite yet...
- We need a higher density of UCN for competitiveness, and an nEDM spectrometer

First UCN: Some impressions



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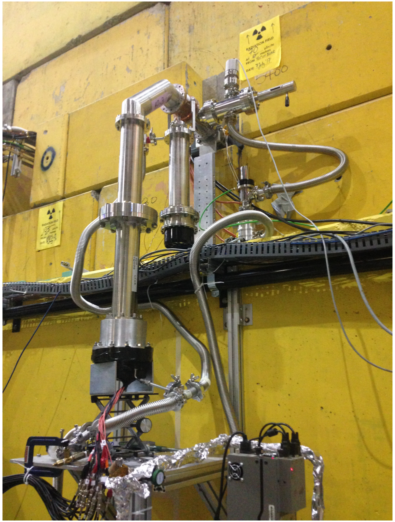
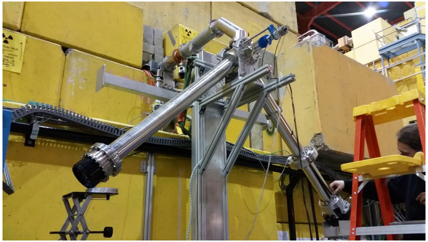
Normalization detector setup

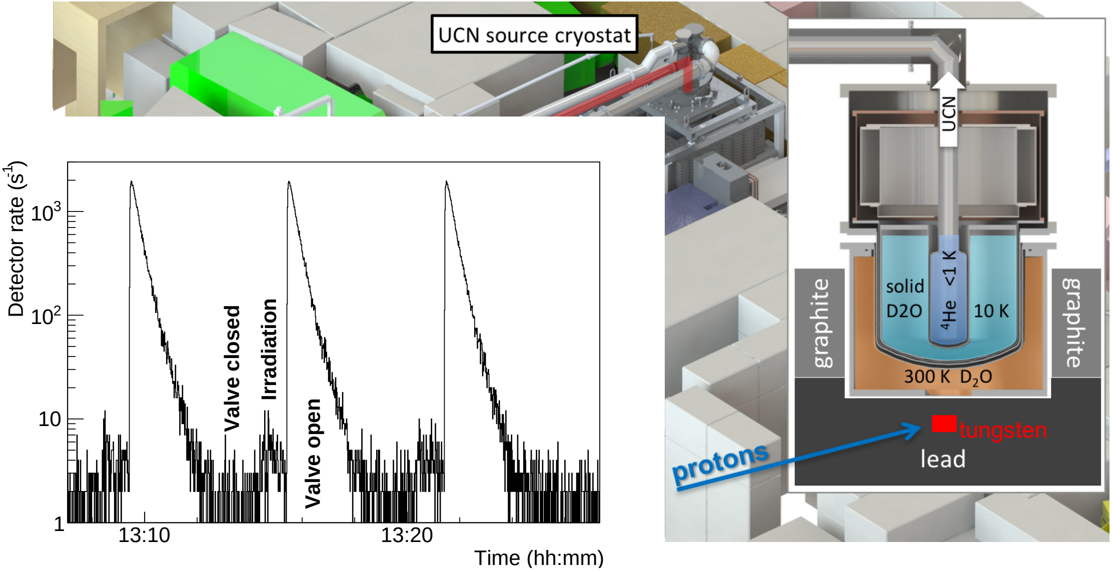


Transmission measurement of 100cm guide

Comparison of two detectors



How do we take data?



UCN data from 2017

- Prototype UCN source cryostat had been developed and operated in Japan [Masuda et al, PRL 108, 134801 (2012)]
- Best results in Japan:
  $\sim 10^5$ UCN per 1μA shot, $\tau_{\text{source}} \sim 80\,$s

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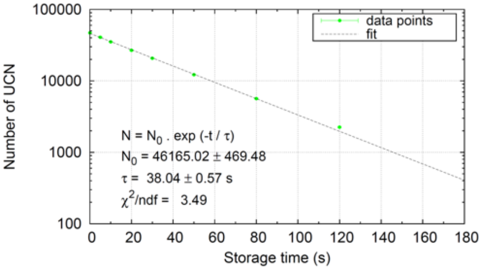
  Our first try:

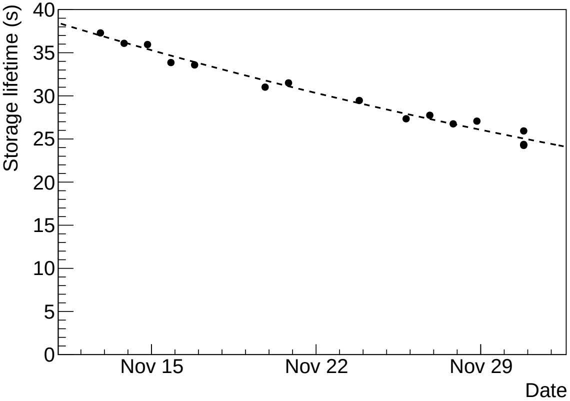
  All numbers are PRELIMINARY
- $\sim 5 \cdot 10^4$ UCN per 1muA shot, $\tau_{\text{source}} \leq 40\,$s
- $> 3 \cdot 10^5$ UCN per 10muA shot
  ($\sim$ 7-fold increase in UCN density)

  Room to improve:
- Use UCN-optimized gate valve
- Improve detector vacuum properties and get rid of Al separation foil
- Repeated cleaning and baking of production volume

τ_{source} at TRIUMF:

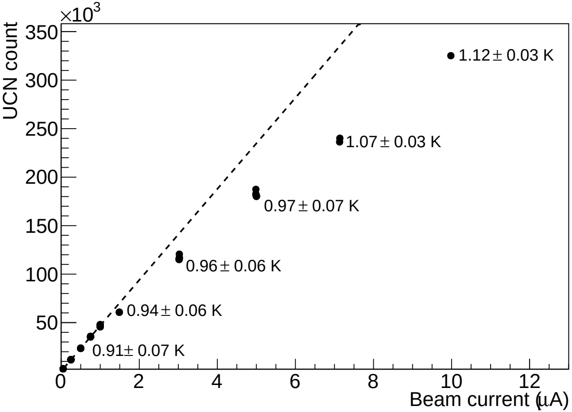


UCN beam line and Li6 detector:



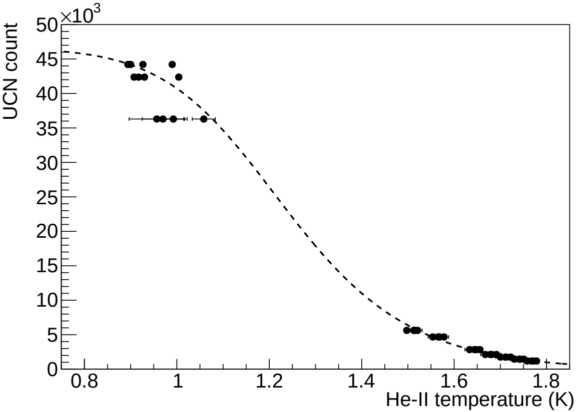
Preliminary result: Storage lifetime of UCN in the source on different days after irradiating the target with 1 μA for 60 s. An exponential fit shows that it dropped by 2.1 %per day.

UCN data from 2017



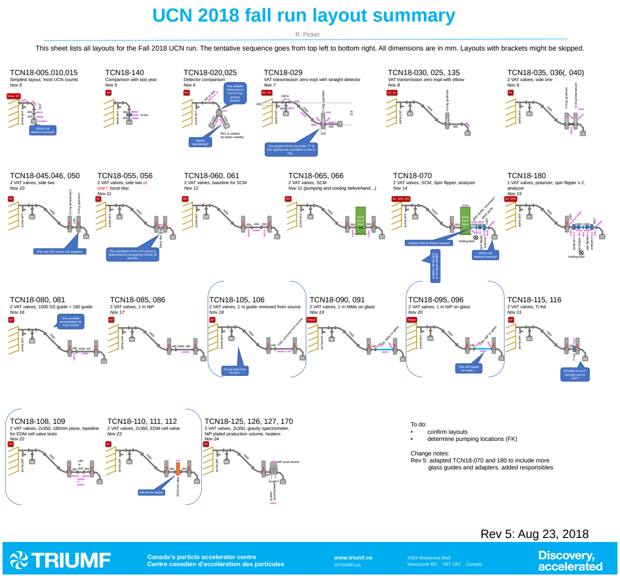
Preliminary result: Number of UCNs extracted from the source after irradiating the target for 60 s with different beam currents. The dashed line linearly extrapolates the data at beam currents below 1 μA. The labels show the range of helium temperatures after the irradiation ended.

UCN data from 2017



Preliminary result: Number of UCNs extracted from the source at different temperatures after irradiating the target with 1 μA for 60 s. Consistent with $\frac{1}{\tau_{\mathrm{He}}} \sim 0.008\mathrm{s}^{-1}\mathrm{K}^{-7}T^7$

Upcoming UCN measurements at TRIUMF (Nov 2018)

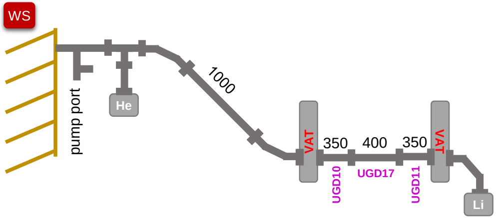


Upcoming UCN measurements at TRIUMF (Nov 2018)

TCN18-060, 061

2 VAT valves, baseline for SCM

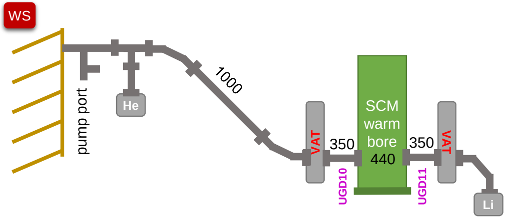
Nov 12



TCN18-065, 066

2 VAT valves, SCM

Nov 11 (pumping and cooling beforehand…)



Planned improvements

- Beam current: 1 μA → 40 μA
- Production volume: 8 L → 34 L
- Cold moderator: sD_2O → LD_2
- Production rate: 20000/s → 2.5×10^7/s
- Cooling power: 0.3 W → 10 W
- He-II temperature: 0.85 K → 1.10 K
- Separation foil

Crucial features

- Heat transport in He-II and heat exchanger
  - Detailed calculations
  - Measurements at KEK
- LD_2 safety
- UCN production/heat load
  - Heavily optimized with MCNP

New source design

Optimized by MC simulation:
Geometry, LD_2 volume, production vs heat load

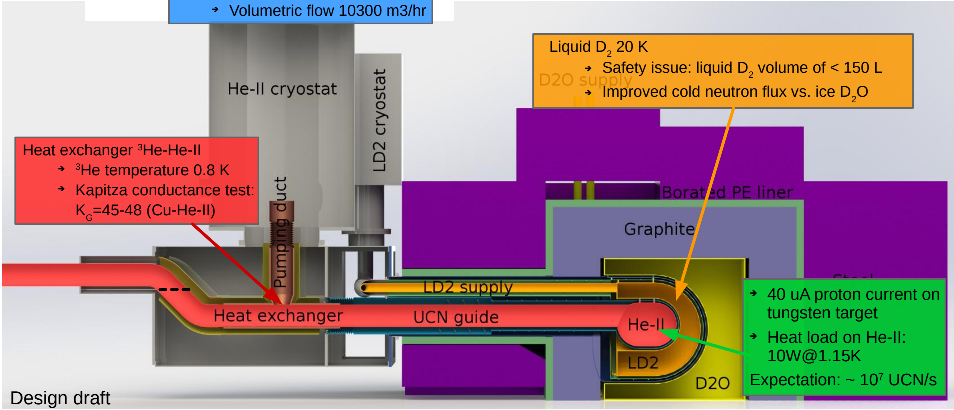
3He pumping system
- Mass flow 1.12 g/s
- Volumetric flow 10300 m3/hr

Liquid D_2 20 K
- Safety issue: liquid D_2 volume of < 150 L
- Improved cold neutron flux vs. ice D_2O

Heat exchanger ^{3}He-He-II
- ^{3}He temperature 0.8 K
- Kapitza conductance test: K_G=45-48 (Cu-He-II)

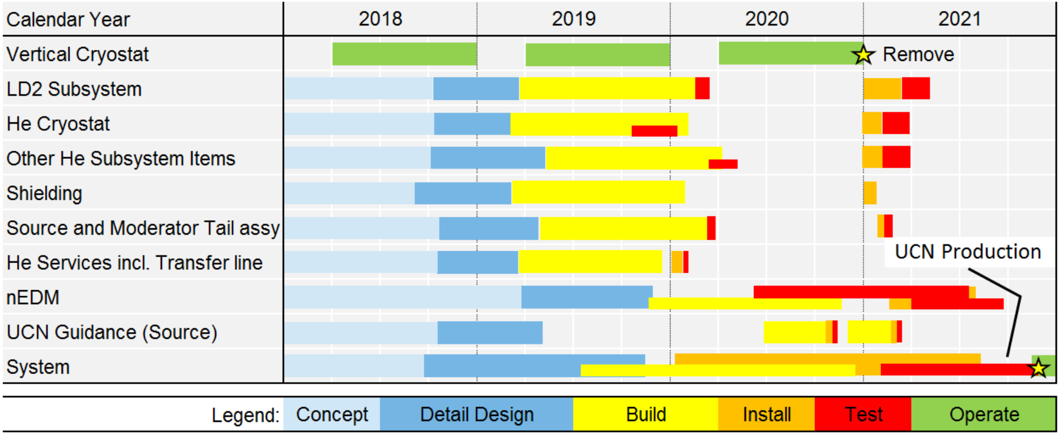
- 40 uA proton current on tungsten target
- Heat load on He-II: 10W@1.15K

Expectation: ~ 10^7 UCN/s



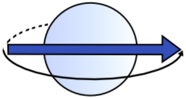
Design draft

TUCAN schedule



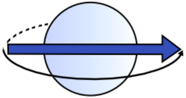
To be competitive we want to achieve statistical sensitivity $\sigma(d_{\mathrm{n}}) = 10^{-27}e$cm within 400 calendar days $\Rightarrow$ increase UCN density by two orders of magnitude!

Thank you for your attention!



How to observe an nEDM?

- Apply a magnetic field $\vec{B}$ and an electric field $\vec{E}$ $\uparrow\uparrow$ or $\uparrow\downarrow$



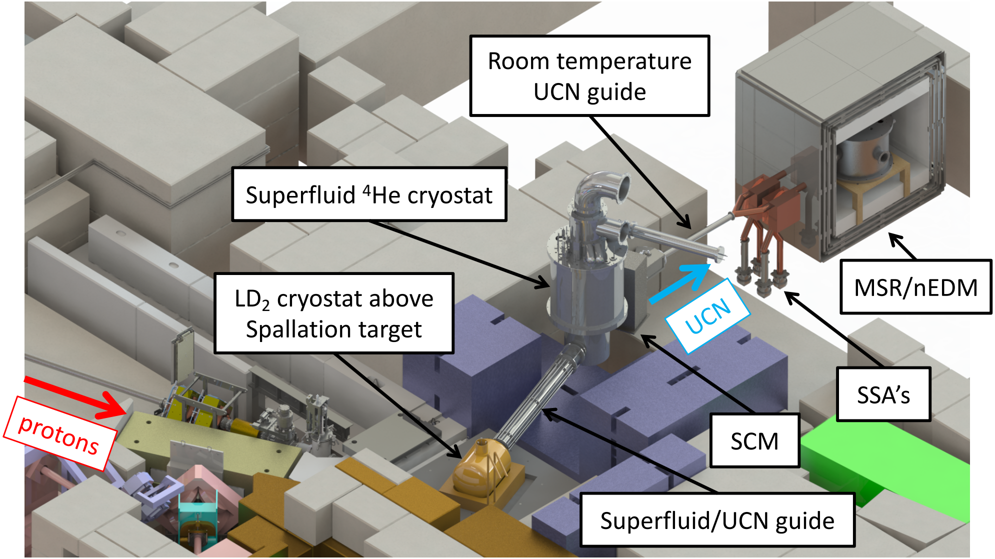
$$h f_{\mathrm{n}} = 2\mu_{\mathrm{n}} B \pm 2 d_{\mathrm{n}} E$$

- Extract nEDM d_{n} from *the difference* of Larmor precession frequencies in $\uparrow\uparrow$ or $\uparrow\downarrow$ fields:

$$d_{\mathrm{n}} = \frac{h\left(f_{\mathrm{n}}^{\uparrow\uparrow} - f_{\mathrm{n}}^{\uparrow\downarrow}\right) - \mu_{\mathrm{n}}\left(B^{\uparrow\uparrow} - B^{\uparrow\downarrow}\right)}{2\left(E^{\uparrow\uparrow} + E^{\uparrow\downarrow}\right)}$$

- Ingredients: stable & homegeneous $\vec{B}$, large $\vec{E}$, many neutrons!
- Tool of choice are ultracold neutrons $\rightarrow$ those allow observation times of $\mathcal{O}(100\,\mathrm{s})$

Experimental layout Phase 2



Experimental layout Phase 2