TUCAN

TRIUMF Ultra Cold
Advanced
Neutron source

TUCAN developments toward first UCN production and nEDM experiment

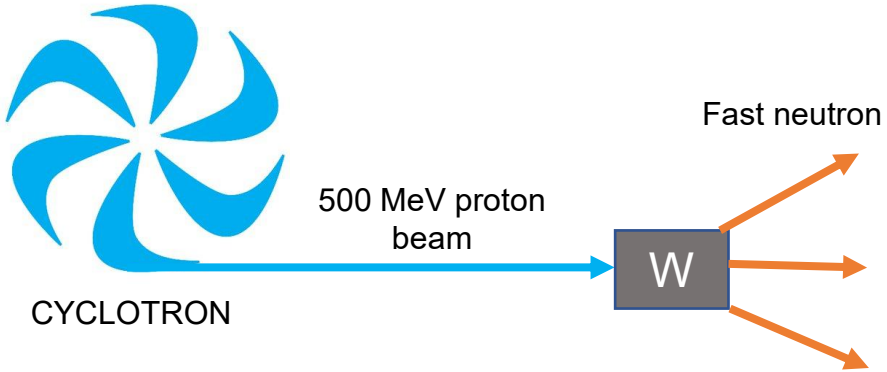
2025 CAP congress

Alexis Brossard
On behalf of the TUCAN collaboration

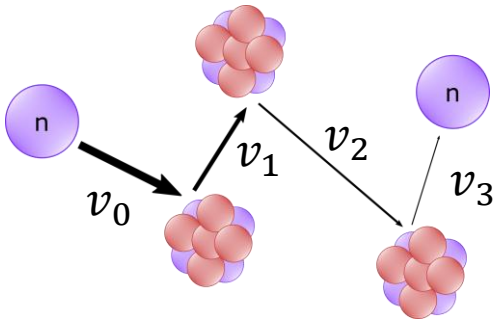
Ultracold Neutron

Neutron production, cooling and ultra-cooling:

- Spallation source:

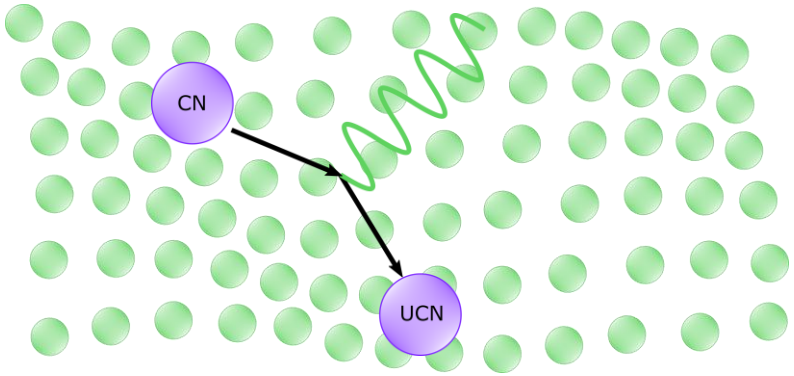


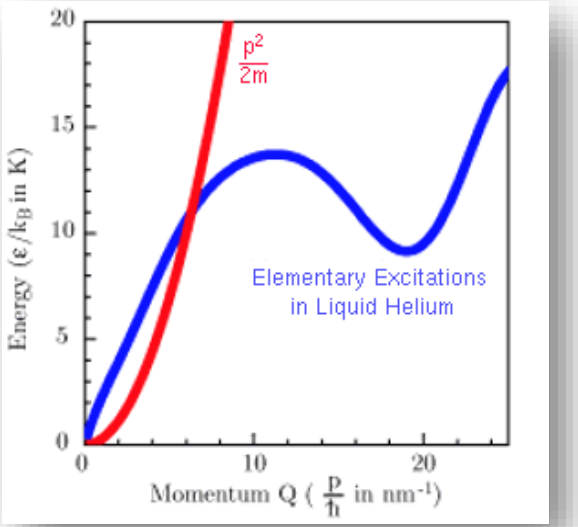
- Cooling with thermal moderator:



$$v_3 < v_2 < v_1 < v_0$$

- Phonon emission in superfluid He-4

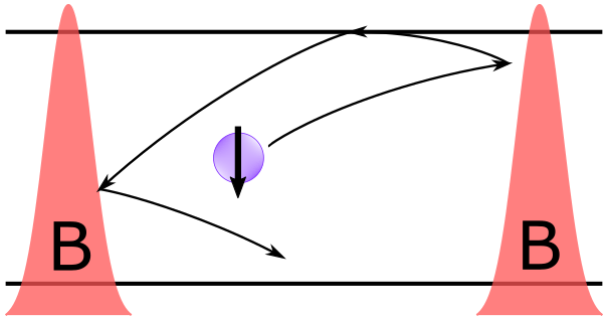




UCN confinement

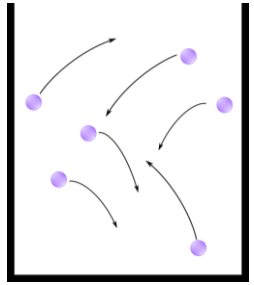
- Magnetic Field:

$$\mu_N = 60.3\ \frac{\mathrm{neV}}{\mathrm{T}}$$



- Gravity:

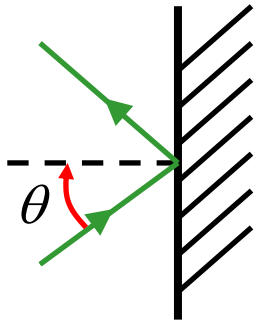
$$V_g = m_n g z = \left(102.5\ \frac{\mathrm{neV}}{\mathrm{m}}\right) z$$



- Strong force:

$$V(\vec{r}) = \frac{4\pi\hbar^2}{2m} \sum_i a_i \delta(\vec{r} - \vec{r}_i{}')$$

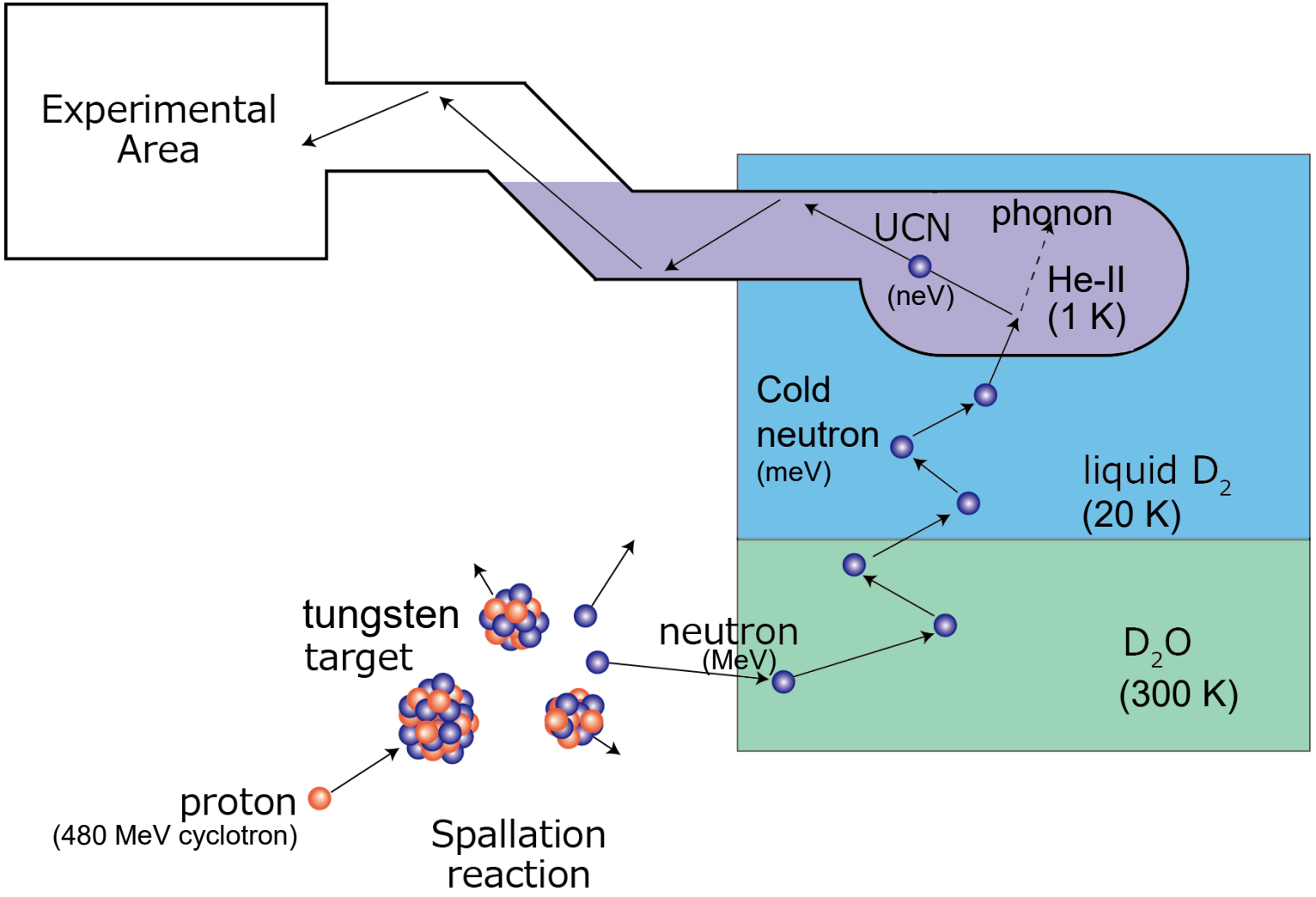
$$E_{kin} < V_F :$$



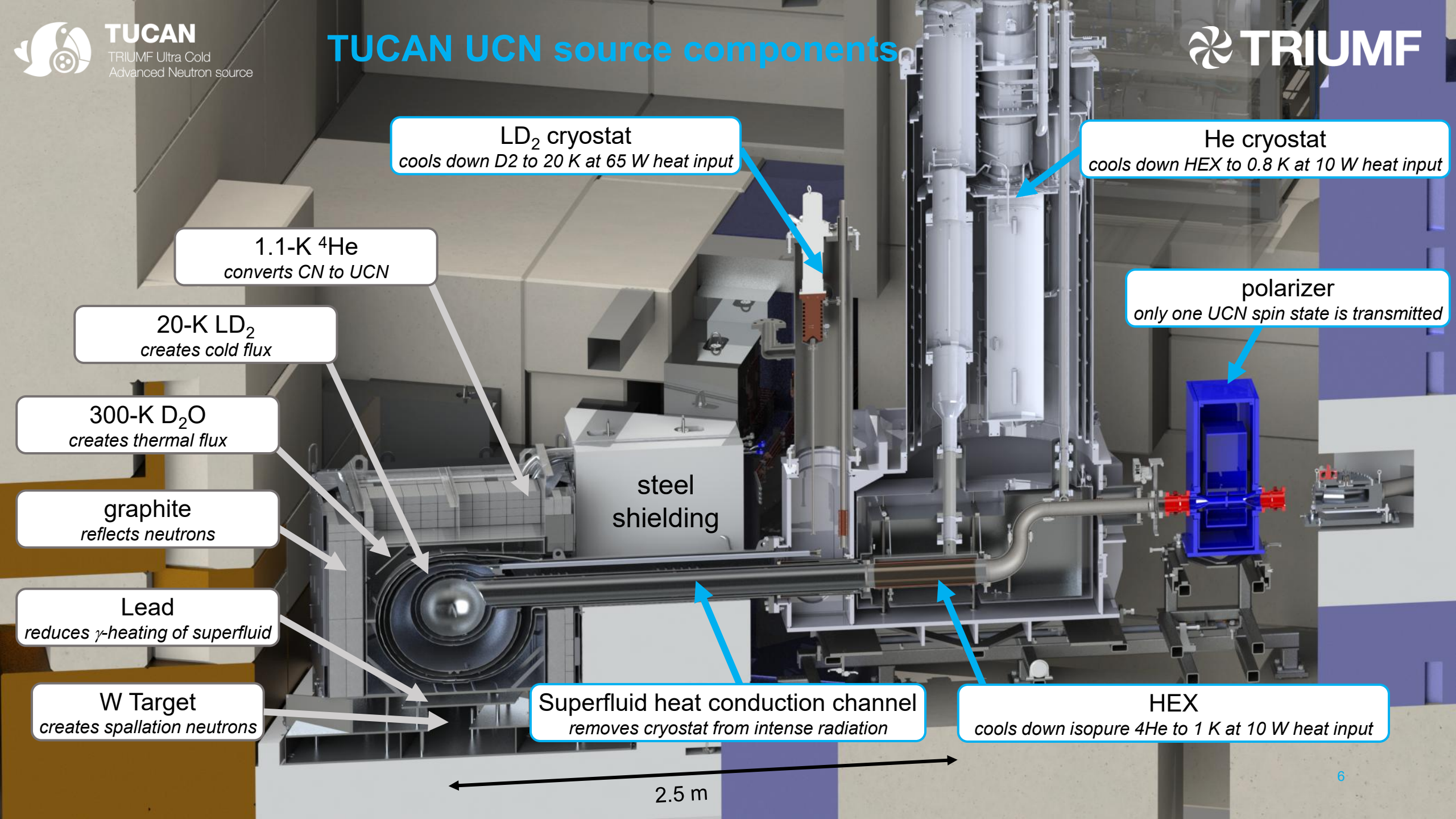
Material	V_F (neV)	v (m/s)
Al	54	3.2
^{58}Ni	350	8.2
Graphite	180	5.9
Stainless Steel	188	6
DLC	282	7.3

UCN can be stored

TUCAN method



TUCAN UCN source components

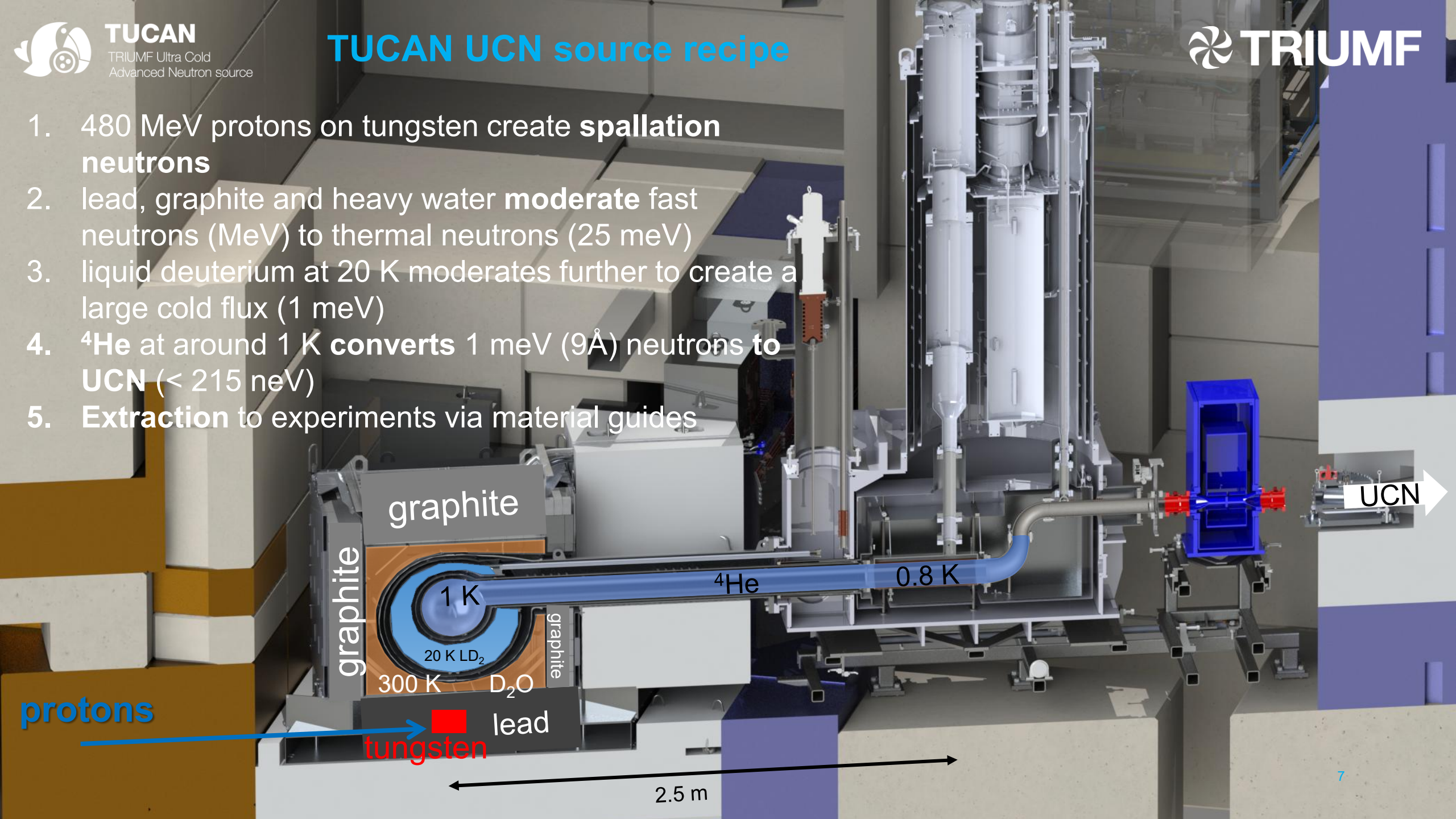


TUCAN
TRIUMF Ultra Cold Advanced Neutron source

TUCAN UCN source recipe

TRIUMF

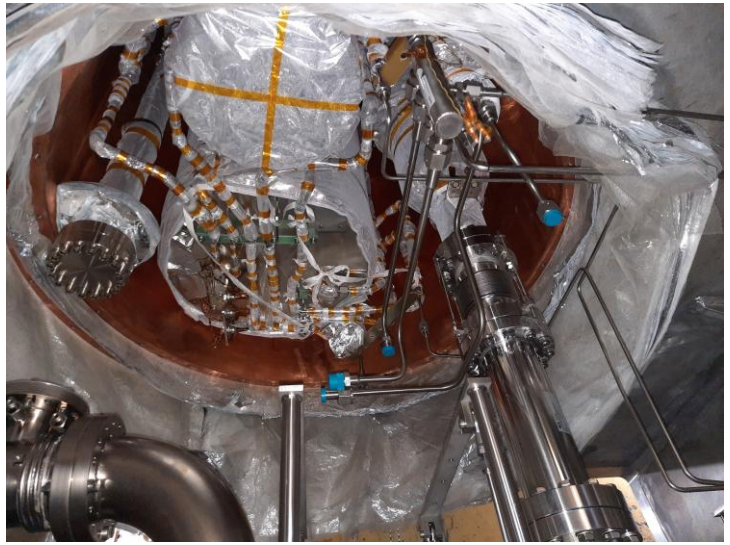
1. 480 MeV protons on tungsten create **spallation neutrons**
2. lead, graphite and heavy water **moderate** fast neutrons (MeV) to thermal neutrons (25 meV)
3. liquid deuterium at 20 K moderates further to create a large cold flux (1 meV)
4. **^{4}He** at around 1 K **converts** 1 meV (9Å) neutrons **to UCN** (< 215 neV)
5. **Extraction** to experiments via material guides

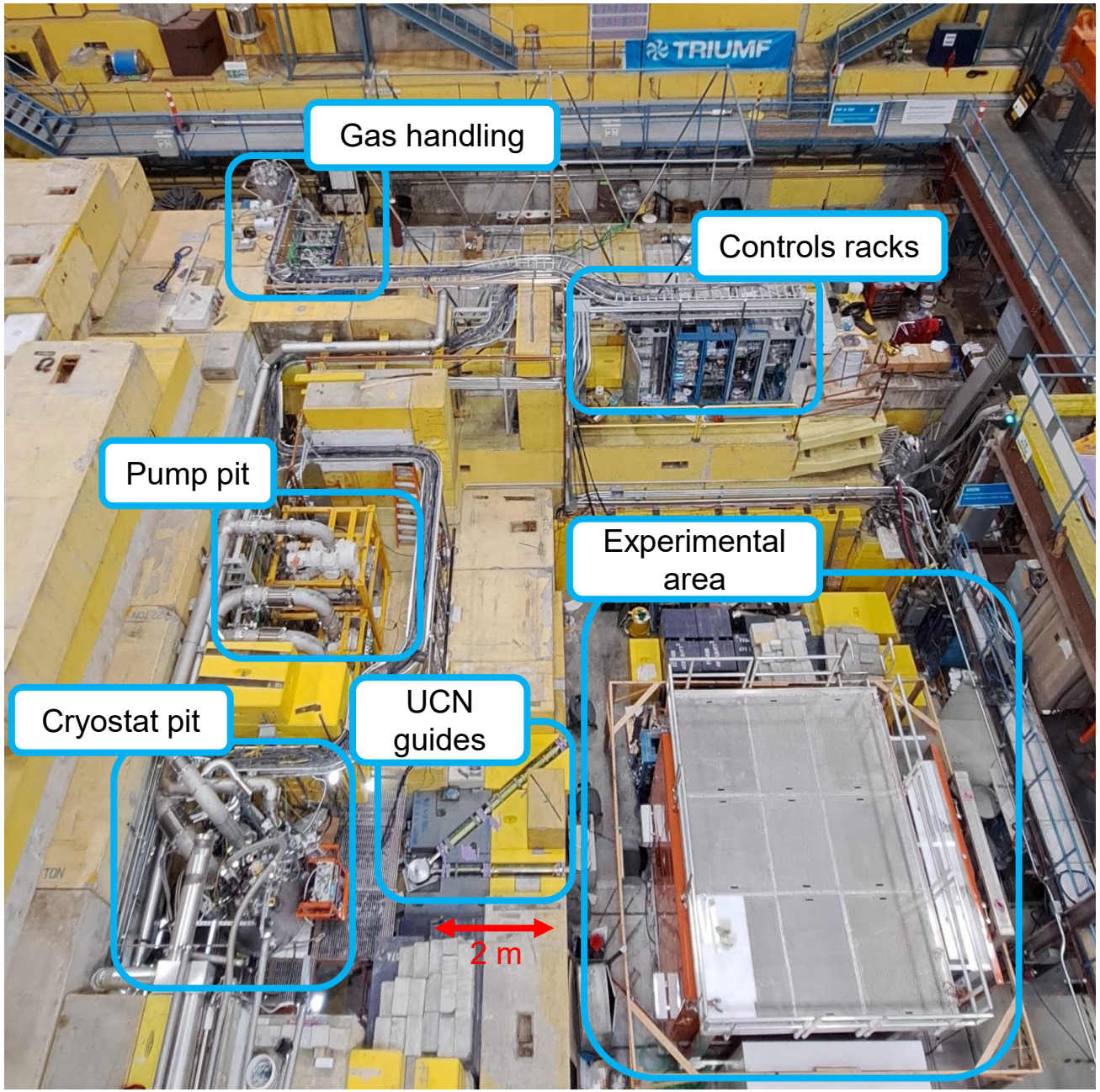


Major millstones accomplished over the last year:

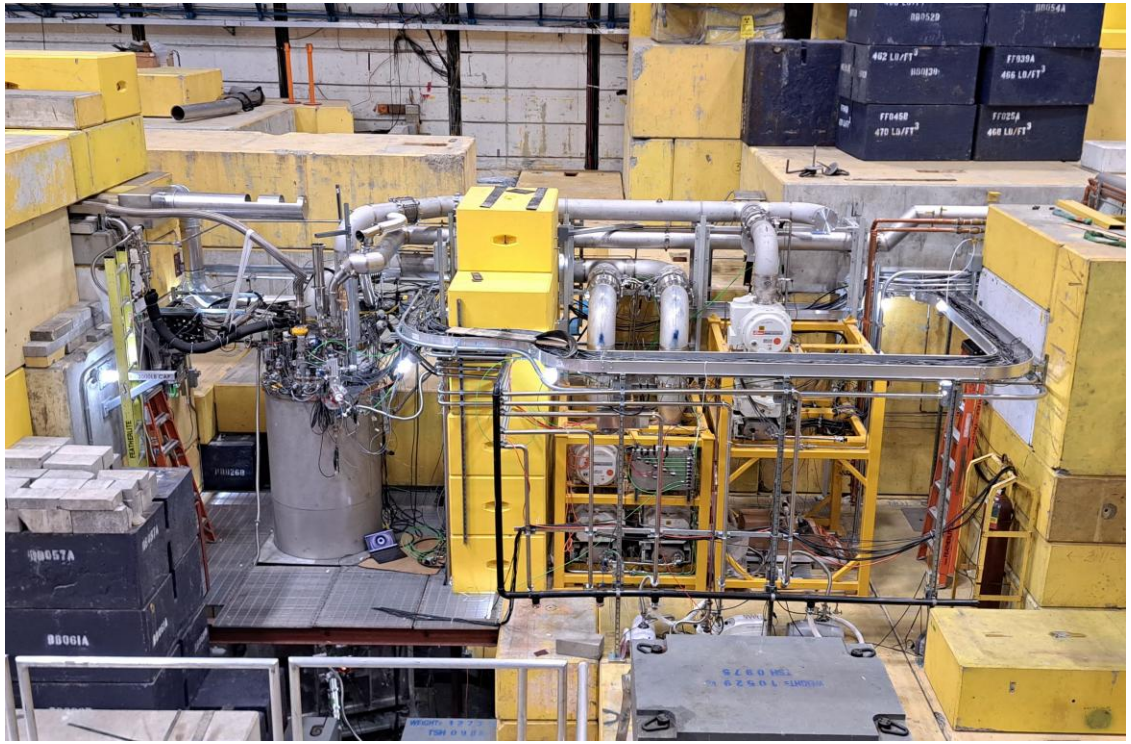
April 2024: Installation of the tail section

July-August 2024:
Installation of the main heat exchanger

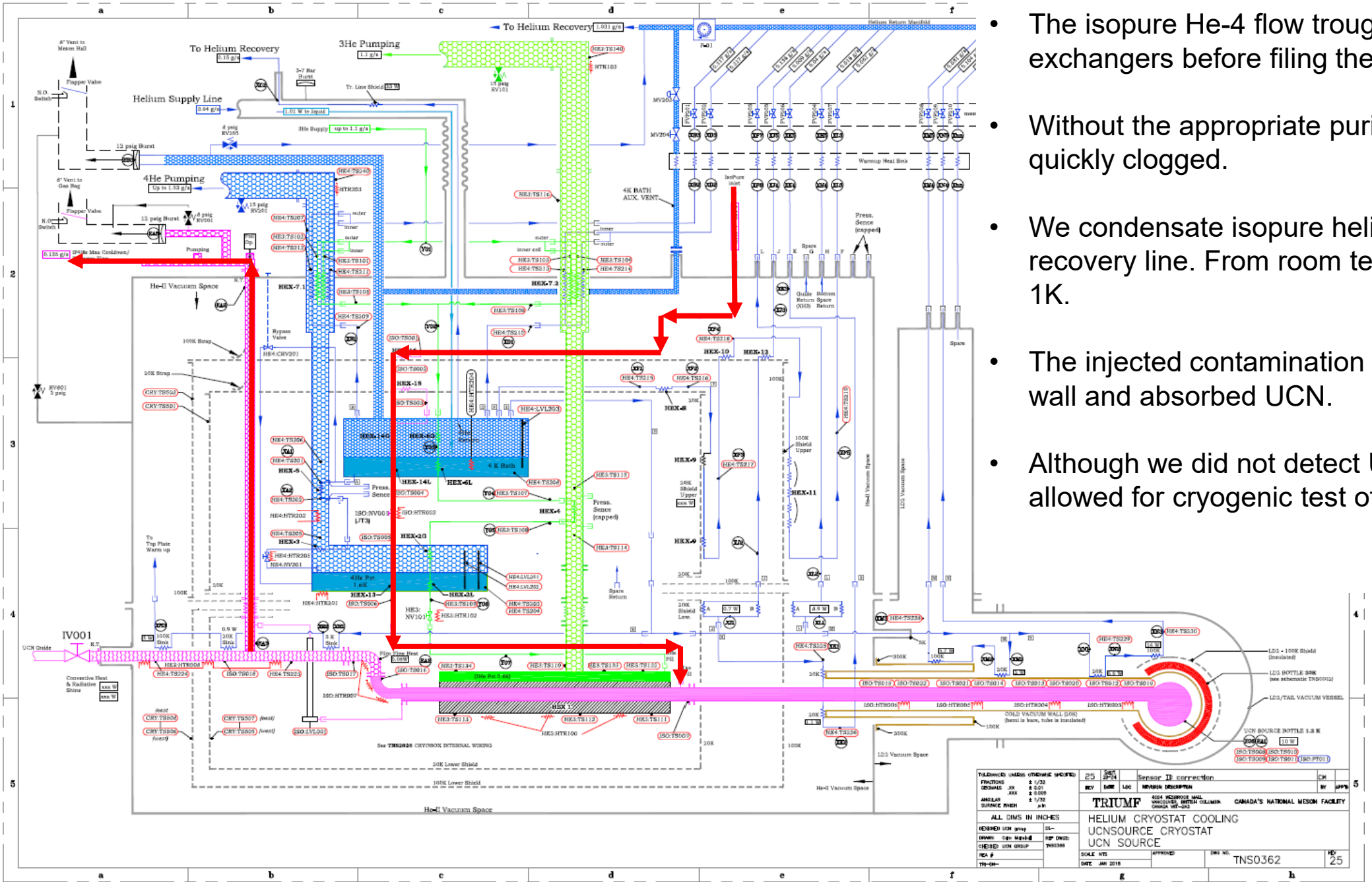




- Beamline commissioned
- Helium gas handling and cryogenic systems tested
- D2O system tested
- LD2 system to be installed
- All performing as expected so far



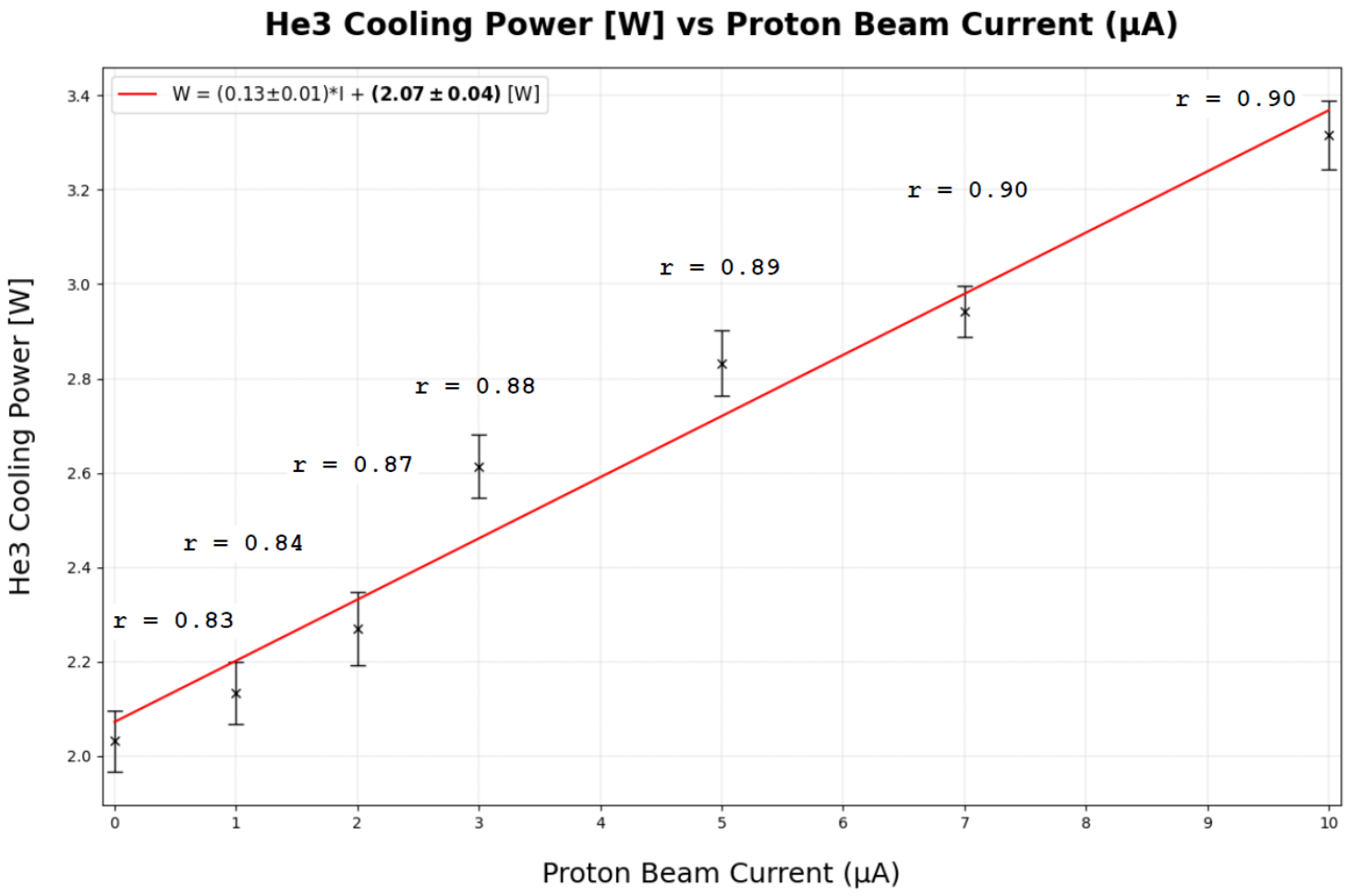
October-November 2024 campaign



- The isopure He-4 flow trough several heat exchangers before filing the tail section at 1K.
- Without the appropriate purifier, the filling line quickly clogged.
- We condensate isopure helium through the recovery line. From room temperature to directly 1K.
- The injected contamination froze on the tail section wall and absorbed UCN.
- Although we did not detect UCN, this campaign allowed for cryogenic test of the experiment.

Preliminary result for cooling power from ^{3}He boiloff rate

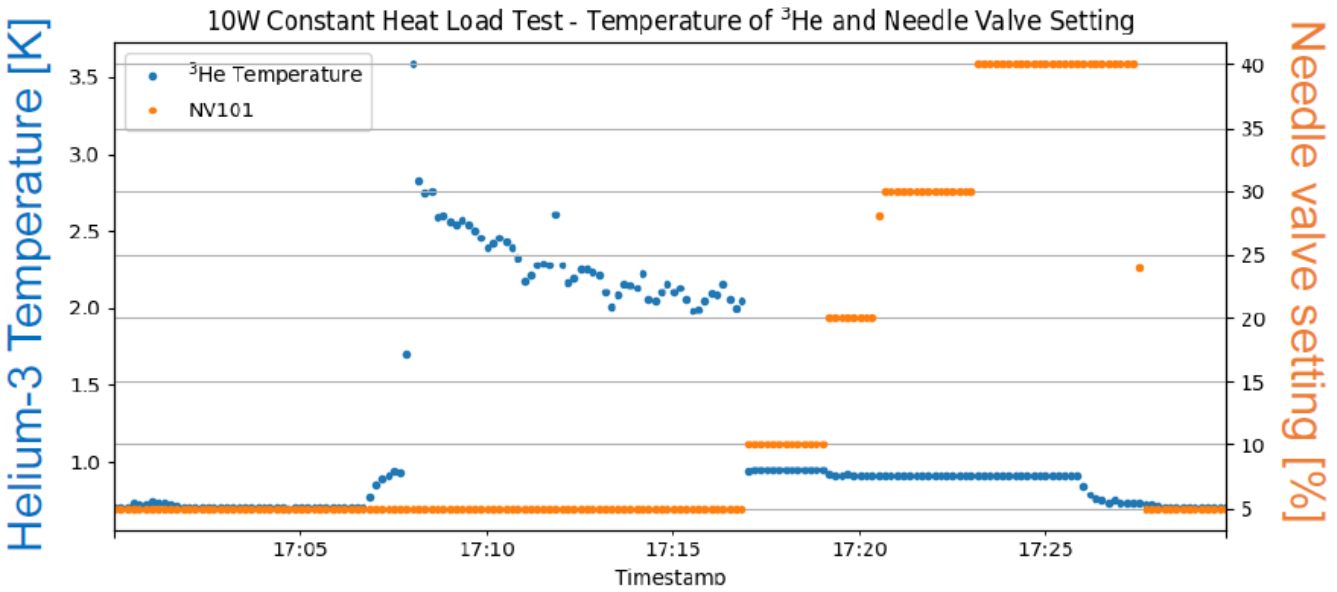
- Using enthalpy tables and measured values of flow rates, temperatures, and pressures
- Slope in fair agreement with simulation of beam heat to helium system

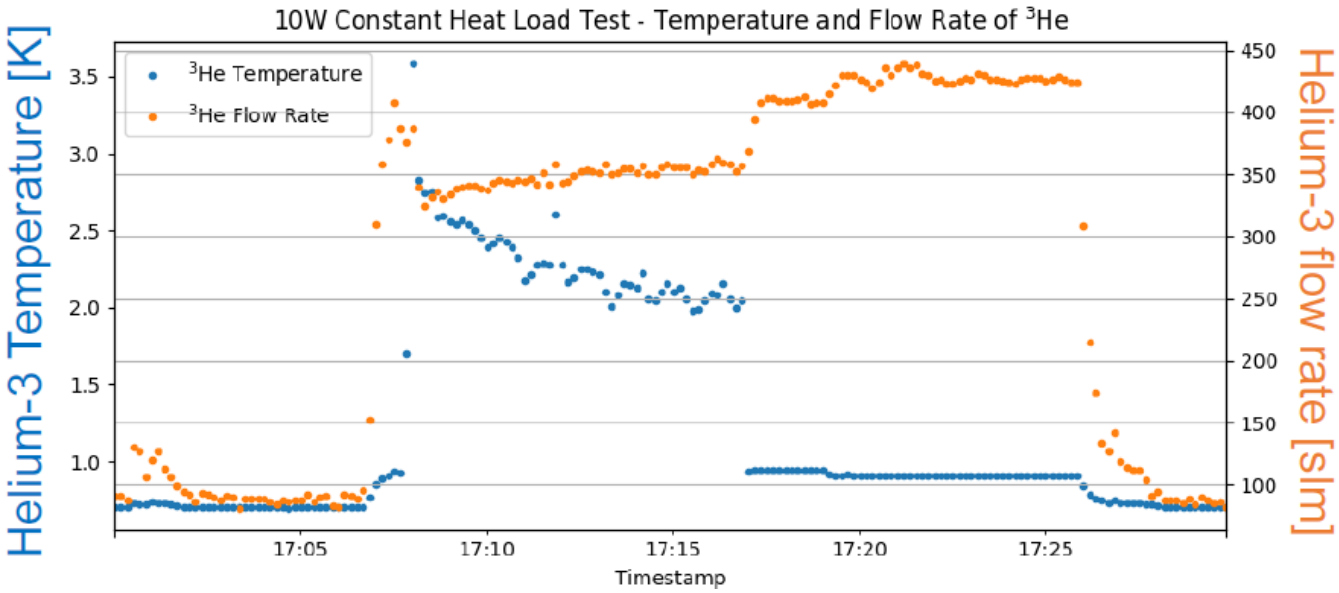


October-November 2024 campaign

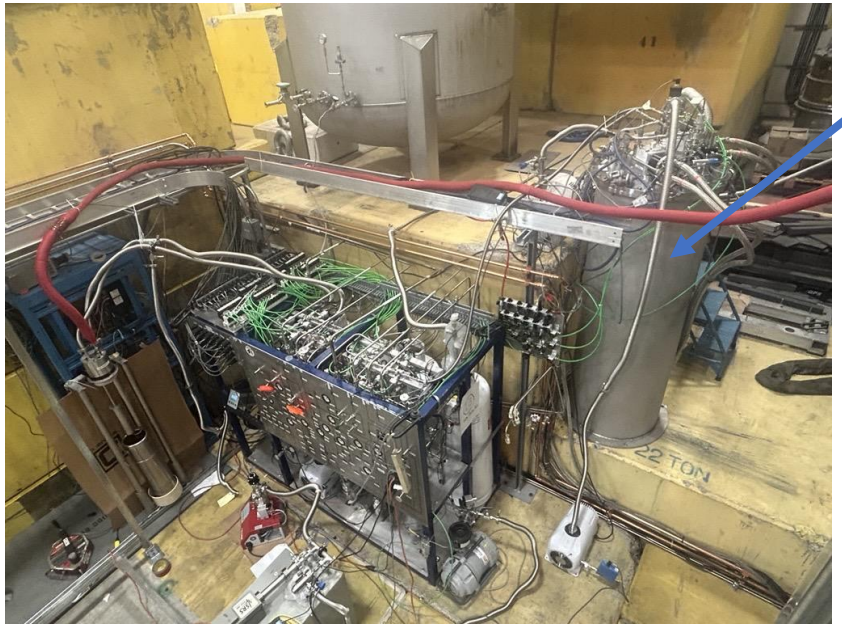
Results of 10 W heater test

- By opening the needle valve, we are able to control the ^{3}He flow and sustain the full design 10 W of heat, while keeping the ^{3}He temperature below 0.9 K.
- Although we do not have a temperature sensor in the UCN volume, we estimate the ^{4}He temperature is < 1.2 K, also meeting our requirement.





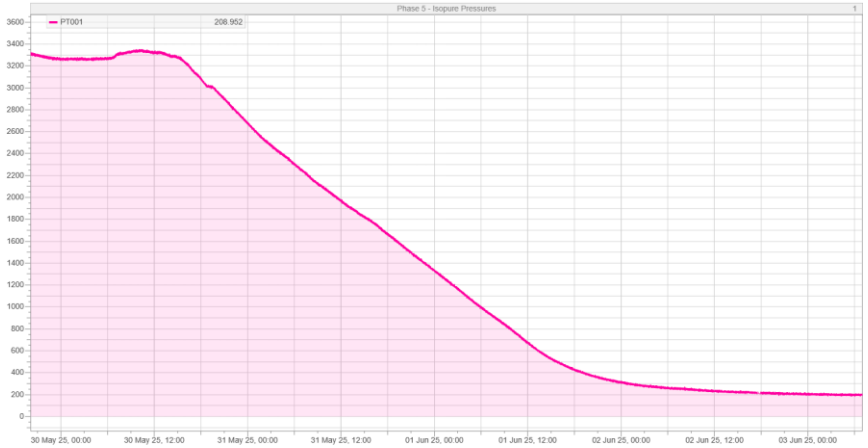
Current campaign:

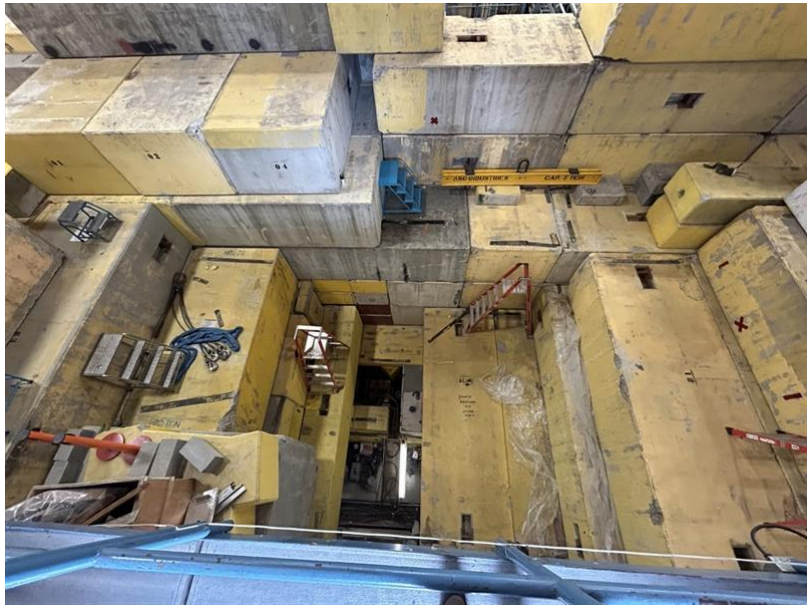


Helium purifier, commissioned in April.

- The source is ready since Tuesday June 3rd. Unfortunately, a leak in the BL1A degraded its vacuum and prevent any proton beam.
- TRIUMF support group are working tirelessly to fix this problem and provide proton beam.
- The first UCN production is imminent!

Isopure Helium-4 tank pressure, 5 days to condense 55 liters at ~1K

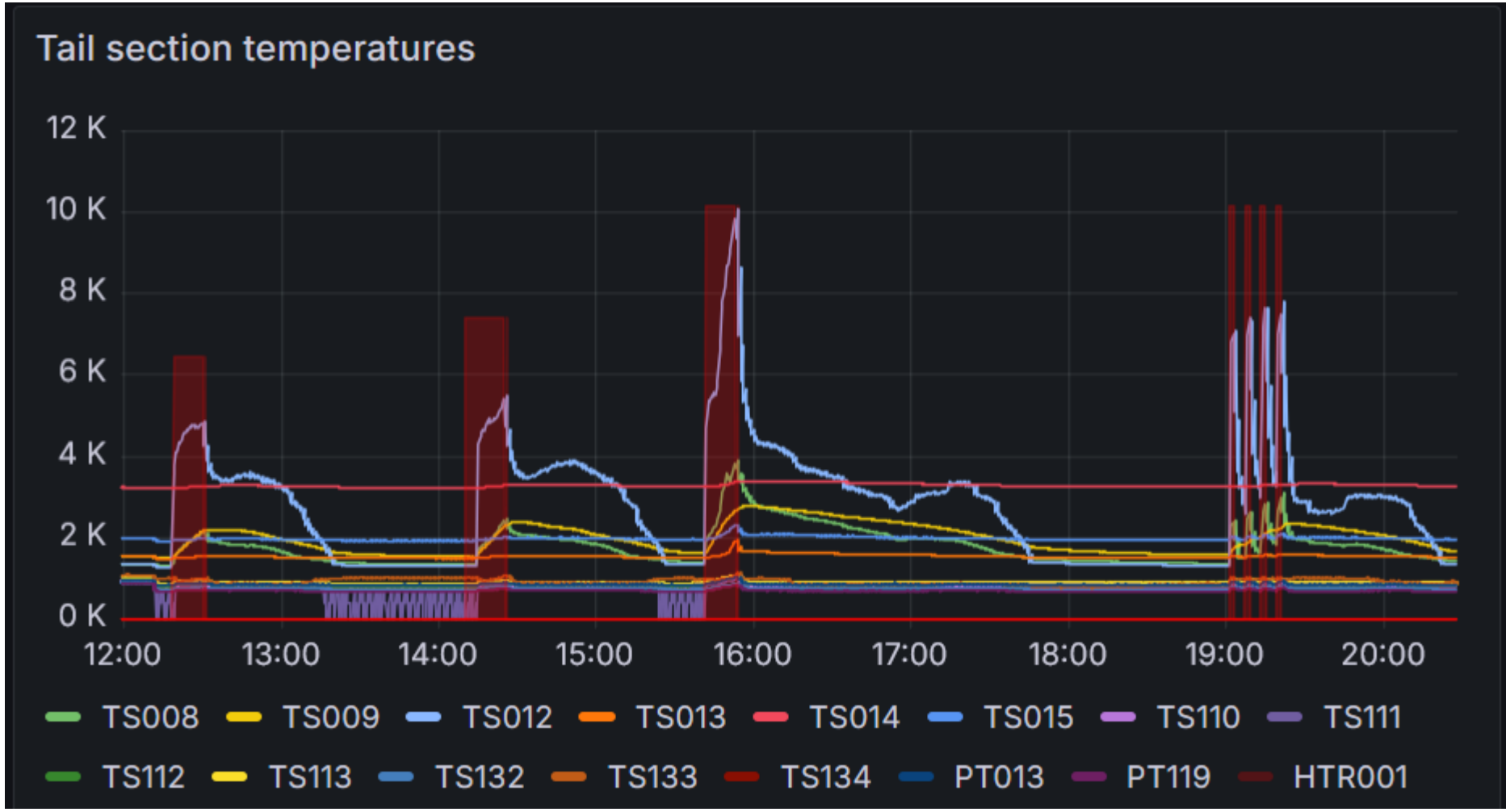




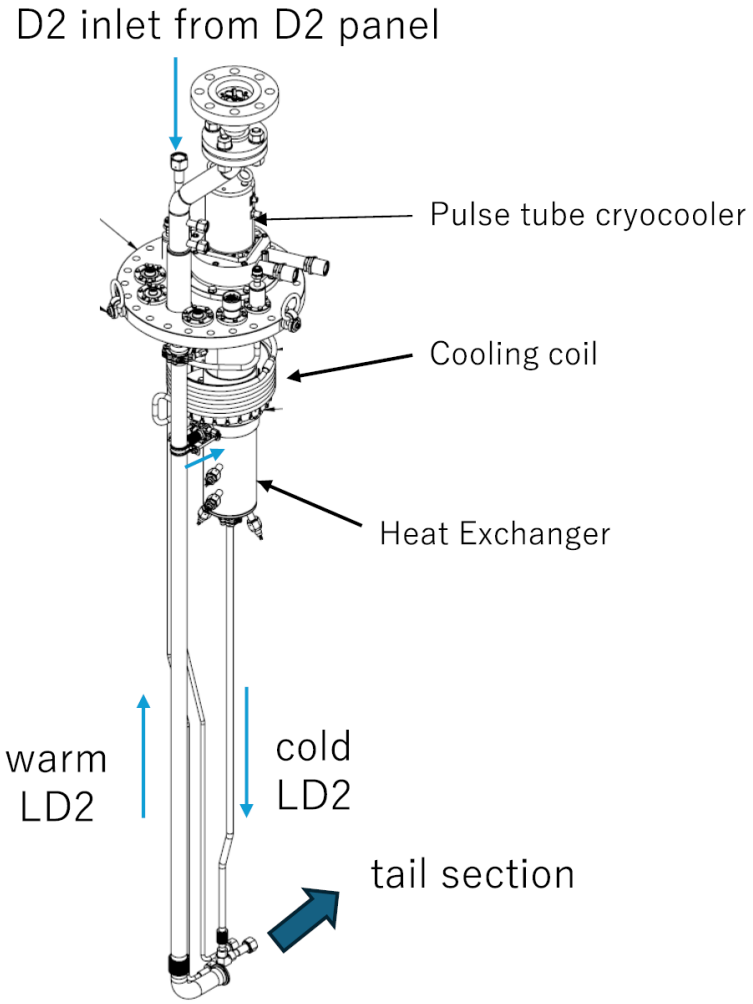
Beamline 1A under meters of concrete shielding

Current campaign:

- Cryogenic test, heat load applied on the tail section containing the isopure Helium-4.
- Heater tests at 4W, 5W, 10W, and intermittent 10W (2min on, 4min off).
- The cryostat can handle the heat load require for nEDM measurement.



Liquid deuterium system

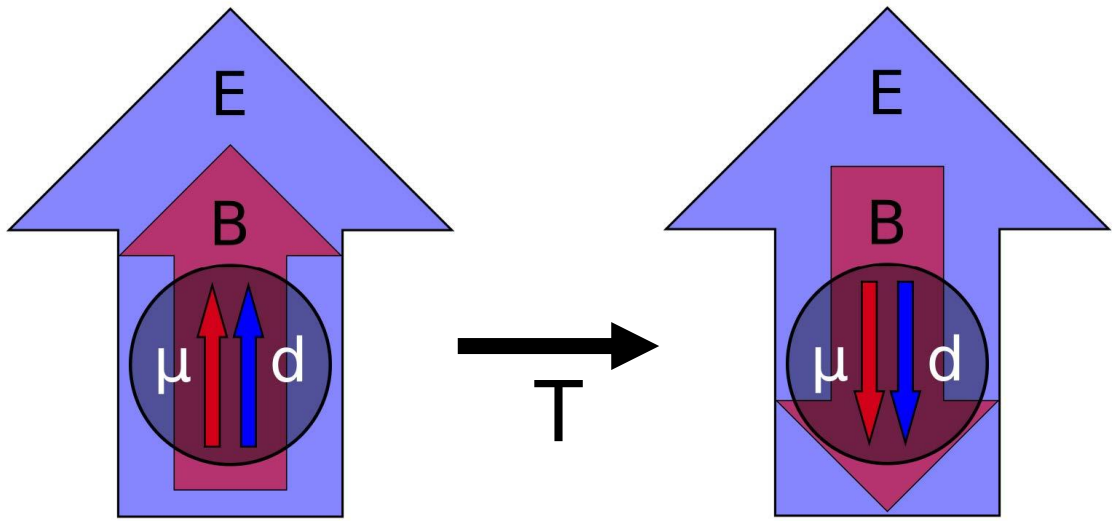


- 125 l of LD2, 63 W heat load
- Cooled/circulated by cryocooler-driven thermosyphon
- Manufactured at KEK
- Arrived at TRIUMF, to be commissioned in August.

Neutron electric dipole moment measurement

Neutron Electric Dipole Moment violates CP symmetry

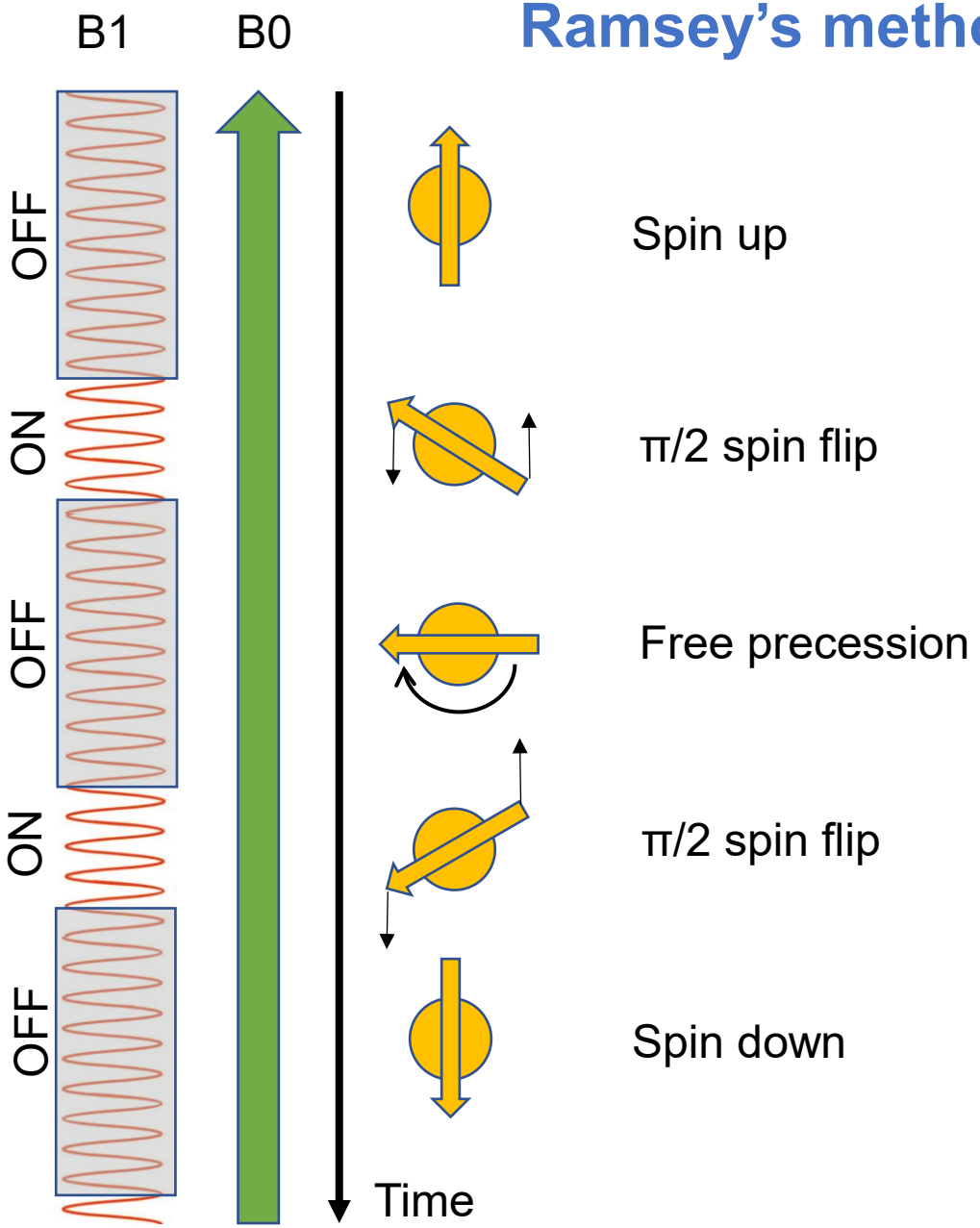
- Violates T & CP symmetry
- Test of beyond-Standard Model theories
- Can be detected by measuring precession frequency in electric and magnetic field
- Ultracold neutron (E<300 neV) are suitable for such measurement.

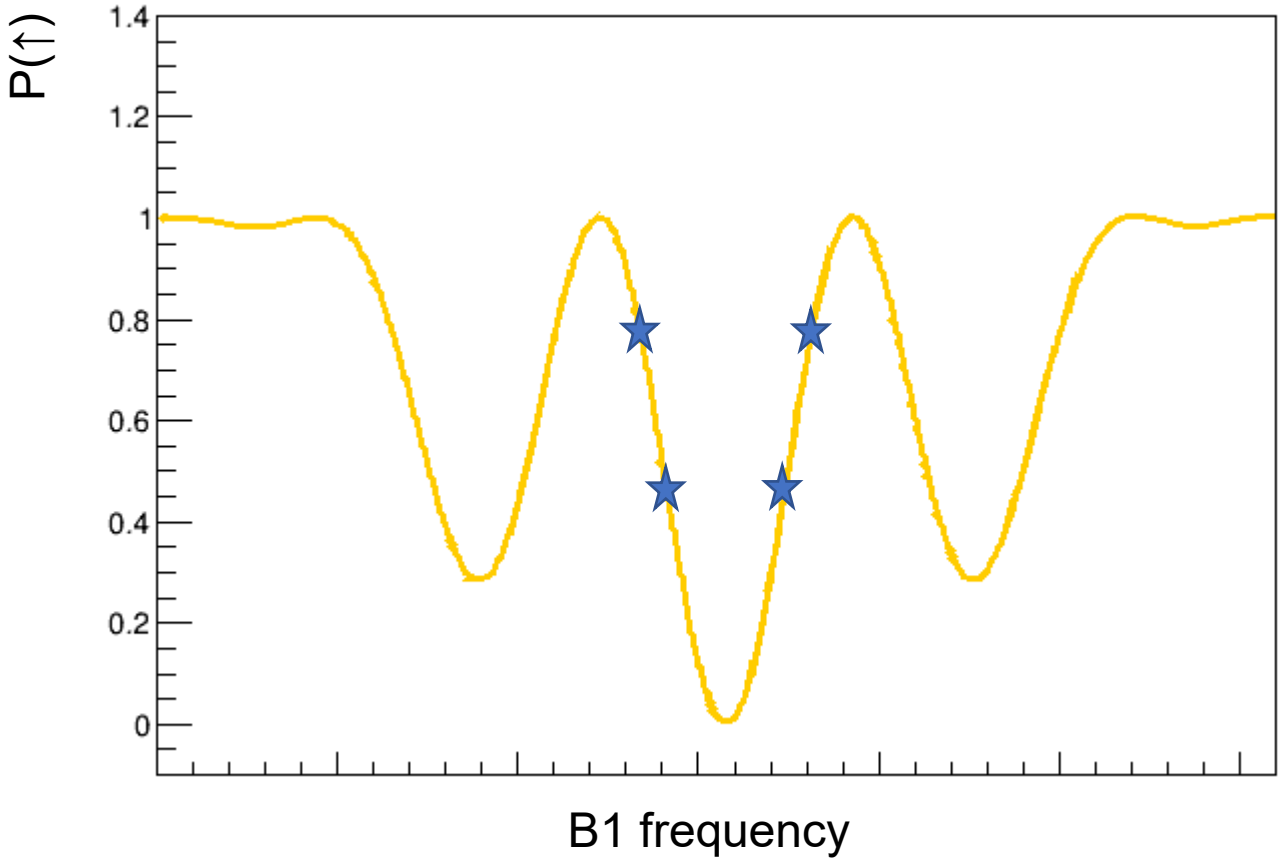


$$H = -\mu \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \vec{B} - d \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \vec{E} \neq -\mu \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \left(-\vec{B}\right) - d \frac{\vec{\sigma}}{|\vec{\sigma}|} \cdot \vec{E}$$

Figures by D. Ries
https://www.youtube.com/watch?v=QBKPQFUdDB0

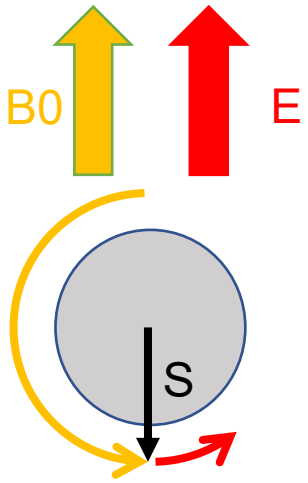
Ramsey's method of separated oscillatory fields



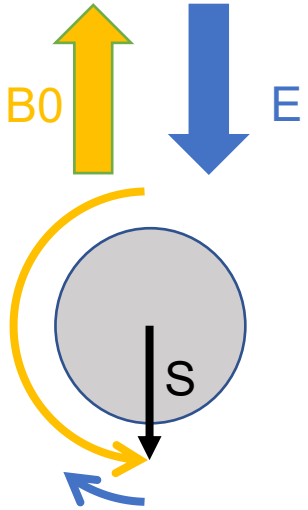


Resonance frequency: $2\pi f = \frac{2\mu_n}{\hbar} \mathrm{B}$

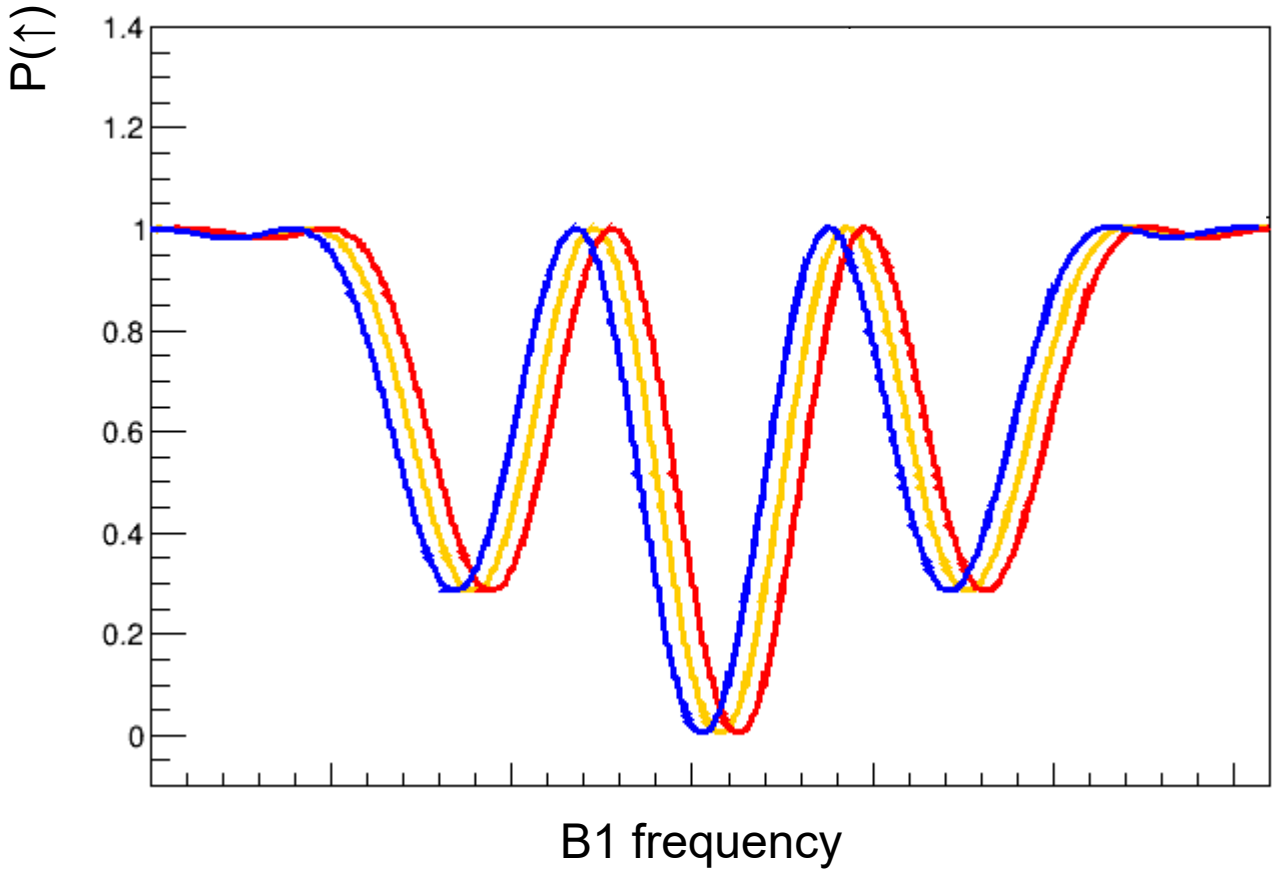
Effect of the E field:



$$2\pi f = \frac{2\mu_n}{\hbar}\mathrm{B} + \frac{2d_n}{\hbar}E$$



$$2\pi f = \frac{2\mu_n}{\hbar}\mathrm{B} - \frac{2d_n}{\hbar}E$$



EDM will cause shift in precession frequency

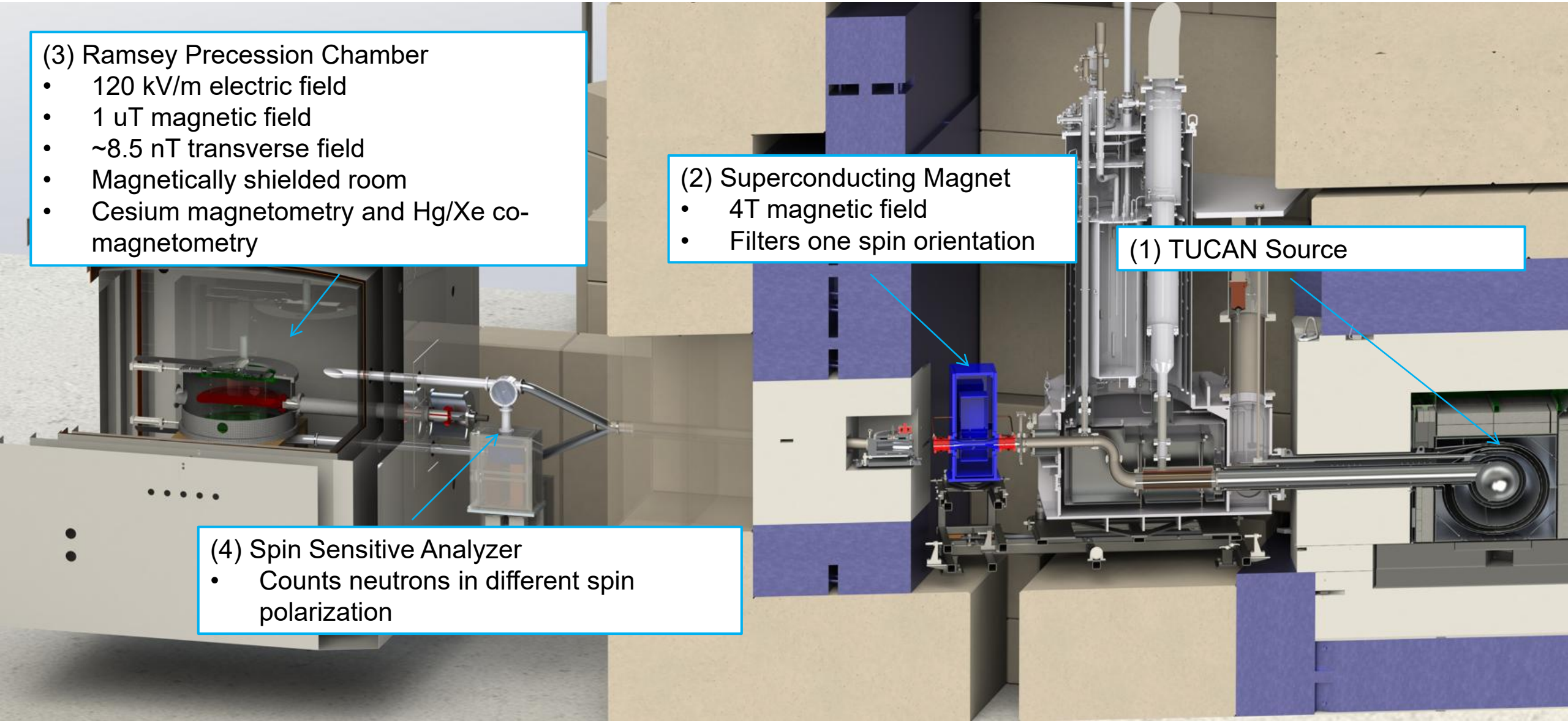
$$f(\uparrow\uparrow) - f(\uparrow\downarrow) = \frac{2\pi}{\hbar} d_n E$$

Statistical uncertainty:

$$\sigma_d = \frac{1}{2\alpha E T \sqrt{N}}$$

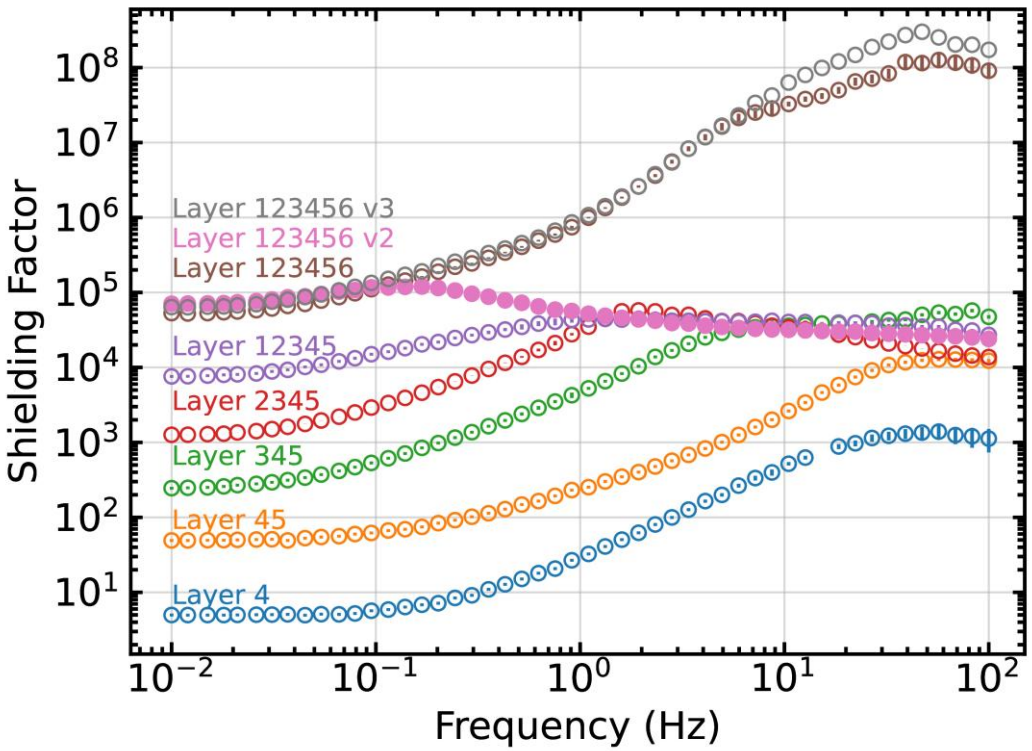
- α: Visibility, neutron polarization. Account for polarization at the beginning of the cycle, depolarization during the cycle and efficiency of the spin analyzer.
- *E:* Electric field strength. Limited by the cell breakdown voltage
- *N*: Number of neutron detected, needs for high efficiency at few 100 kHz detection rate
- *T:* Free precession time, must be optimized considering neutron decay, absorption, storage lifetime, de-polarization…

TUCAN METHOD:

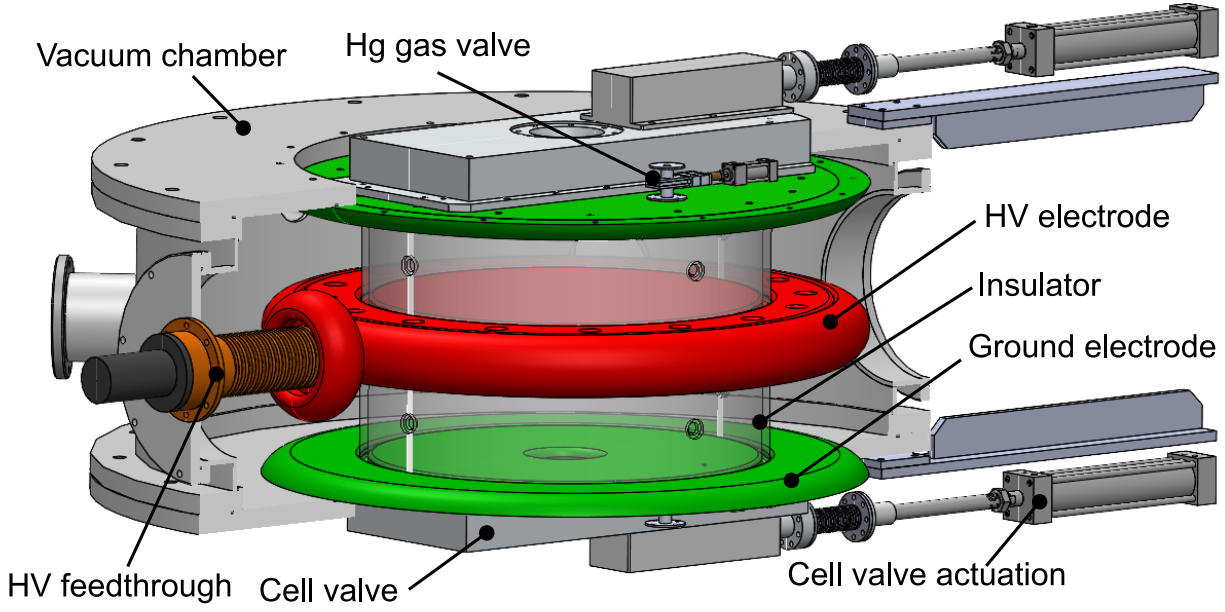


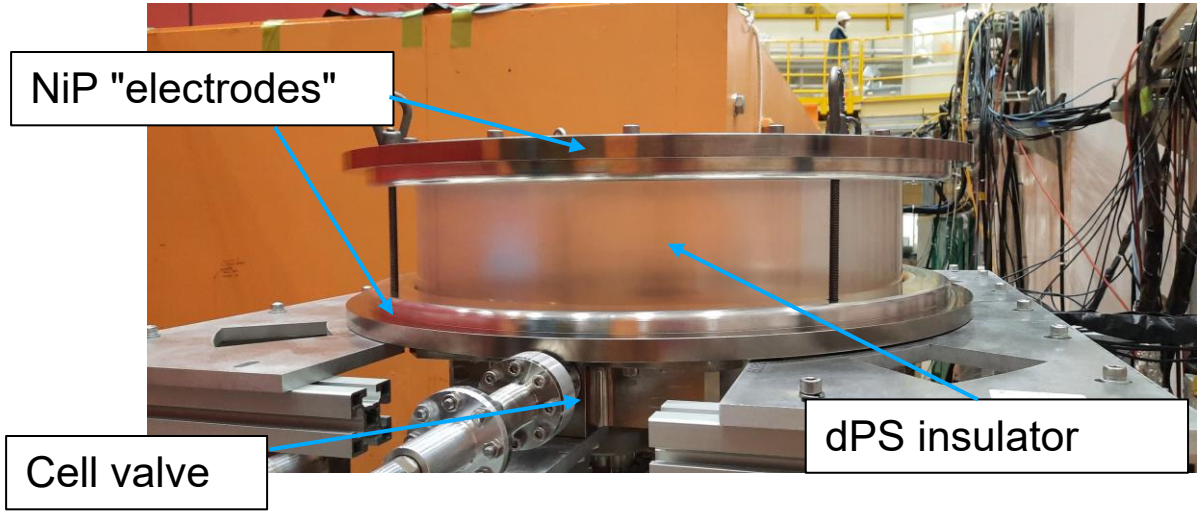
Magnetically shielded room

Six layer magnetically-shielded room built by Magnetic Shields Ltd 5 layers of MuMetal + 1 copper layer

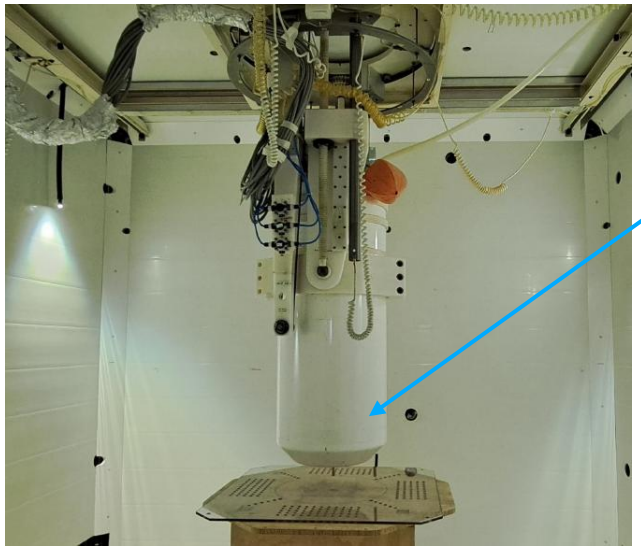


At 18 μT applied field
~ 70000 @ 0.01 Hz





- 0.5m diameter cells, 0.16m height
- Prototype storage cell lifetime measured at J-PARC to be 132.5 ± 2.5 s
- Sample measurements at PTB Berlin to identify non-magnetic materials

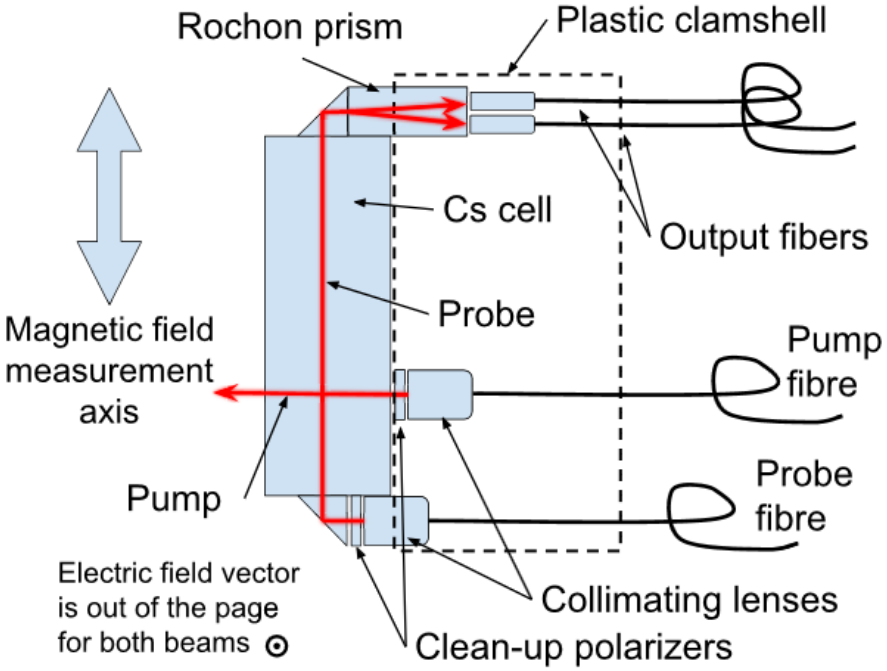


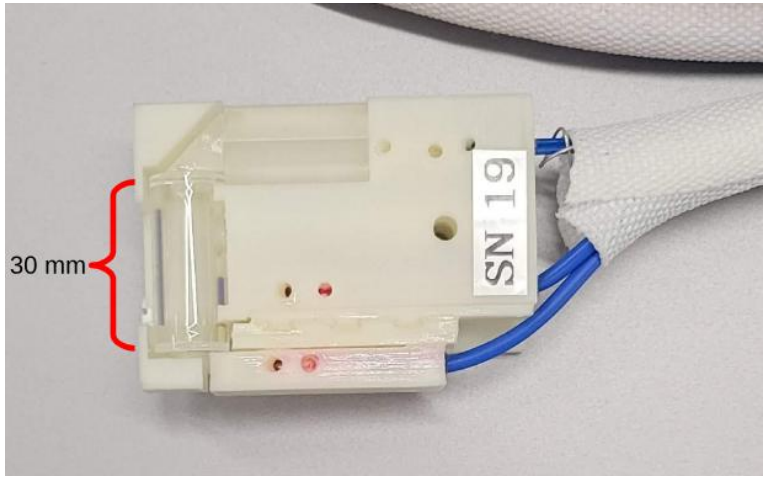
SQUID array in BMSR2

- OC100 version to be built next year and studied with HV

Magnetometry: Cesium

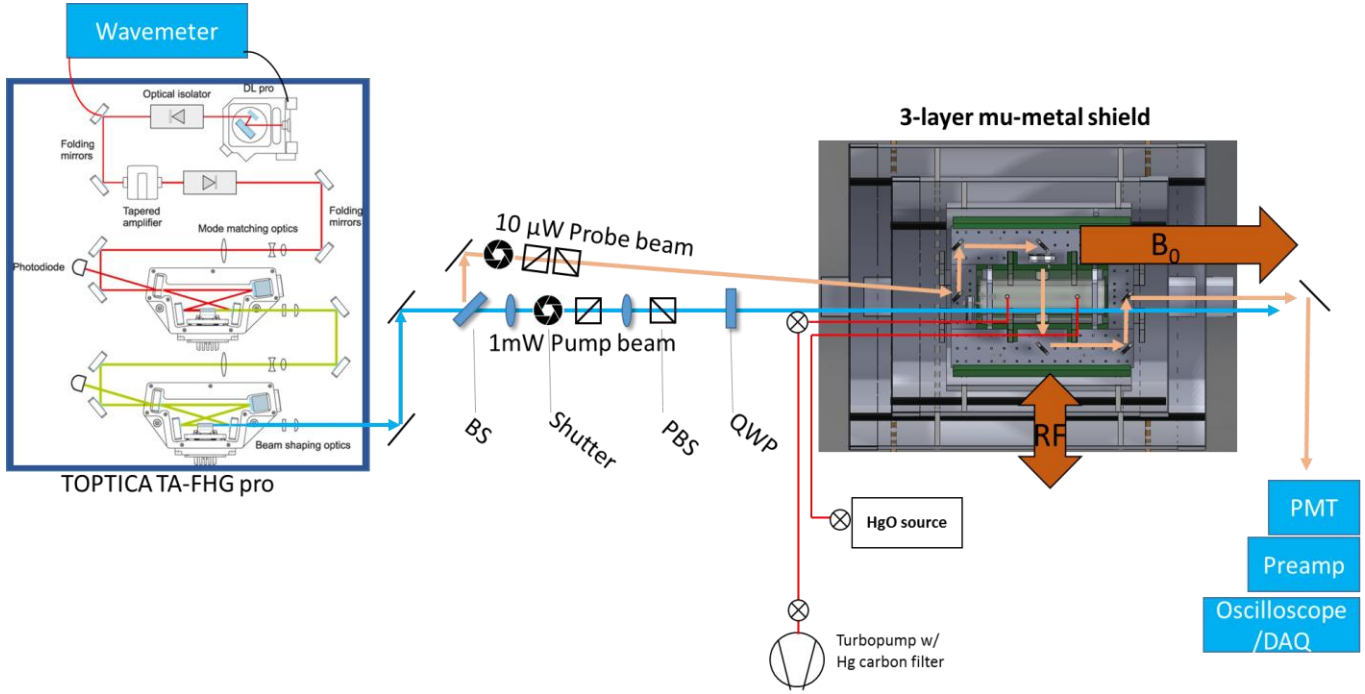
- Optically pumped cesium magnetometers for online measurement of gradients (https://doi.org/10.1140/epjc/s10052-024-13544-5)
- Achieved sensitivity of 3.5 pT/√Hz at 1 Hz and a stability of 90 fT over 150 s of measurement
- 20 magnetometers in hand, planned to be increased to 48
- Current work is on operating and characterizing all 20 sensors at the same time in the MSR

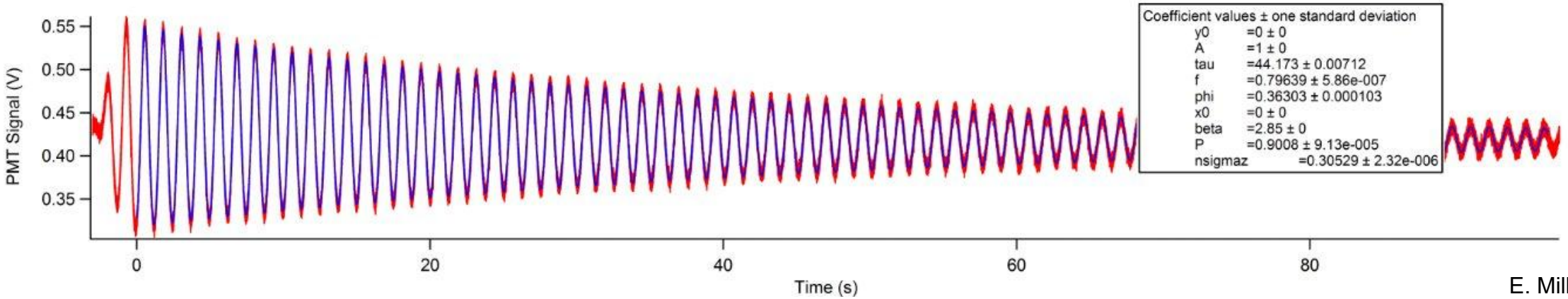




Magnetometry: Mercury

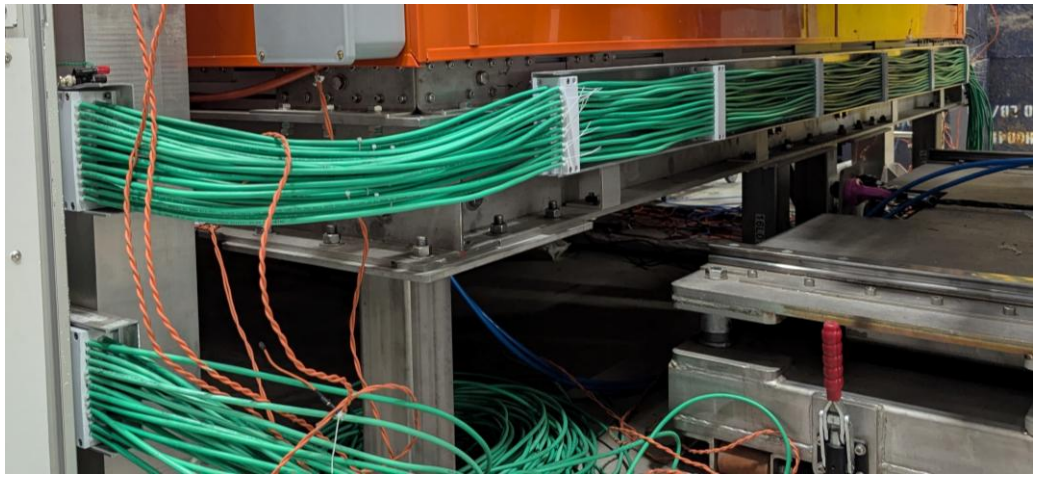
- Laser pumped/probed Hg comagnetometer with target 10 fT precision to correct field fluctuations
- Currently limited to 1ppm (1 pT on 1 μT) by gradients and field stability in test setup
- Other development on light shifts, etc. ongoing
- Ready to move into MSR end of 2025

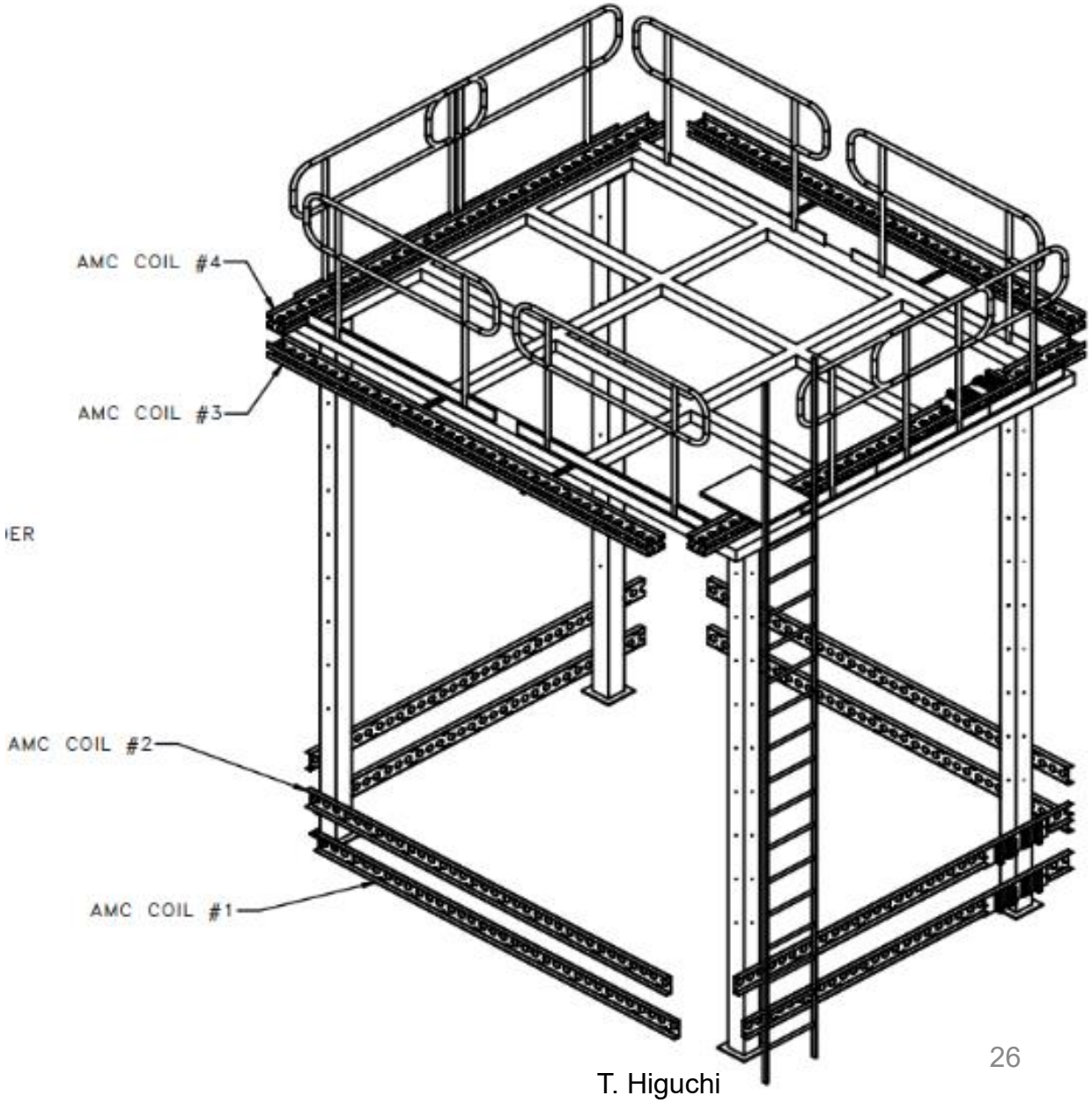




Ambient Magnetic Compensation

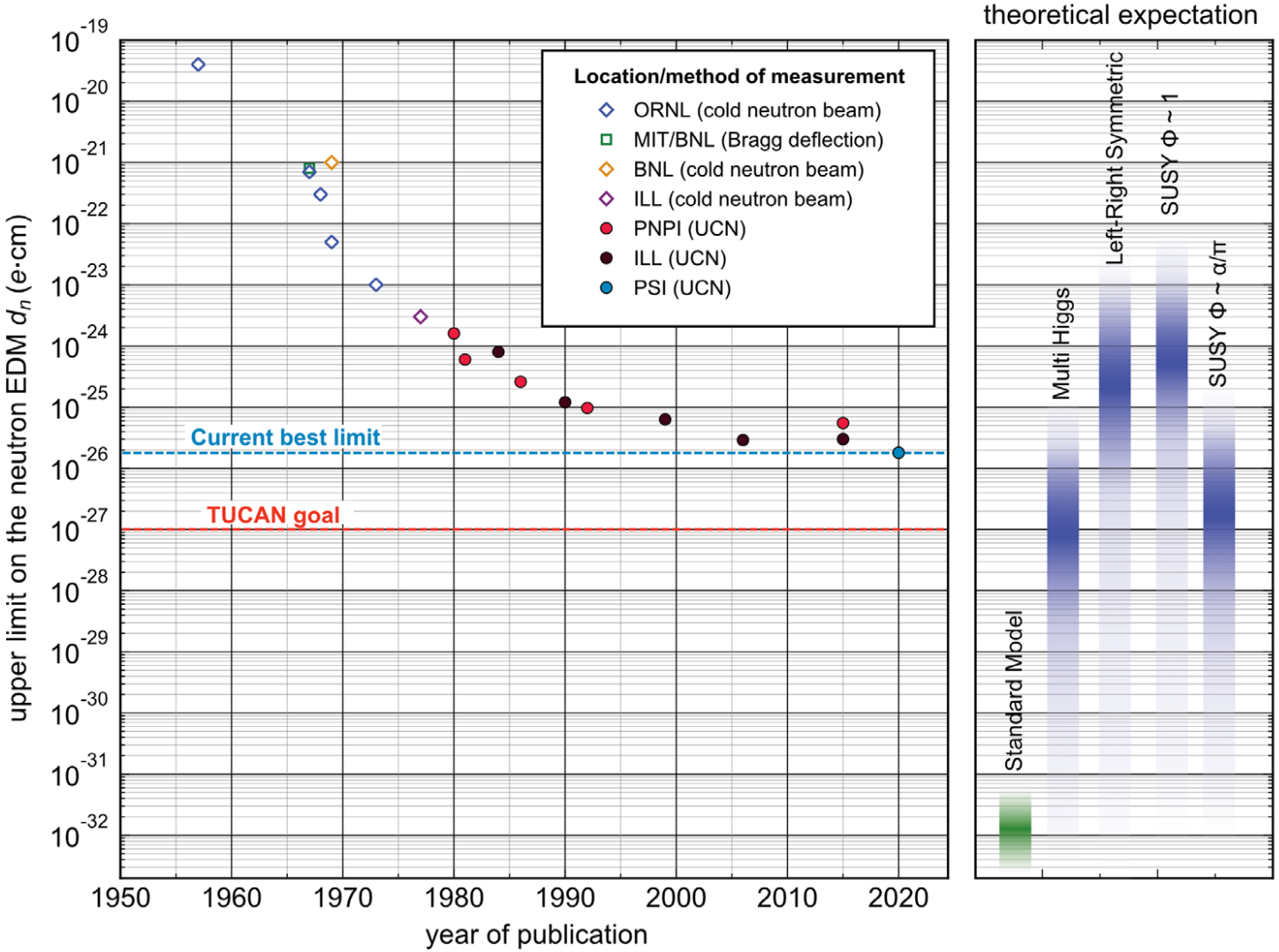
- Single-purpose coils to counter specific field sources
- Biggest problem is the TRIUMF cyclotron fringe field: 400 μT
- Installation currently ongoing.





T. Higuchi

Projected nEDM sensitivity



- $d_n < 1.8 \times 10^{-26}$ ecm (90% C.L.)
  C. Abel et al., Phys. Rev. Lett. 124, 081803 (2020)
- Many groups pursuing ~ 10^{-27} ecm measurement as next step

T. Higuchi on behalf of the TUCAN collaboration EPJ Web of Conferences 262, 01015 (2022)

CONCLUSION:

- The UCN source is built.
- Cryogenic test show good performances.
- First UCN production is imminent, as soon as beamline is fixed.
- Last component, the LD2 system, to be commissioned in August.
- Magnetically shielded room is built and perform as expected.
- Significant development in magnetometry, coil, neutron transport and storage ongoing.

TRIUMF UBC UNBC SFU University of Manitoba The University of Winnipeg NC State University University of Saskatchewan

TUCAN

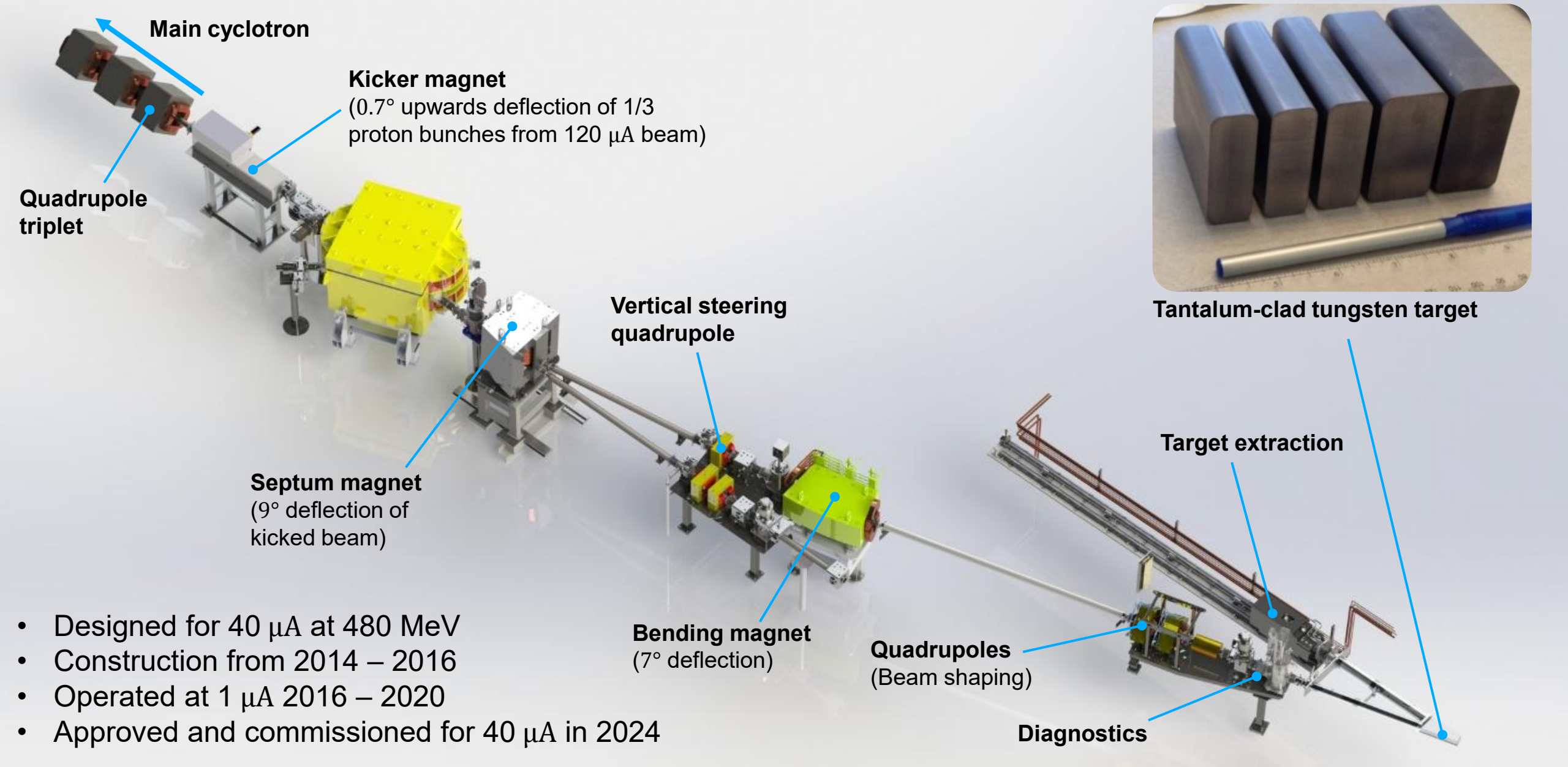
TRIUMF Ultra Cold
Advanced
Neutron source

March 2025 Collaboration Meeting, TRIUMF

KEK RCNP Nagoya University Japan Society for the Promotion of Science · Founded 1932 · NSERC CRSNG INNOVATION.CA Canada Foundation for Innovation | Fondation canadienne pour l'innovation

Backup slides

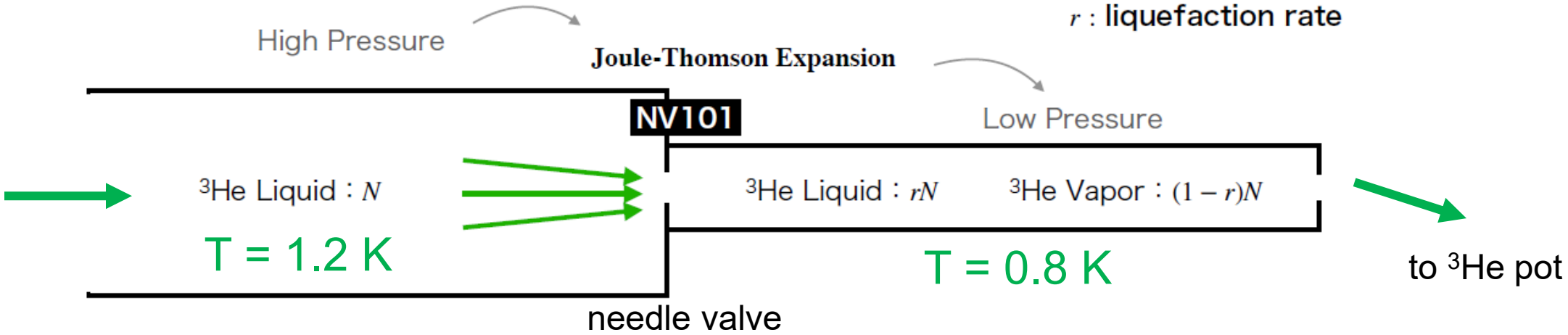
TRIUMF Beamline 1U



- Designed for 40 μA at 480 MeV
- Construction from 2014 – 2016
- Operated at 1 μA 2016 – 2020
- Approved and commissioned for 40 μA in 2024

The deepest, coldest part of our refrigerator

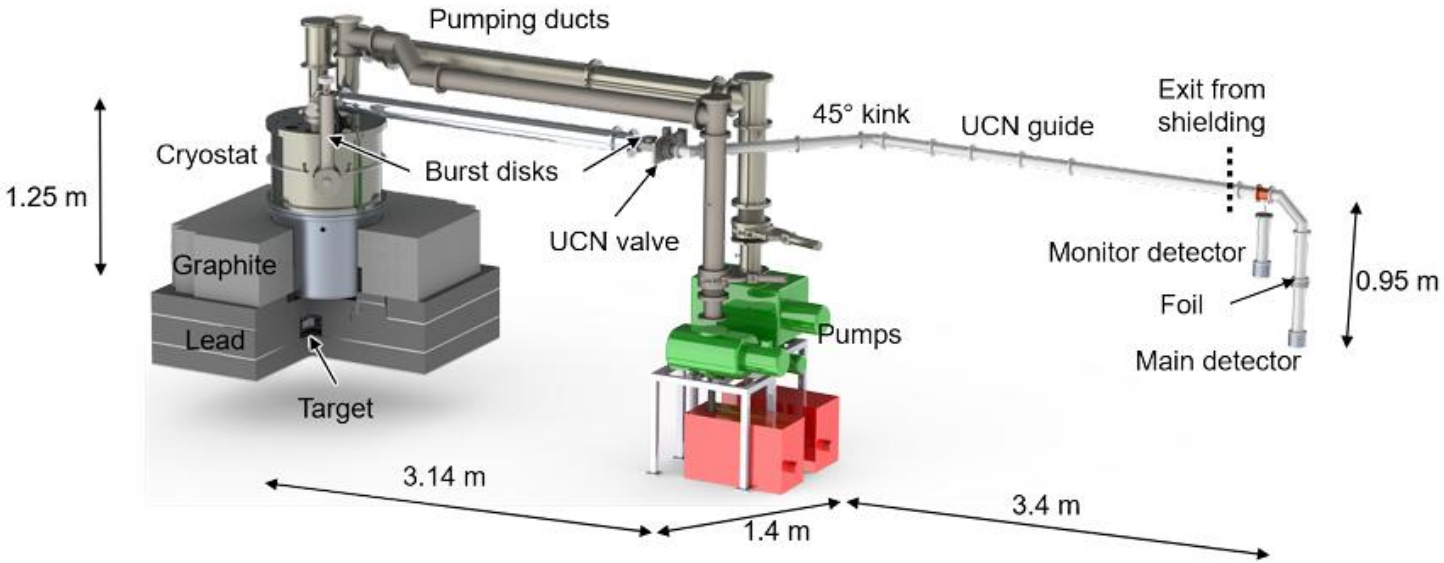
- Cooling is produced by the Joule-Thomson effect. A high-pressure, warmer liquid expands (to a lower pressure) through needle valve, and cools.



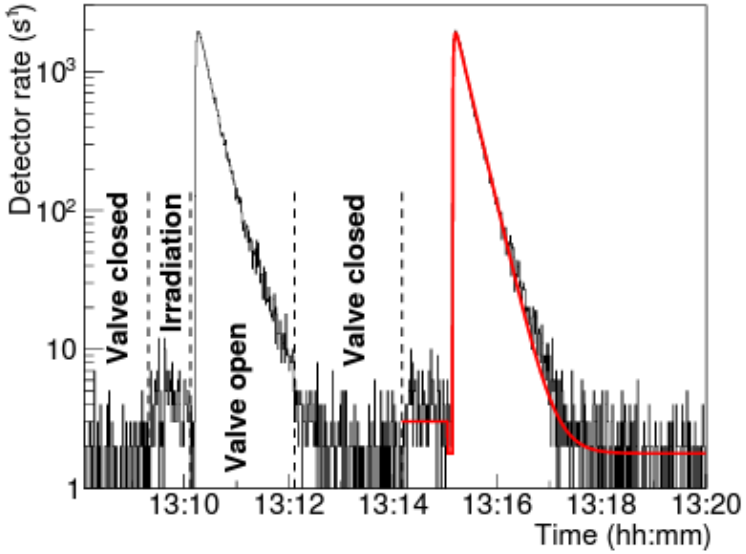
- Joule-Thomson effect conserves enthalpy *H*

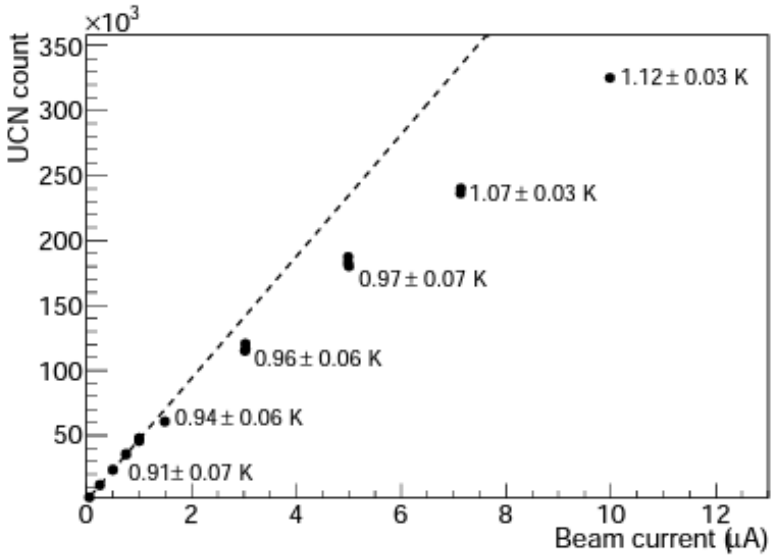
$$\underline{H_{\text{Liqiud/HighPressure}}}\ [\text{J/kg}] = r \cdot \underline{H_{\text{Liqiud/LowPressure}}} + (1-r) \cdot \underline{H_{\text{Vapor/LowPressure}}}\ [\text{J/kg}]$$

TUCAN first prototype:



- First UCN on November 13, 2017
- 2 10^4 UCN/s
- Decommissioned in 2019
- Validate components and simulation for the new source
- Gives first operational experience





Predicted Statistical Performance

EDM Experiment	published		future					
	ILL-RAL-Sussex	PSI nEDM	PSI n2EDM*	LANL EDM**	panEDM stage I***	panEDM stage II***	TUCAN OC100****	TUCAN 2C200****
UCN detected per cycle	14 000	15 000	121 000	78 000	51800[x]	1 380 000[x]	846 000	1 420 000
Size	20 l	20 l	116 l	40 l	34 l	34 l	31.5 l	63 l
Density detected (1/cc)	0.7	0.75	1	2	1.5[x]	40[x]	27	23
Publication	(1)	(2)	(2)	(3)	(4)	(4)		(5)
							Bottom cell only	

* expected, based on PSI nEDM.
** expected, based on storage expts.
*** estimation based on loss factors
**** expected, extensive MC.
[x] at end of Ramsey cycle

(Likely outdated for the non-TUCAN experiments)

Publications:
(1) C.A. Baker, et al, 2006: http://dx.doi.org/10.1103/PhysRevLett.97.131801
(2) G. Pignol, et al, 2021: https://doi.org/10.21468/SciPostPhysProc.5
(3) T. Ito et al, 2020: http://dx.doi.org/10.1103/PhysRevC.97.012501
(4) D. Wurm, 2021: https://mediatum.ub.tum.de/doc/1631520/1631520.pdf
(5) S. Sidhu et al, 2022: https://doi.org/10.1051/epjconf/202328201015