Ultracold Neutron Sources for Fundamental Physics — Status at TRIUMF and Future Prospects

TRIUMF Science Week 2025

July 29, 2025

Takashi Higuchi[1,2] for the TUCAN collaboration

([1]KURNS, Kyoto Univ.. , [2]RCNP, Univ. Osaka)


TRIUMF
520 MeV Cyclotron
520 Million Electron Volts Cyclotron
TRIUMF
TUCAN

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TRIUMF Ultracold Advanced Neutron Collaboration

February 2025 collaboration meeting

TRIUMF
SFU SIMON FRASER UNIVERSITY
UBC THE UNIVERSITY OF BRITISH COLUMBIA
UNBC UNIVERSITY OF NORTHERN BRITISH COLUMBIA
UNIVERSITY OF SASKATCHEWAN
University of Manitoba
THE UNIVERSITY OF WINNIPEG
KEK
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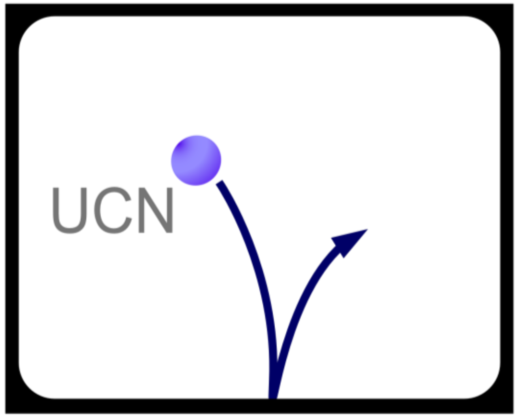
Outline

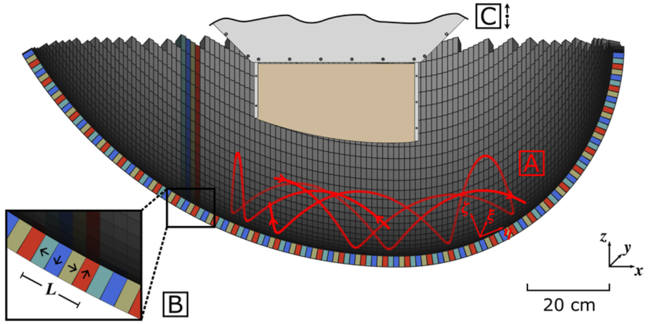
- Ultracold neutrons (UCNs)
- The TRIUMF Ultracold Advanced Neutron Source
- Recent progress and upcoming developments
- Future prospects

Ultracold Neutrons (UCNs)

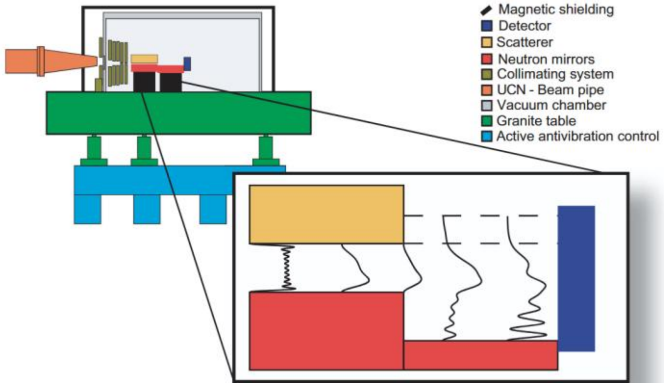
- Kinetic energies ≲ 300 neV (v ≲ 8 m/s, λ ≳ 50 nm)
  - Neutron-nucleus potential (Fermi potential): 245 neV for ^{nat}Ni
  - Can be stored in a material vessel for O(100) s
- Unique probe sensitive to all fundamental interactions
  - Magnetic: 60 neV/T
  - Gravitational: 102 neV/m
  - Strong: Fermi potential O(10-100) neV
  - Weak: β decay
- Important roles in particle physics
  - Neutron lifetime
  - Gravitational & quantum interference



$$\tau_n = 877.75 \pm 0.28_{sta}\,{}^{+0.11}_{-0.16}{}^{sys}\ \mathrm{s}$$



F. M. Gonzalez et al., Phys. Rev. Lett. **127**, 162501 (2021)

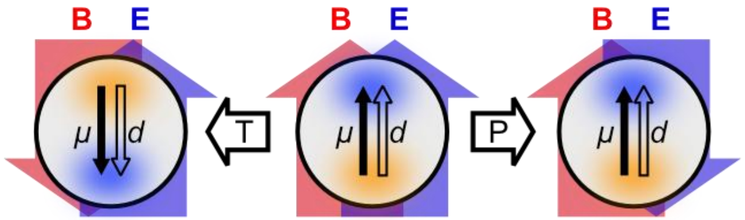


T. Jenke et al., Nucl. Inst. Meth. A **611**, 318 (2009)

Neutron Electric Dipole Moment (nEDM)

- Finite nEDM implies time-reversal (T) symmetry violation → CP violation assuming CPT symmetry
- Measured by spin resonance of free neutrons under electric and magnetic fields
- Use of UCNs essential to suppress systematic effect $\propto \vec{v} \times \vec{E}$
- Current limitation: UCN statistics

$$H = -\mu_n \vec{B} \cdot \frac{\vec{S}}{S} - d_n \vec{E} \cdot \frac{\vec{S}}{S}$$



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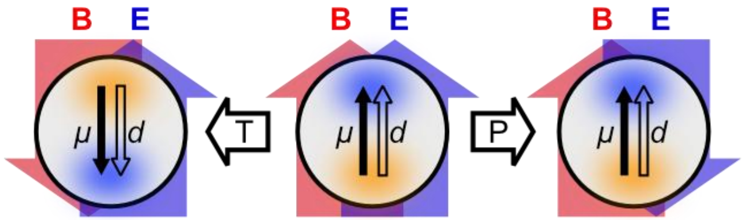
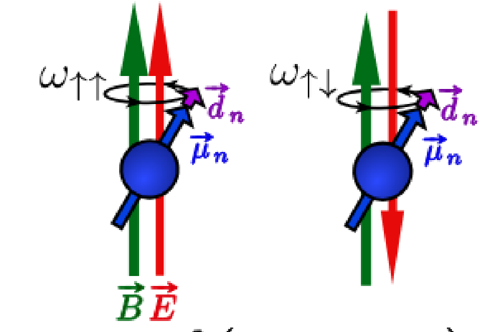
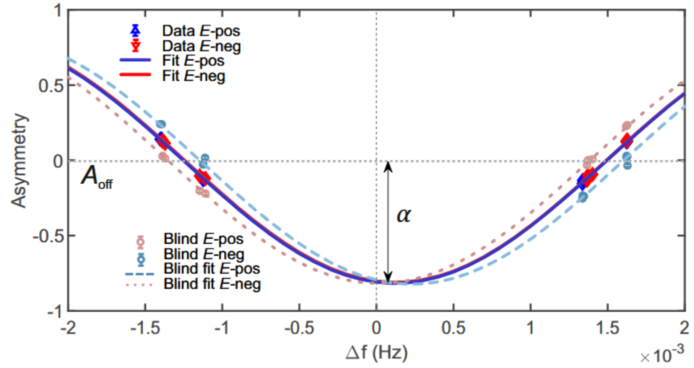




$$d_n = \frac{\hbar(\omega_{\uparrow\uparrow} - \omega_{\uparrow\downarrow})}{4|E|}$$



$$d_n = (0.0 \pm 1.1_{\text{stat.}} \pm 0.2_{\text{sys.}}) \times 10^{-26}\, e \cdot \text{cm}$$
$$\Rightarrow |d_n| < 1.8 \times 10^{-26}\, e \cdot \text{cm}\ (90\%\text{C.L.})$$

C. Abel et al., Phys. Rev. Lett. **124**, 081803 (2020).

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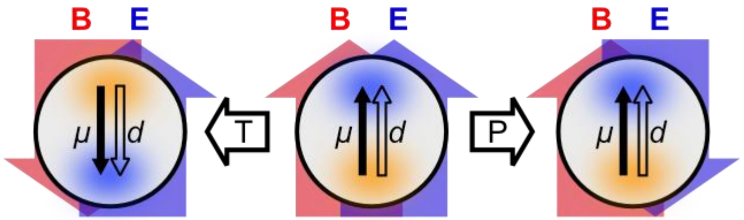

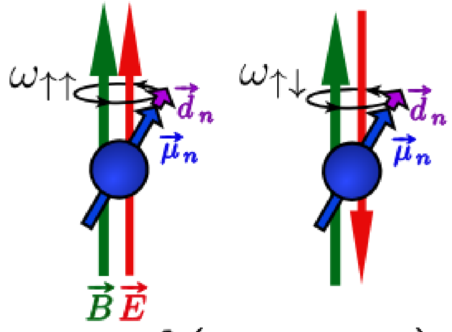

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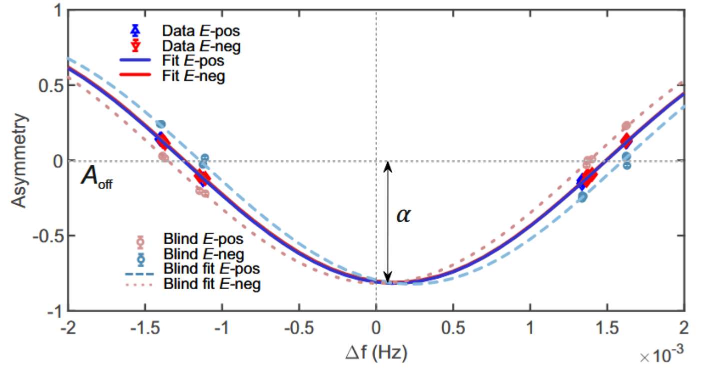

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C. Abel et al., Phys. Rev. Lett. **124**, 081803 (2020).

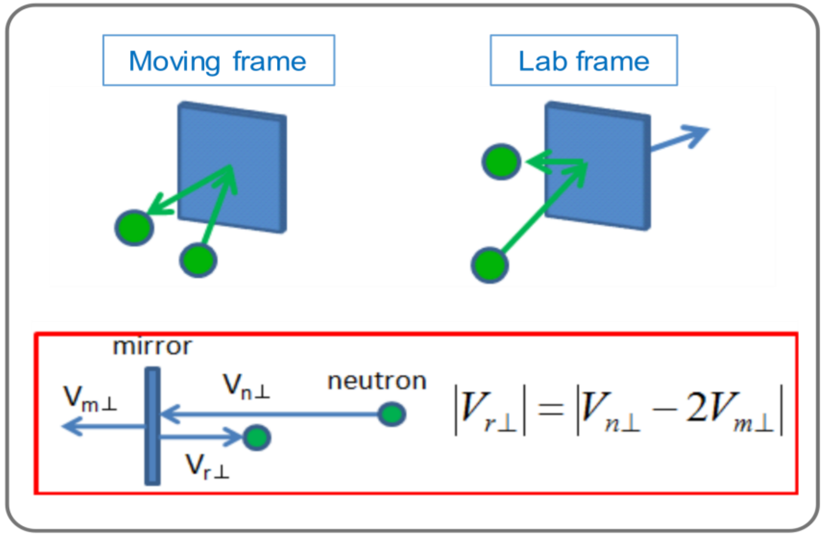
TUCAN
TRIUMF Ultra Cold Advanced Neutron Collaboration

- Developing an intense UCN source that enables x200 UCN statistics
- Aiming at 10^{-27} *e*cm nEDM measurement with 280 days of data taking

S. Sidhu et al., EPJ Web Conf.. **124**, 081803 (2020).

UCN production principles

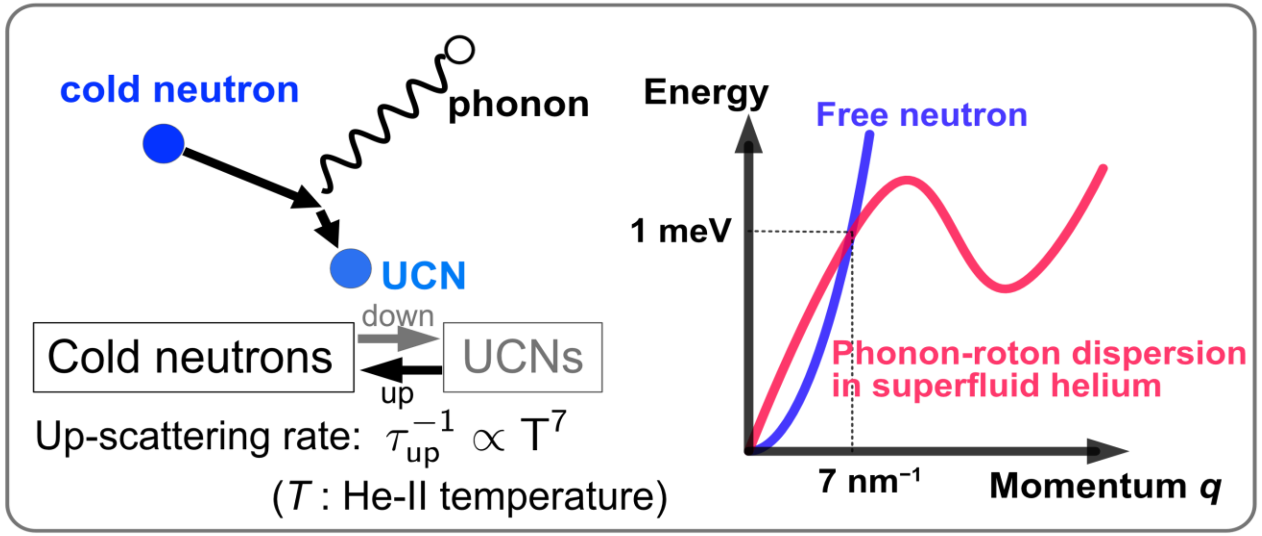
Mechanical deceleration
(ILL/PF2, J-PARC/BL05)



A. Steyerl et al,.Phys. Lett. A, **116**, 347 (1986)
S. Imajo et al.,Prog. The. Exp. Phys. **2016**, 013C02 (2016)

→ Limited UCN density

Super-thermal production
(PSI, LANL (sD_2), ILL/SuperSUN, TRIUMF (He-II))



R. Golub & J.M. Pendlebury, Phys Lett A 62, 337 (1977)

→ High density possible

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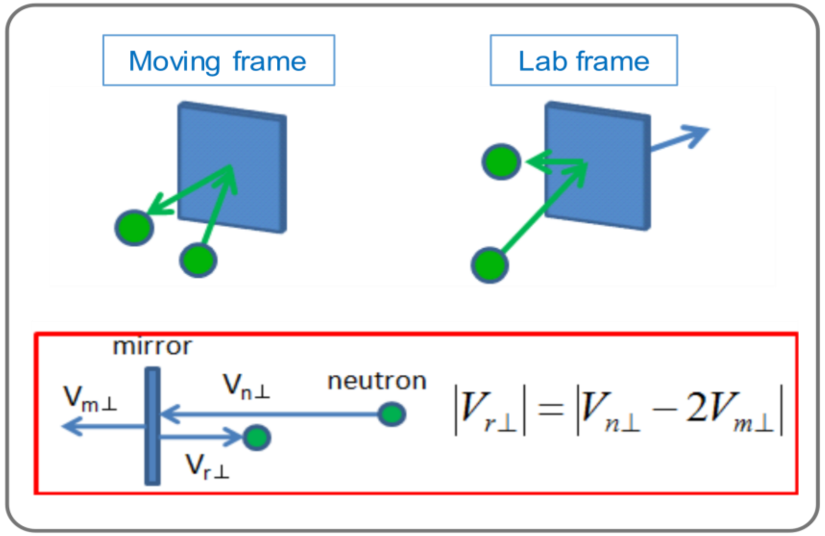

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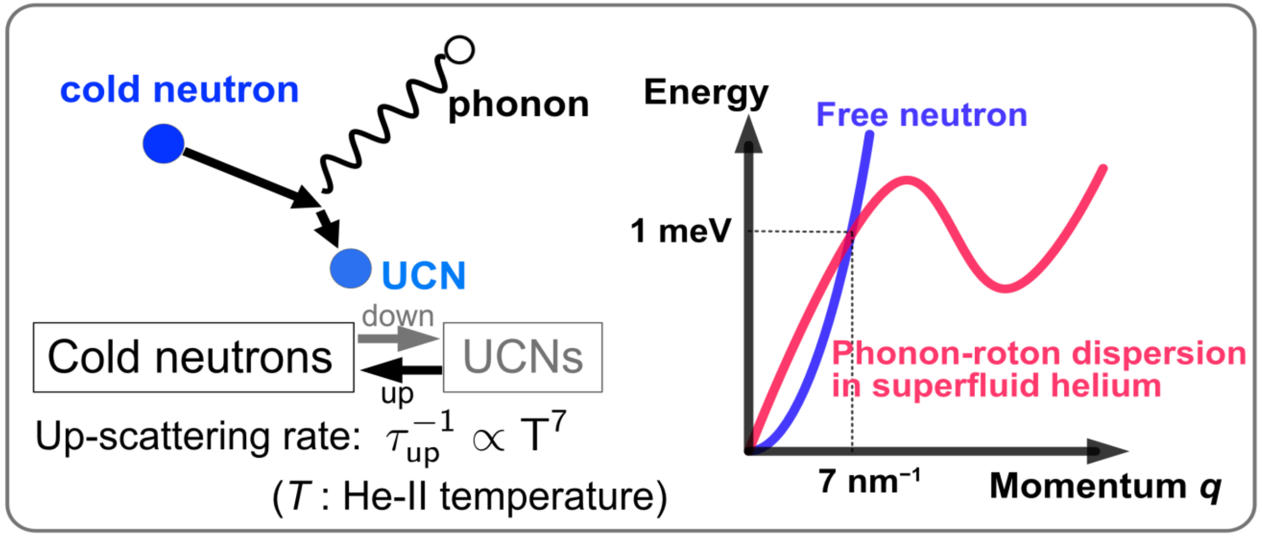

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→ High density possible

Keys:
- Cold neutron flux at ~1 meV
- He-II temperature ≲1 K (under beam heat load)

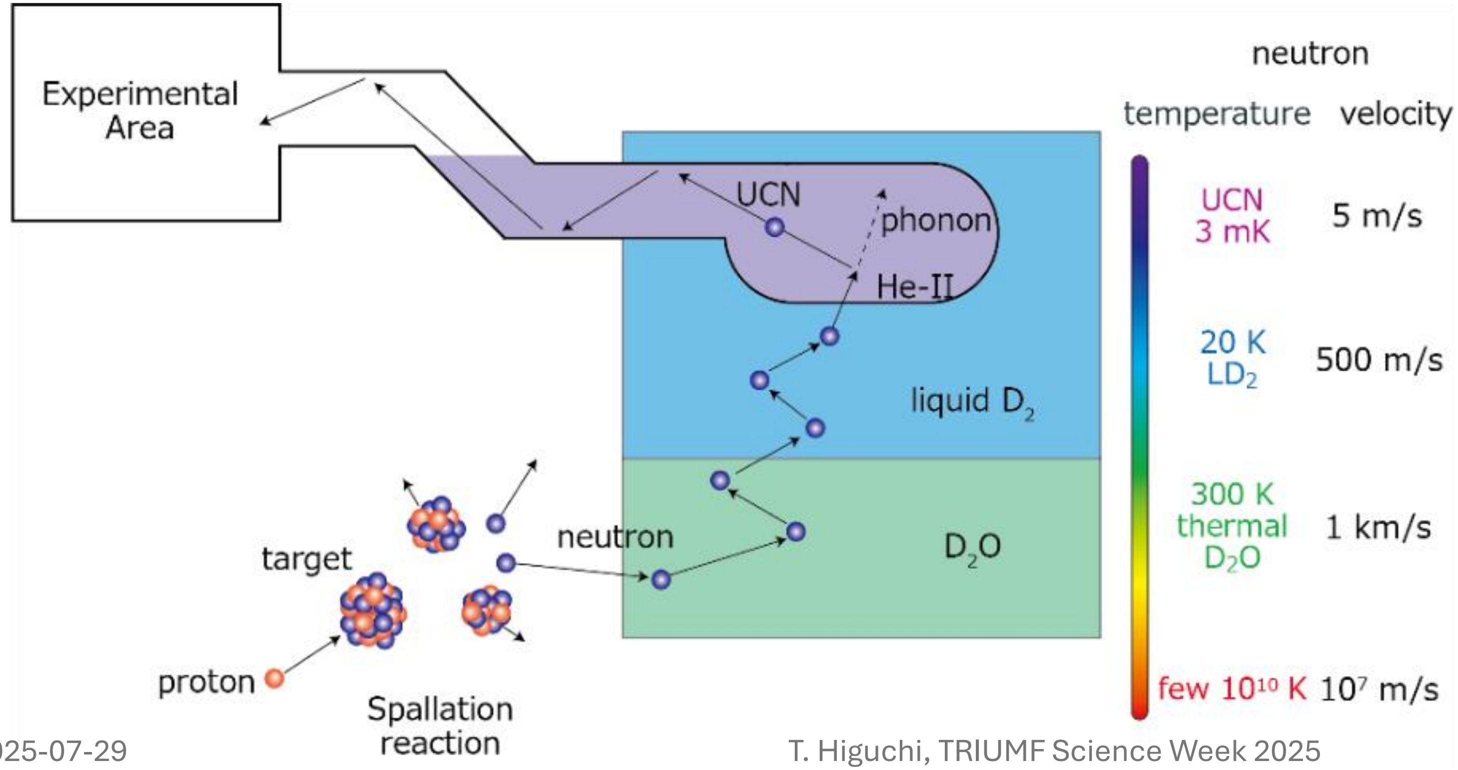
TUCAN UCN production scheme

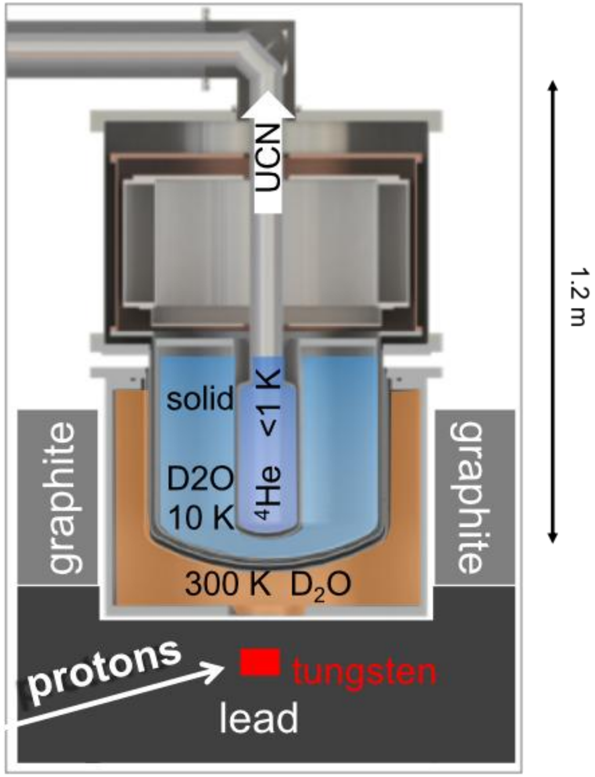
- Combined the He-II superthermal UCN production with an accelerator-driven neutron source
- Prototype source developed at the cyclotron facility of RCNP, Osaka, operated at TRIUMF (2017-2019)

  → First UCNs at TRIUMF! 2×10^4 UCN/s (@1 μA proton beam)
  → Source characterization, tests of UCN handling components
  → Limited by the cooling power of the He cryostat (0.3 W)

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

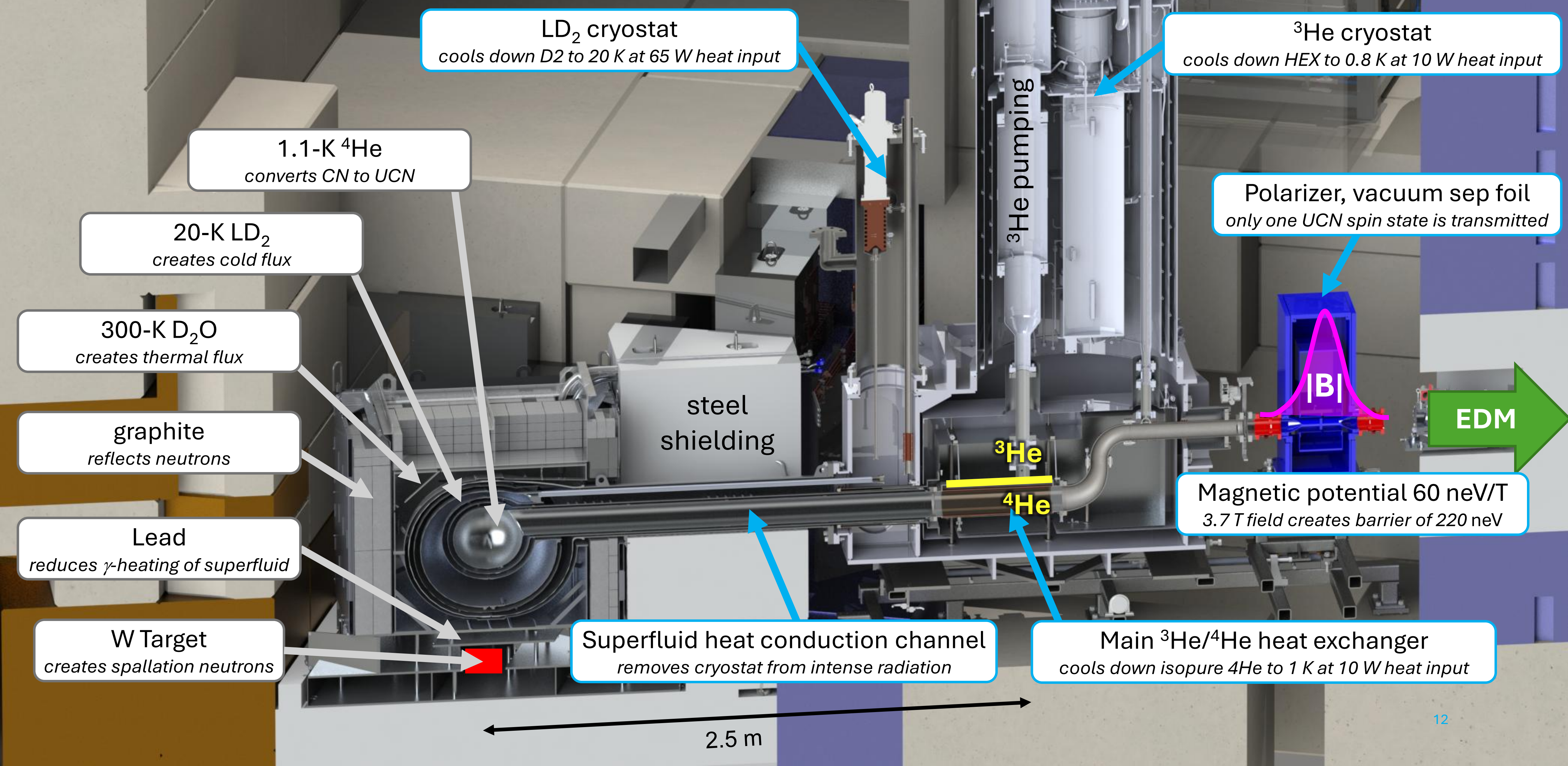
S. Ahmed et al., Phys. Rev. C **99**, 025503 (2019).
H. Akatsuka et al., NIM A 1049, 168106 (2023).





The TUCAN source

TUCAN
TRIUMF Ultra Cold Advanced Neutron source



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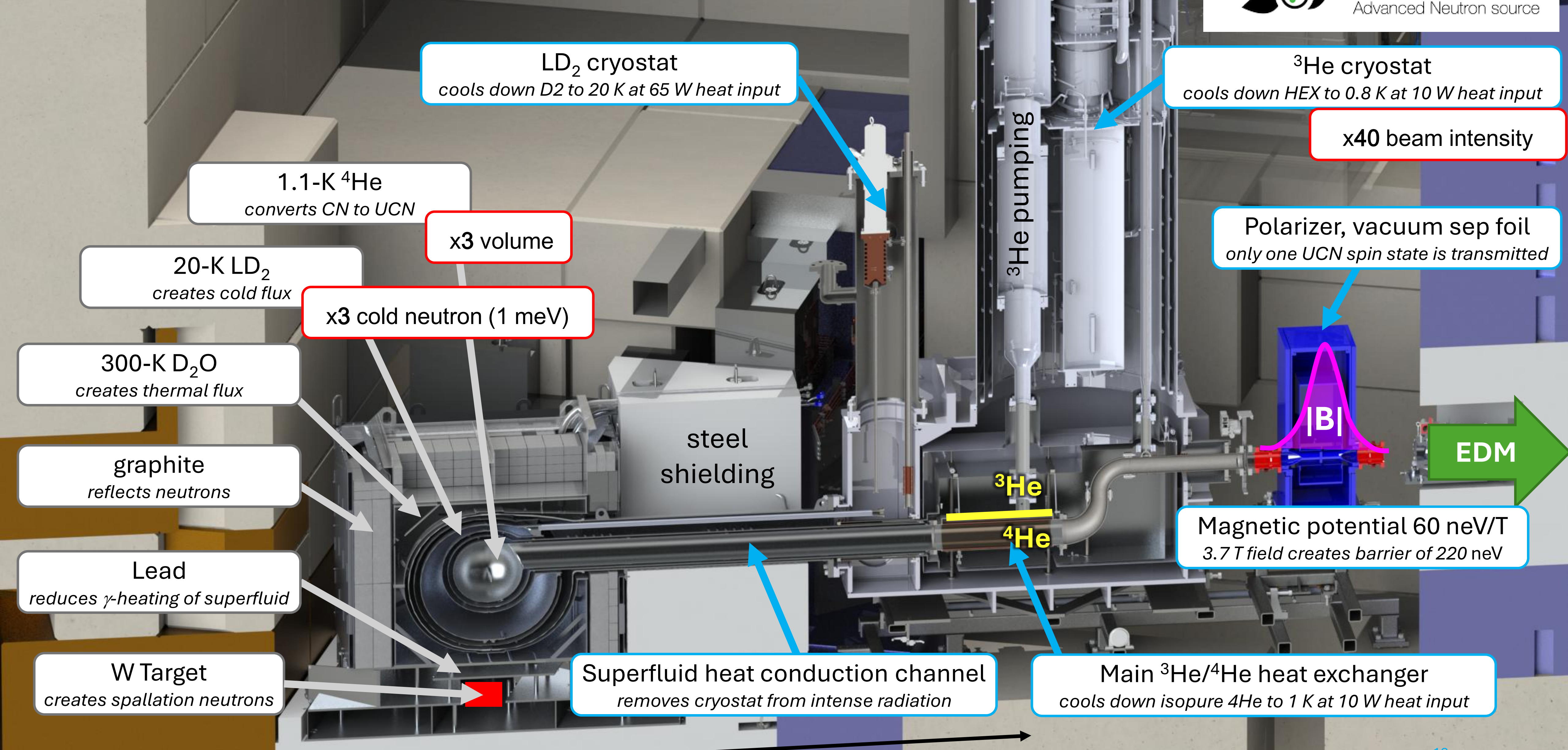


Expected yield: 1.4×10^7 UCN/s @ 40 μA (x500 of prototype)

TUCAN source timeline

2017 Prototype source installed at TRIUMF. **First UCN production at TRIUMF**

2018 Conceptual Design Report of the TUCAN source

2019 Last beamtime with the prototype source → decommissioned

2021 The helium cryostat shipped to TRIUMF

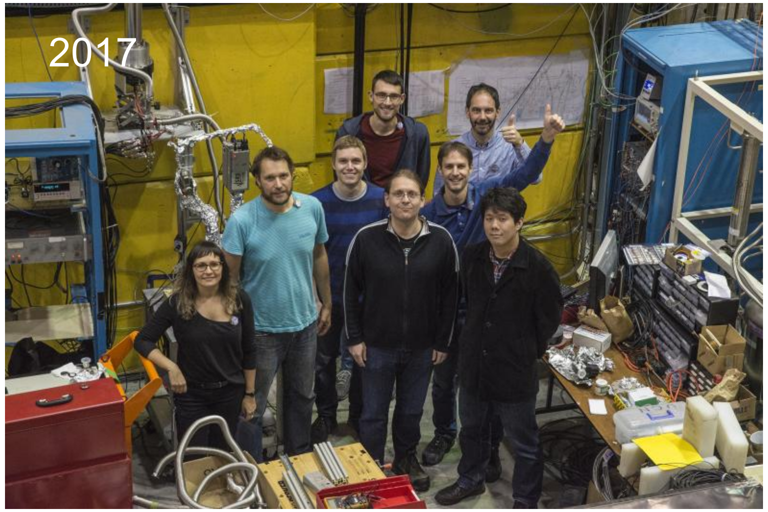
The innermost vessel of the production volume tested at LANL

2023 Started manufacturing the rest of the production volume vessels

2024 Major manufacturing completed (apart from the LD_2 cryostat)

First attempt of UCN production with the TUCAN source

2025.06 First UCN production from the TUCAN source



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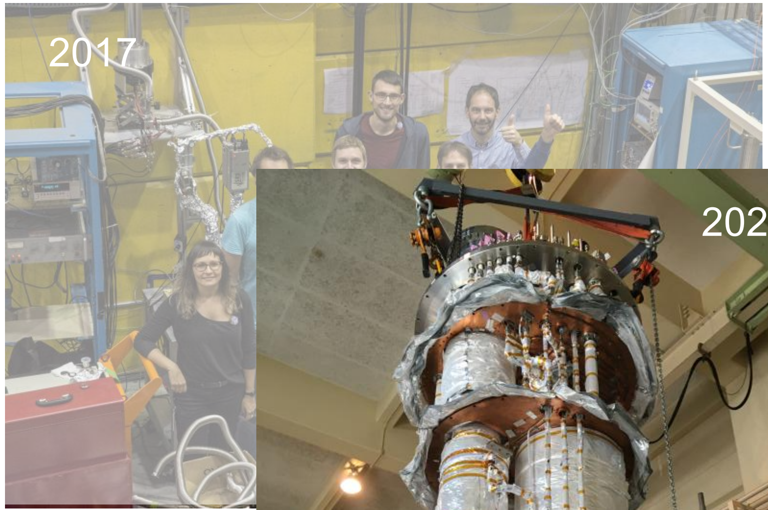

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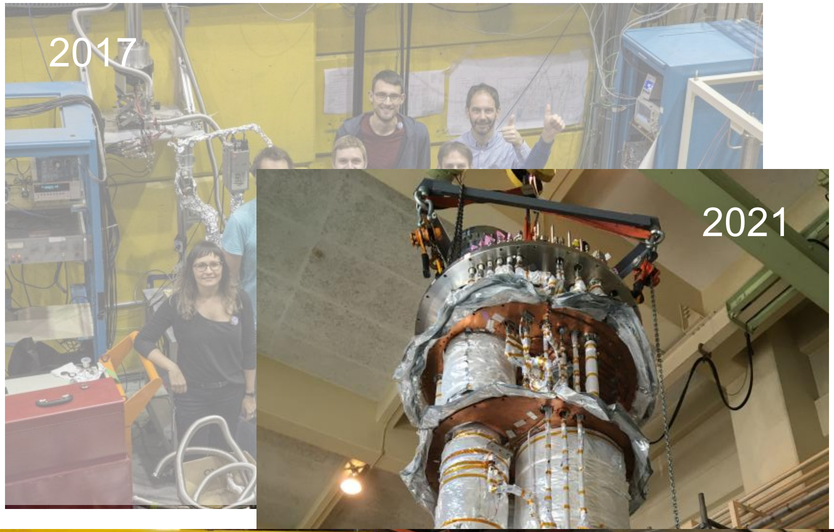

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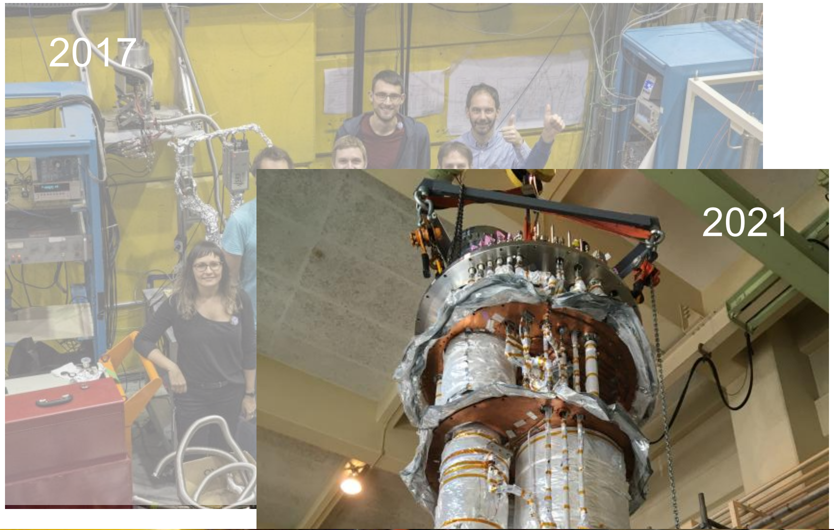

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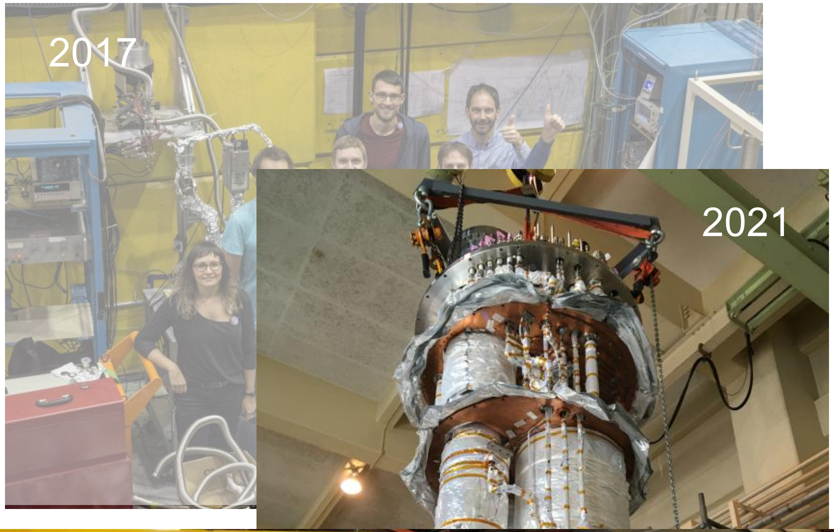
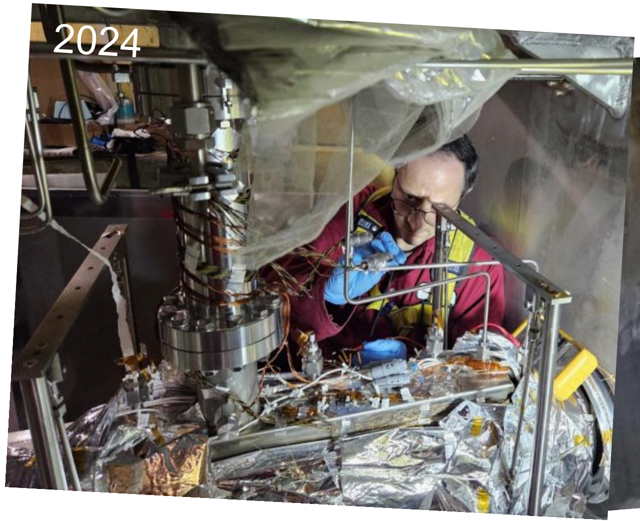
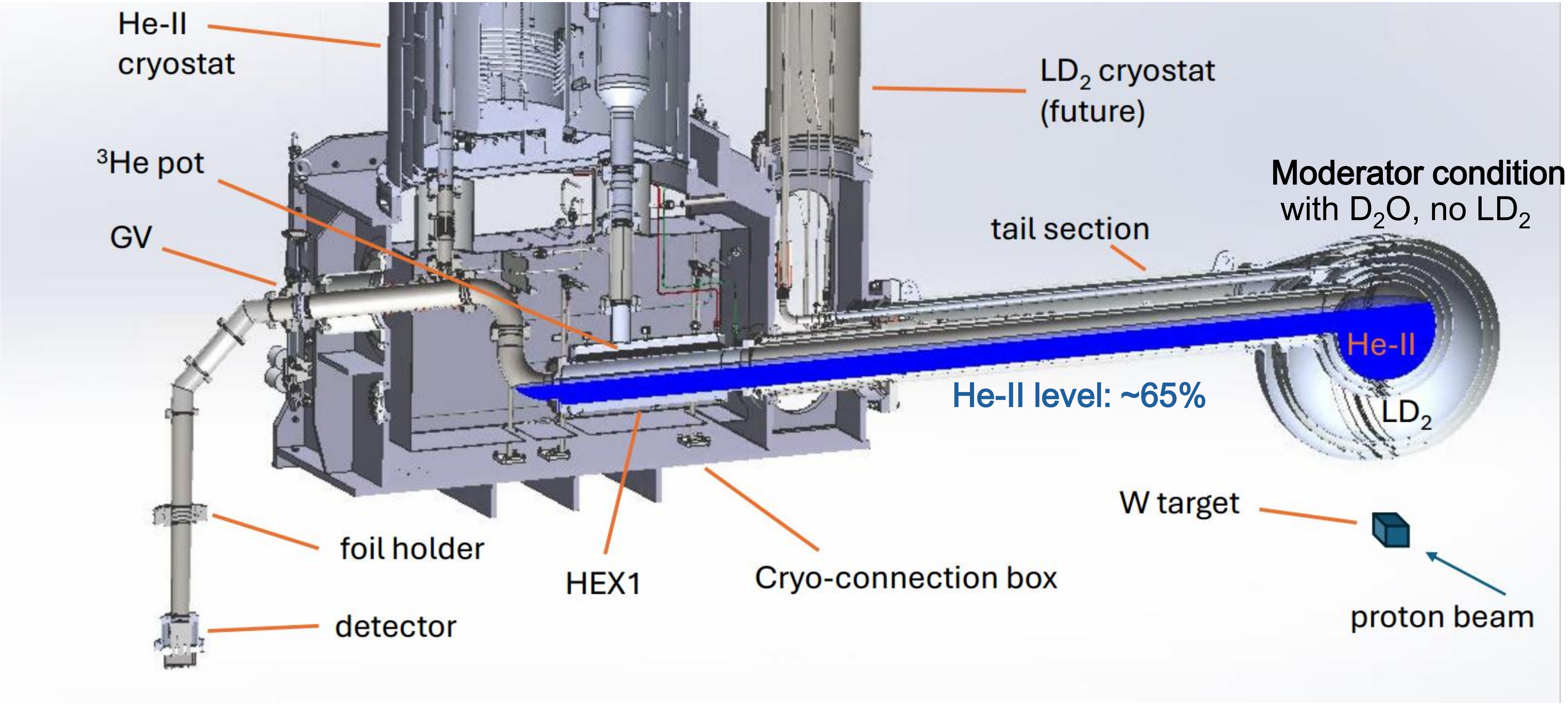




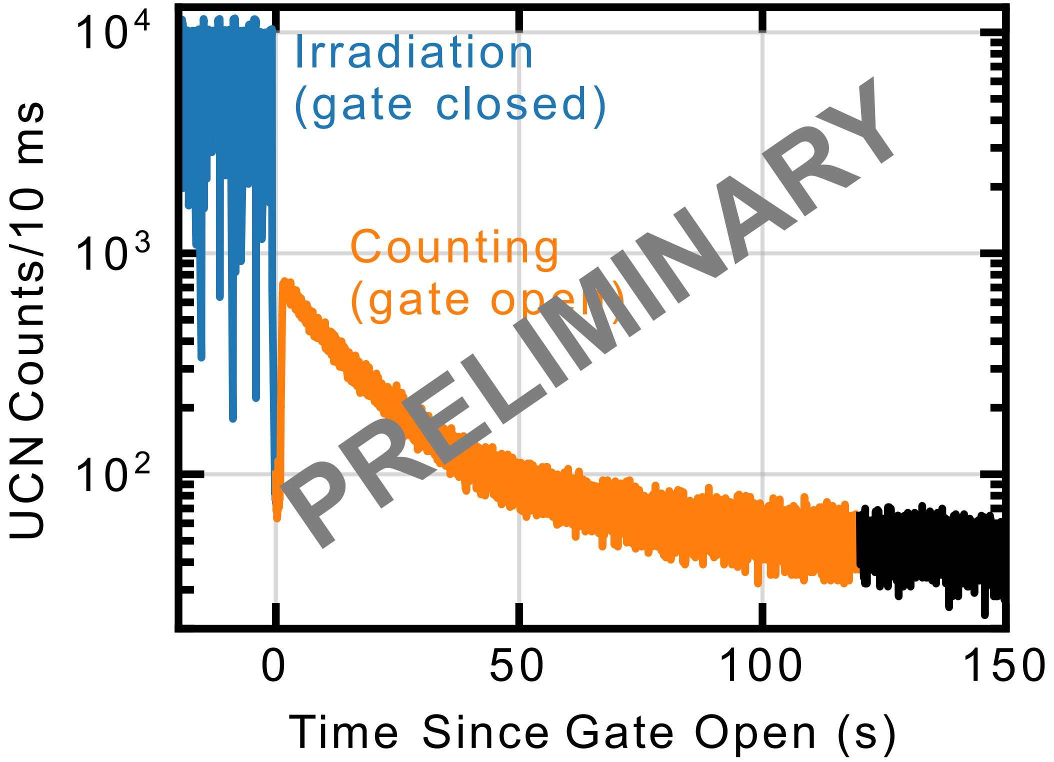
Experiment in June 2025



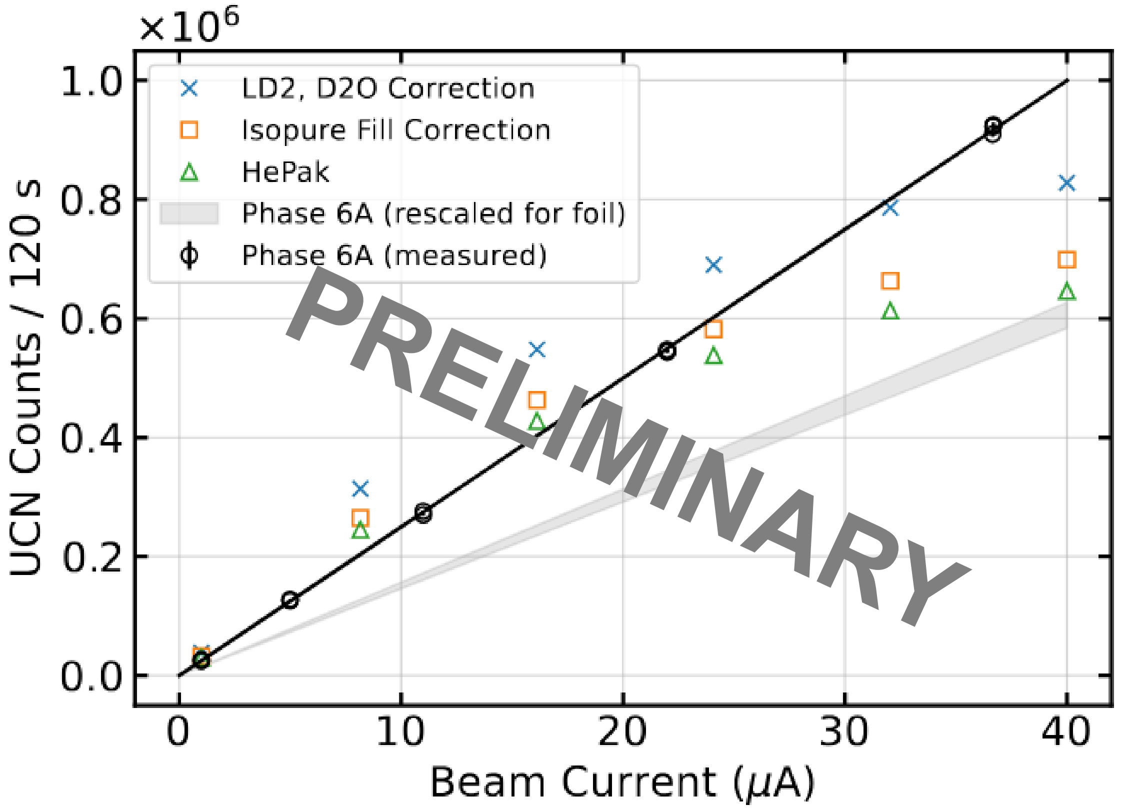
Experiment in June 2025

- **June 13, 2025: First UCN production with the TUCAN source**
- Characterized the UCN yields with different proton beam current (1-36 μA)

60 s irradiation / 120 s counting (36 μA)

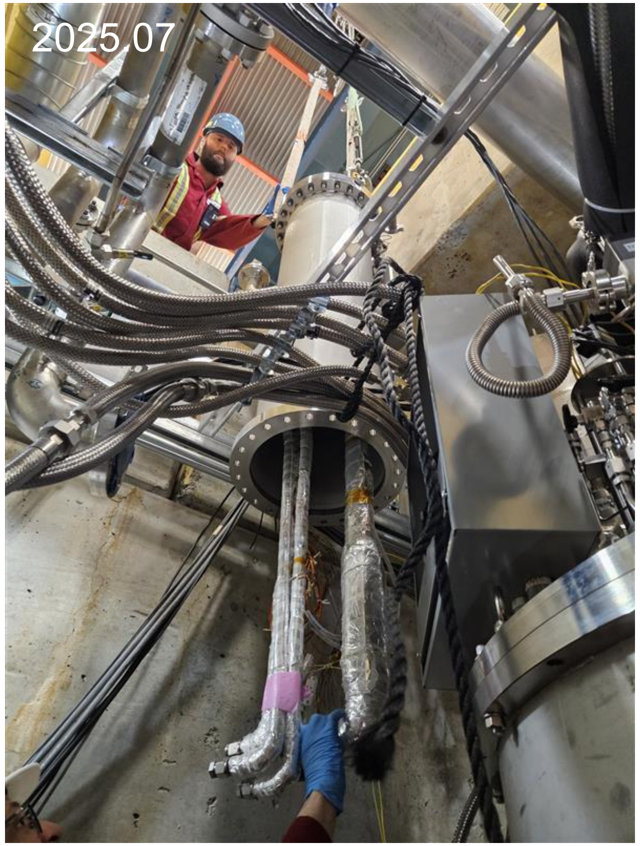


→ About 9x10⁵ UCNs detected



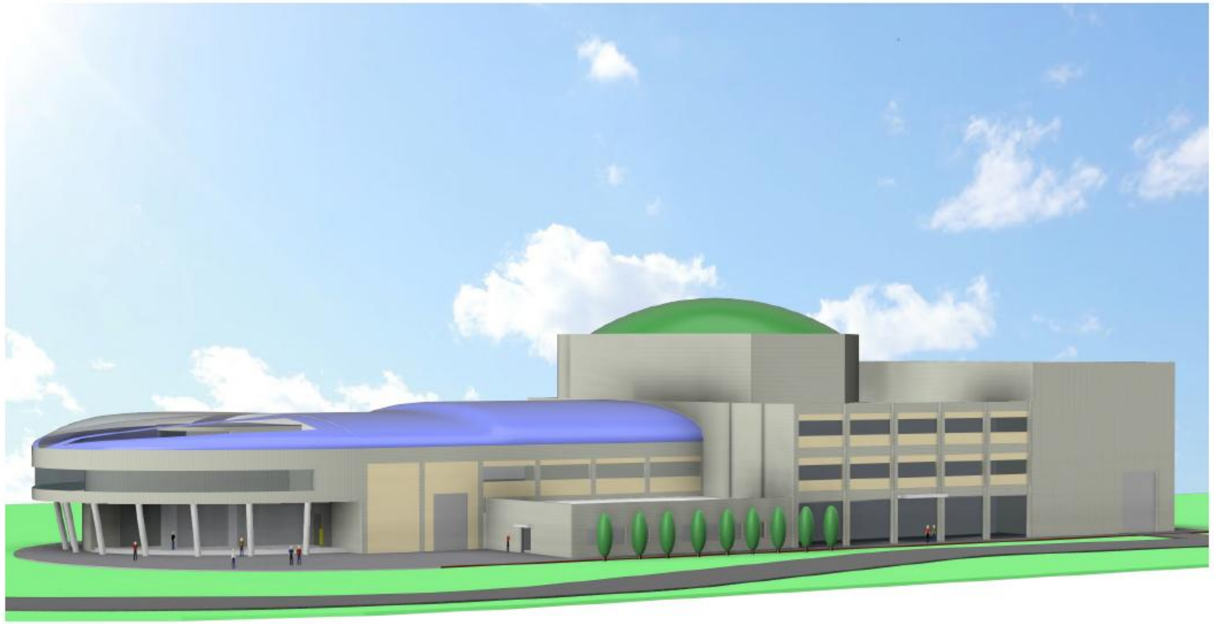
Next steps

- Source commissioning with the LD_2 system
  - Operation of the full TUCAN source (x30 in UCN yield)
- Extraction of UCN out from the shielding
- UCN experiments:
  - Storage lifetime measurements
  - Spectrum characterization
  - Guide UCNs into the Magnetically Shielded Room
  - Polarization
  - ….
- 2027- Commissioning of the nEDM spectrometer

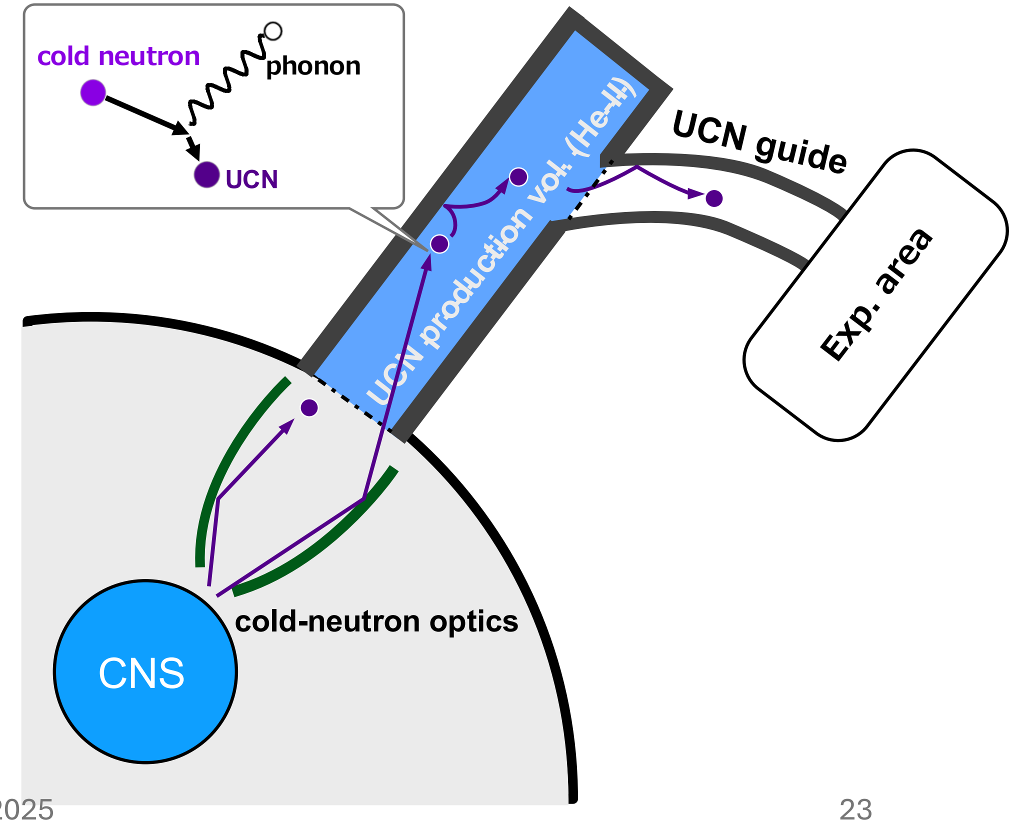


Future project: new research reactor in Japan

- Based on the expertise developed with TUCAN, a reactor-based He-II superthermal UCN source is proposed for a new research reactor in Fukui, Japan (operational in 10-15 years)
- Uniqueness: dedicated upstream neutron optics optimized for the UCN source



Other proposals: e^+ source, ν detectors, …



Summary

- The TUCAN source has been successful operated without the LD_2 moderator
- The full source with the LD_2 system is the next major step
- Proceeding to experiments with extracted UCNs, commissioning of the nEDM spectrometer towards the nEDM measurement with a goal precision of 10^{-27} $e$cm

Postdoc position at KEK in call: https://inspirehep.net/jobs/2948313

Acknowledgements

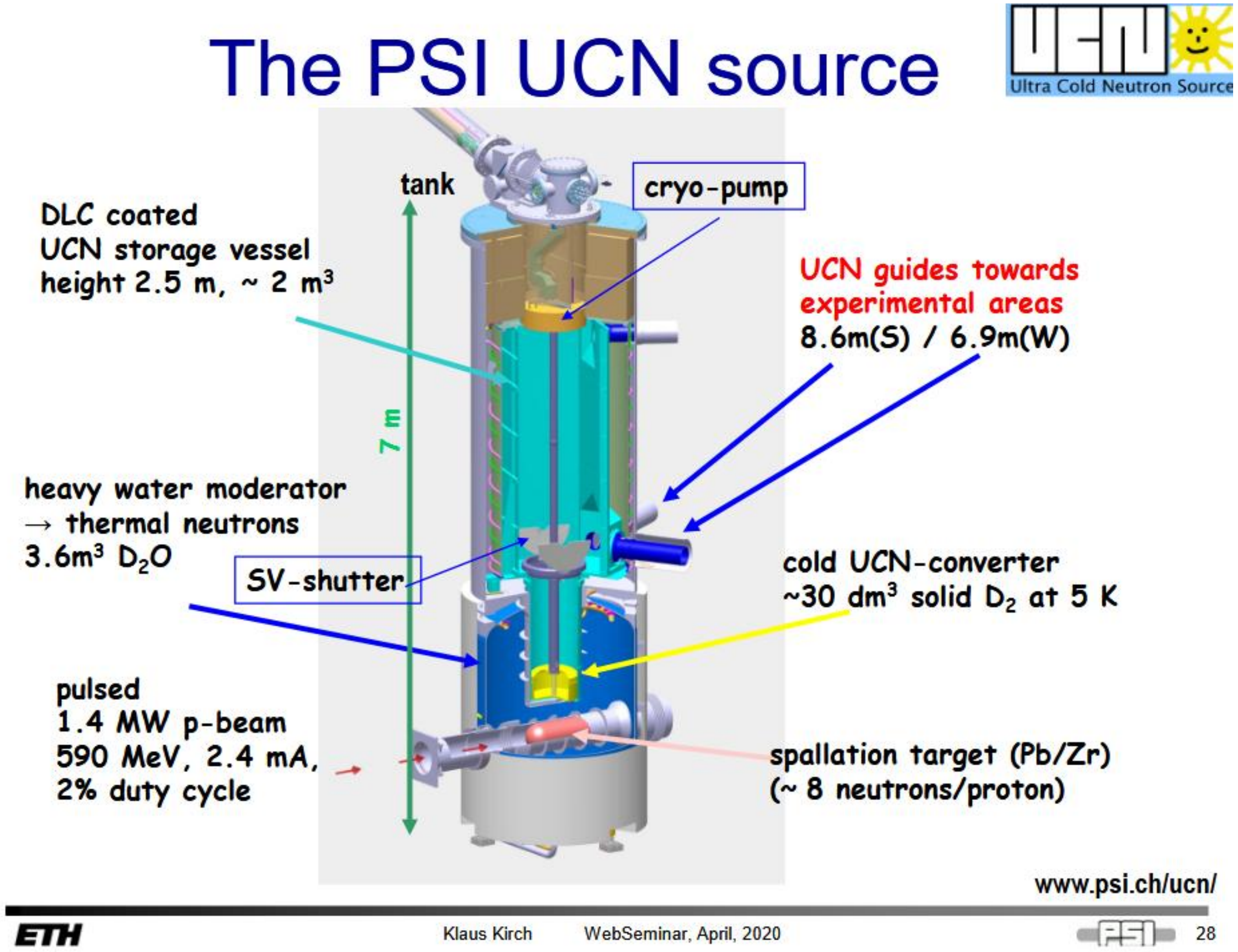
Thank you for your attention!

UCN convertor: sD_2 and He-II

Slide: Klaus Kirch

$$\rho_{\rm UCN} = \Phi_{\rm CN} R \tau_{\rm UCN}$$

	R (cm^{-1})	$\tau_{\rm UCN}$ (s)
sD_2	10^{-8}	0.03–0.1
He-II	$1–3 \times 10^{-9}$	10–1000



Experimental searches (historical development)

- Limitation of the cold-neutron beam method: $\boldsymbol{B}_m \propto \boldsymbol{v} \times \boldsymbol{E}$ systematics
  →**overcome by ultracold neutrons**

Neutron velocity

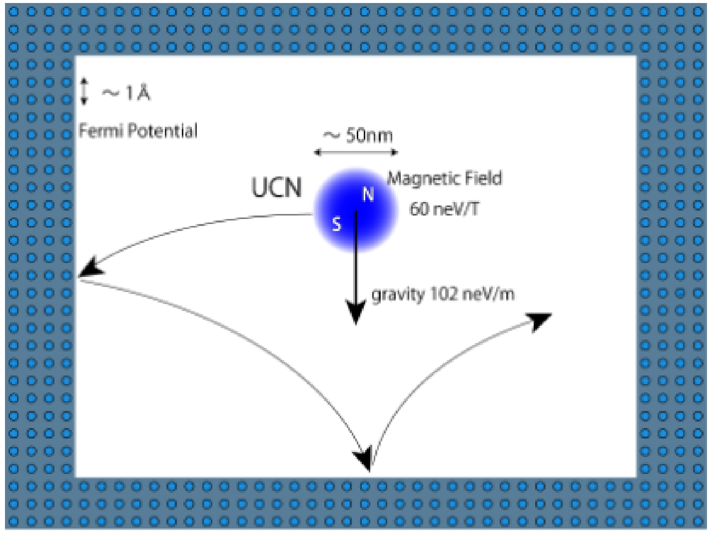
Cold neutrons: v=100–1000 m/s

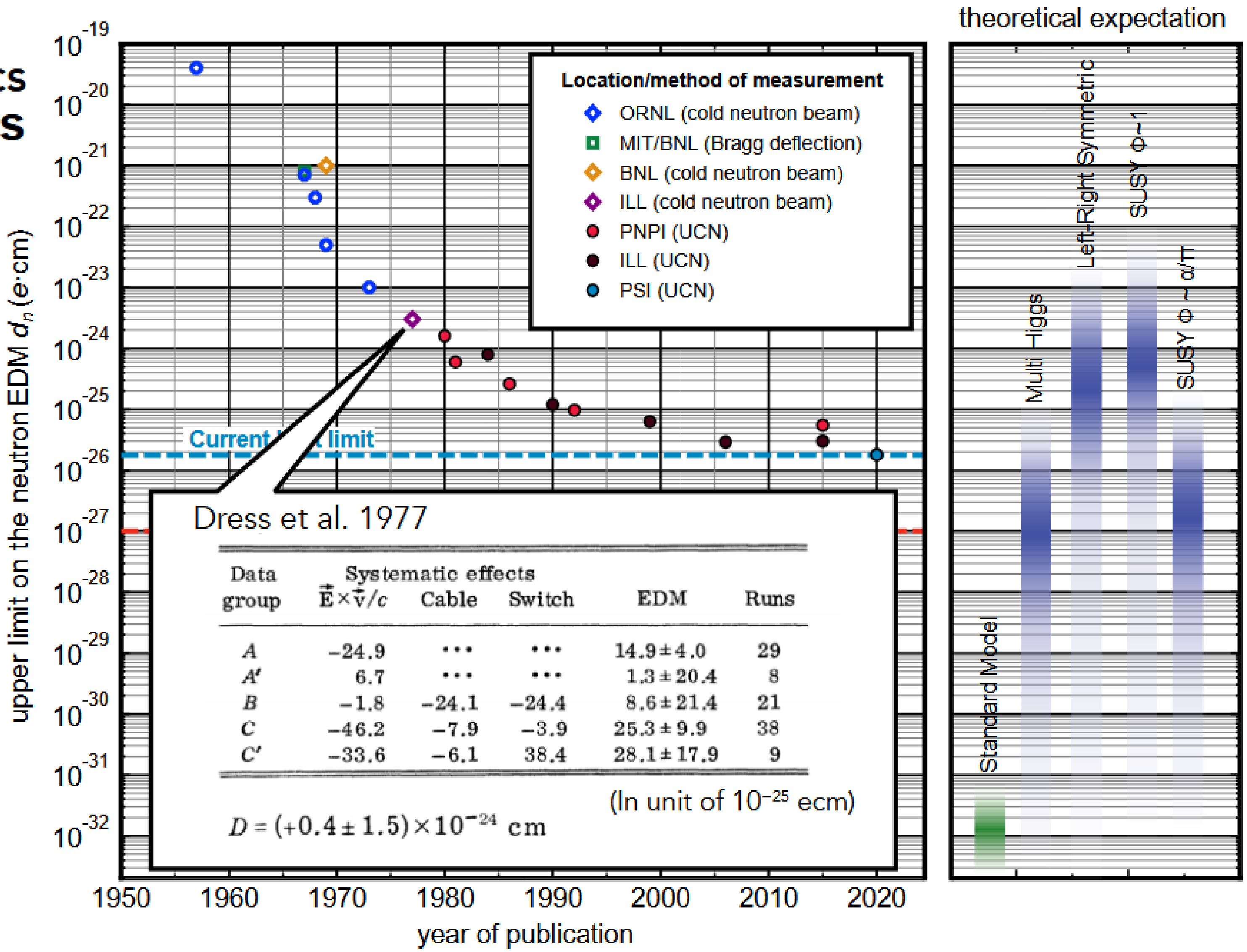
⇒ UCN: v ≲ 10 m/s (K ≲ 300 neV)

Free precession time

Cold neutrons: 0.1–1.0 ms

⇒ UCN: 10–100 s





Data group	Systematic effects $\vec{E}\times\vec{v}/c$	Cable	Switch	EDM	Runs
A	−24.9	···	···	14.9±4.0	29
A′	6.7	···	···	1.3±20.4	8
B	−1.8	−24.1	−24.4	8.6±21.4	21
C	−46.2	−7.9	−3.9	25.3±9.9	38
C′	−33.6	−6.1	38.4	28.1±17.9	9

$D = (+0.4 \pm 1.5) \times 10^{-24}$ cm

J.M. Pendlebury & E. Hinds NIM A, **440** (2000), 471

T. Chupp et al., Rev. Mod. Phys., **91** (2019) 015001

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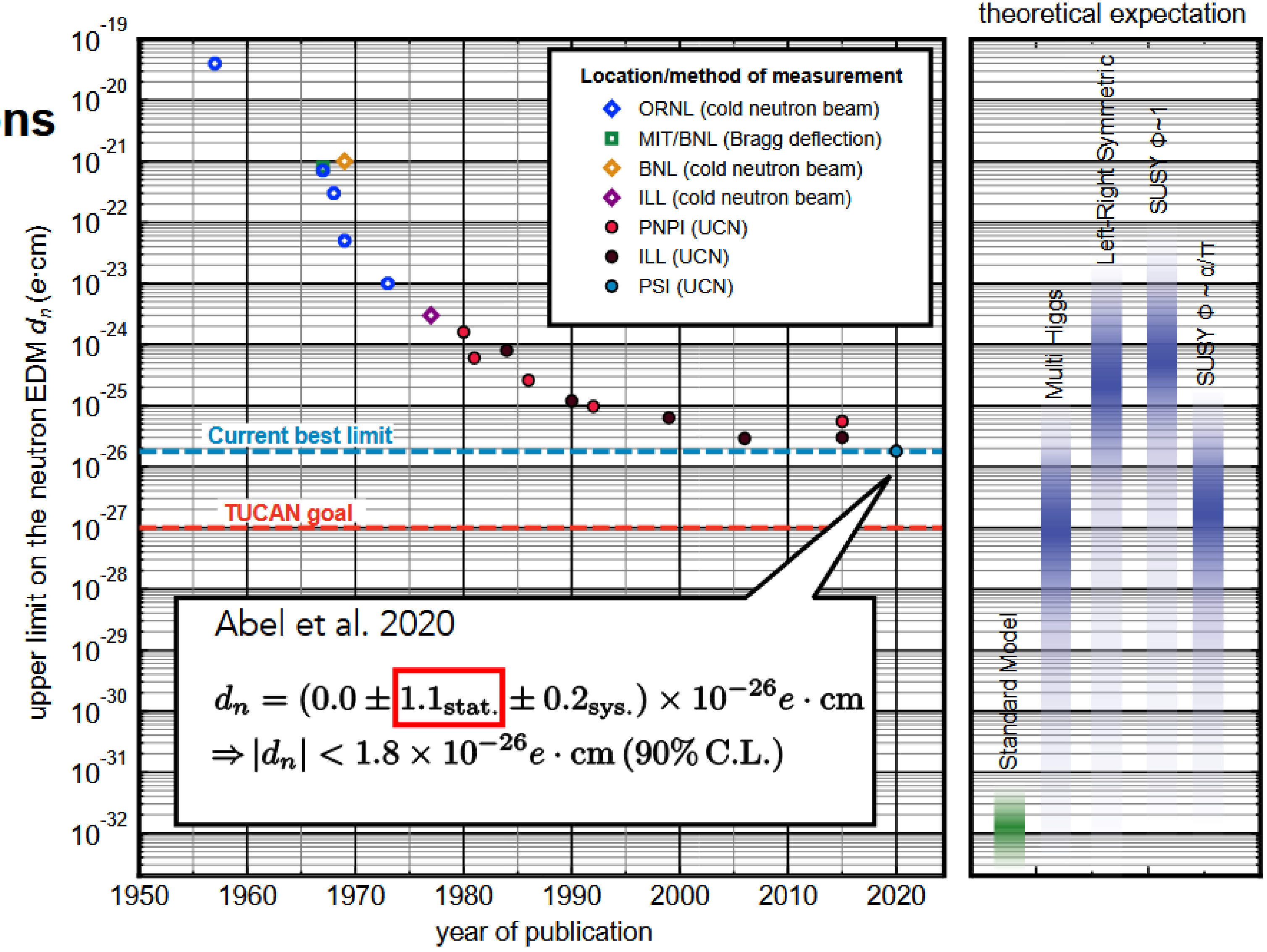
Cold neutrons: 0.1–1.0 ms
⇒ UCN: 10–100 s

- Limitation of the recent UCN measurements: **statistics**

The key for the next-generation:

Intense UCN source!



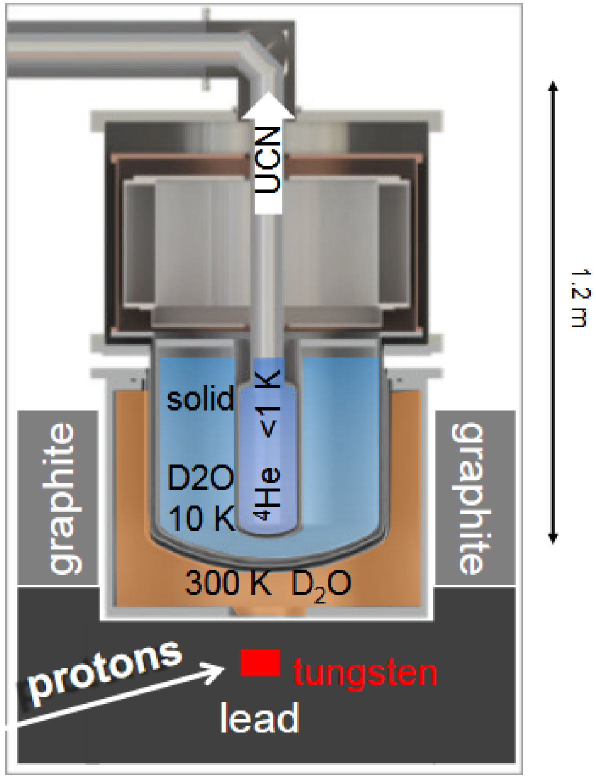
J.M. Pendlebury & E. Hinds NIM A, **440** (2000), 471
T. Chupp et al., Rev. Mod. Phys., **91** (2019) 015001

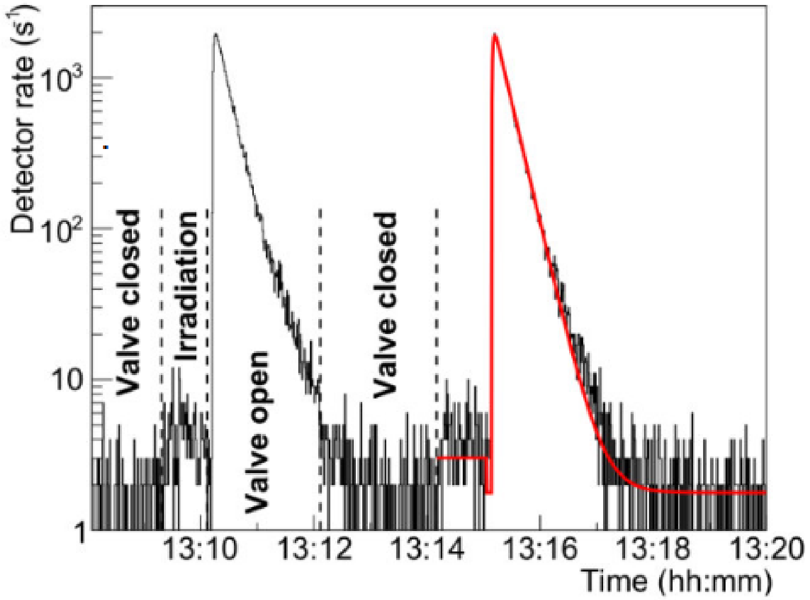
UCN production at TRIUMF in 2017

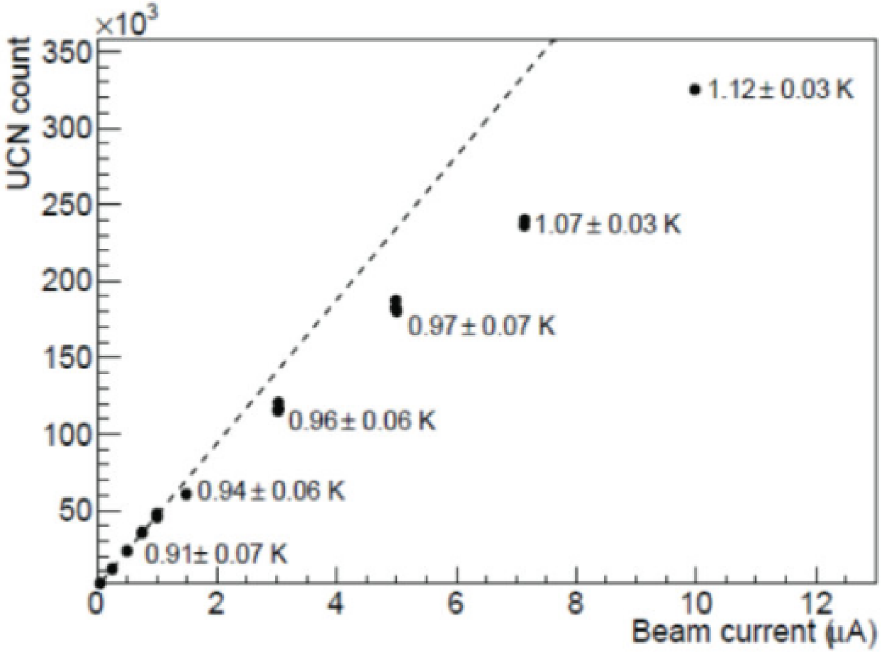
- First UCN production at TRIUMF with a prototype UCN source
- Major results

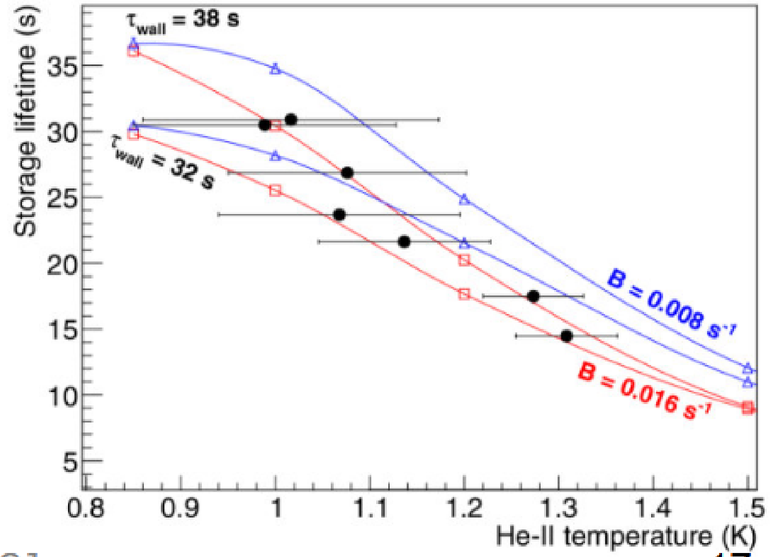
S. Ahmed et al., PRAB, **22** (2019)102401
S. Ahmed et al., PRC, **99** (2019) 025503

  - Successful UCN production:
    - 2×10^4 UCN/s (3.25×10^5 UCN/cycle) @ 1 μA proton beam current
  - Limited by cooling power of the helium cryostat
  - Characterized the scaling of the UCN lifetime: $\tau \propto T^{-7}$









Overview of the TUCAN apparatus