# The liquid deuterium system for TUCAN


**TRIUMF UltraCold Advanced Neutron Collaboration**

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The University of Winnipeg

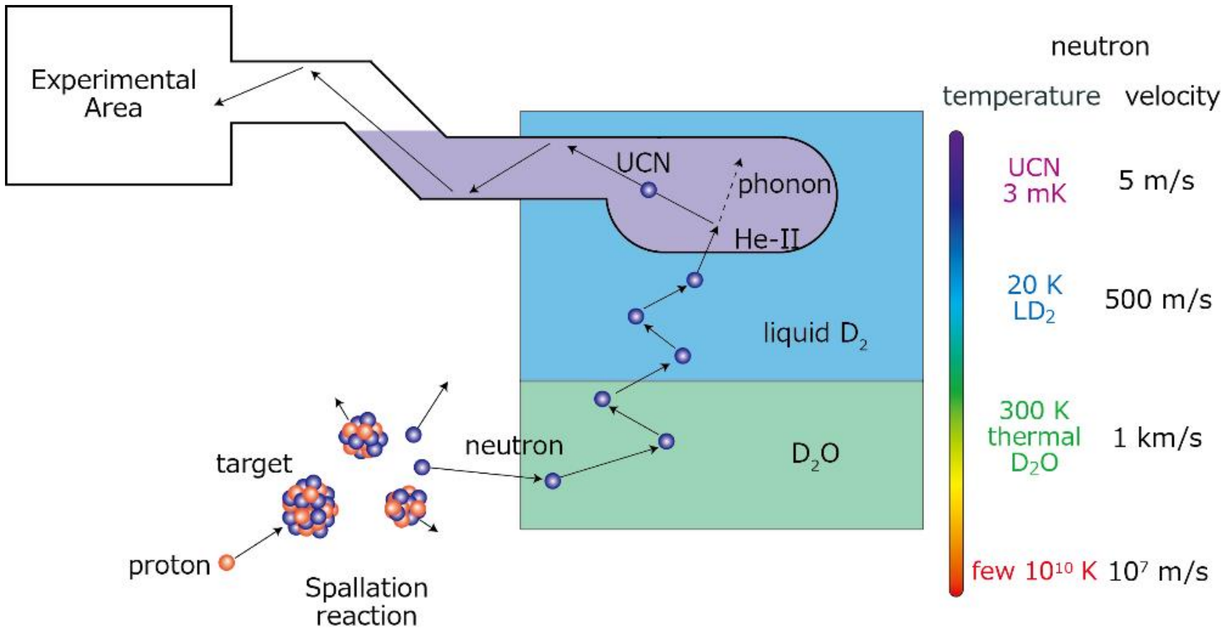

**Land acknowledgement**

*I acknowledge that my university is on ancestral lands, on Treaty One Territory. These lands are the heartland of the Métis people. We acknowledge that our water is sourced from Shoal Lake 40 First Nation.*

# TRIUMF Ultracold Advanced Neutron (TUCAN) Source

TUCAN

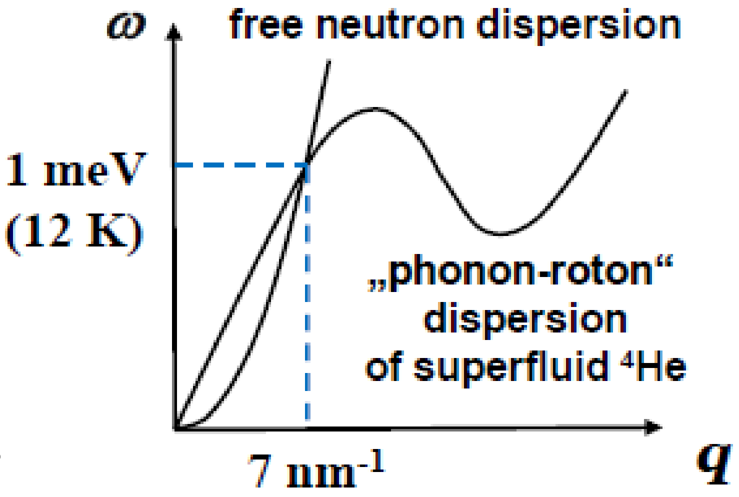
- Concept:
  - Use superfluid helium (He-II) to convert cold neutrons into **ultracold neutrons**.
  - Couple the He-II directly to a spallation source of neutrons and cold moderators that can be optimized fully.
  - Transport UCN to a room-temperature **neutron EDM experiment** located farther away from the neutron source and cryogenic systems.
- We have been operating this system first at RCNP Osaka, then at TRIUMF. We are now completing a **new upgrade**, scaling up the previous system with several key improvements to reach world-record UCN performance.
- A major part of this upgrade is a **new liquid $D_2$ cold neutron moderator**.



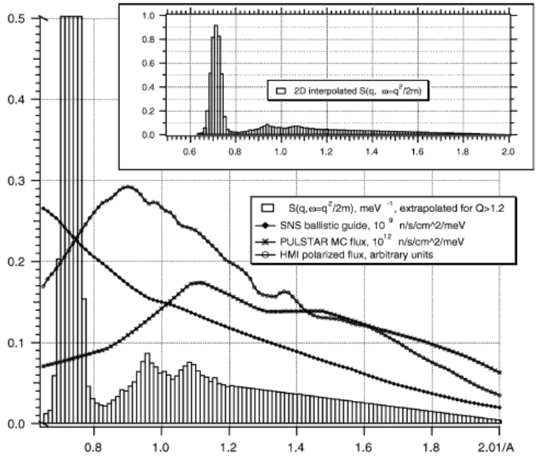
# UCN production and losses in superfluid $^4$He (He-II)

- Production:
  - Incident CN @ 1 meV excites one phonon
    Golub and Pendlebury, 1975, 1977
  - Multiphonon excitation give additional production.
- Losses:
  - Loss rate dominated by 2-phonon upscattering ~ $T^7$
  - $T$ = 1.1 K gives $\tau_{UCN}$ = 64 s
  - We must keep the superfluid much colder than $T_\lambda$

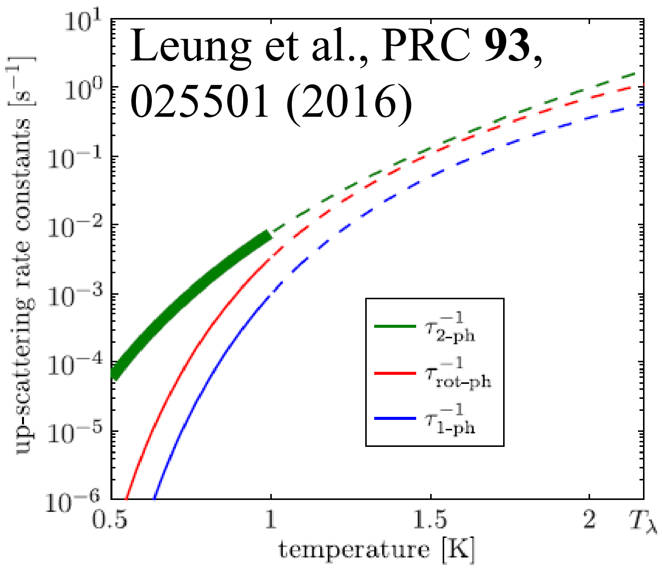
Maximize 1 meV neutrons;
Minimize losses, heat.

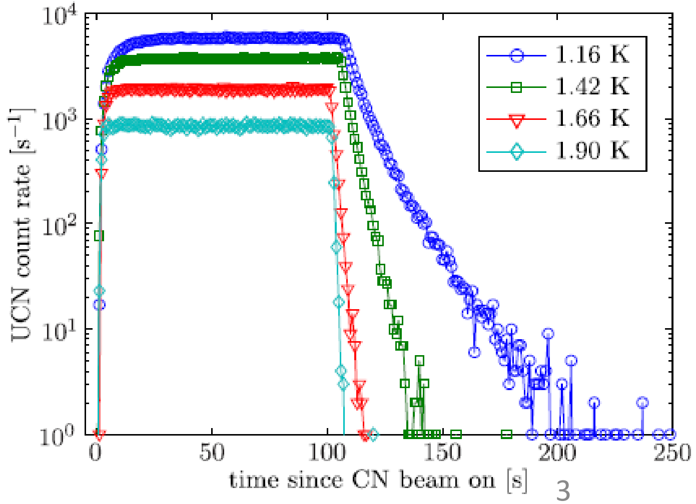



Courtesy of O. Zimmer



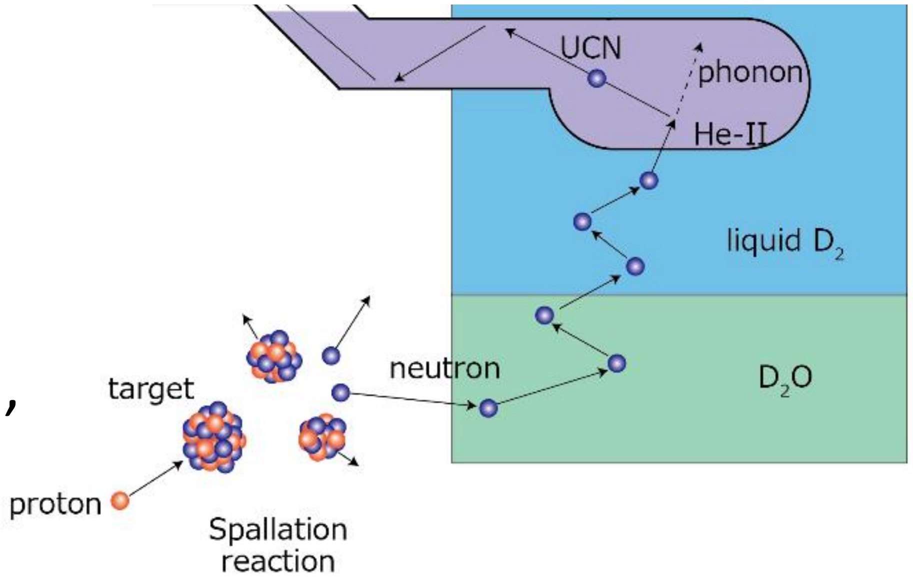

Korobkina et al., PLA **301** (2002) 462



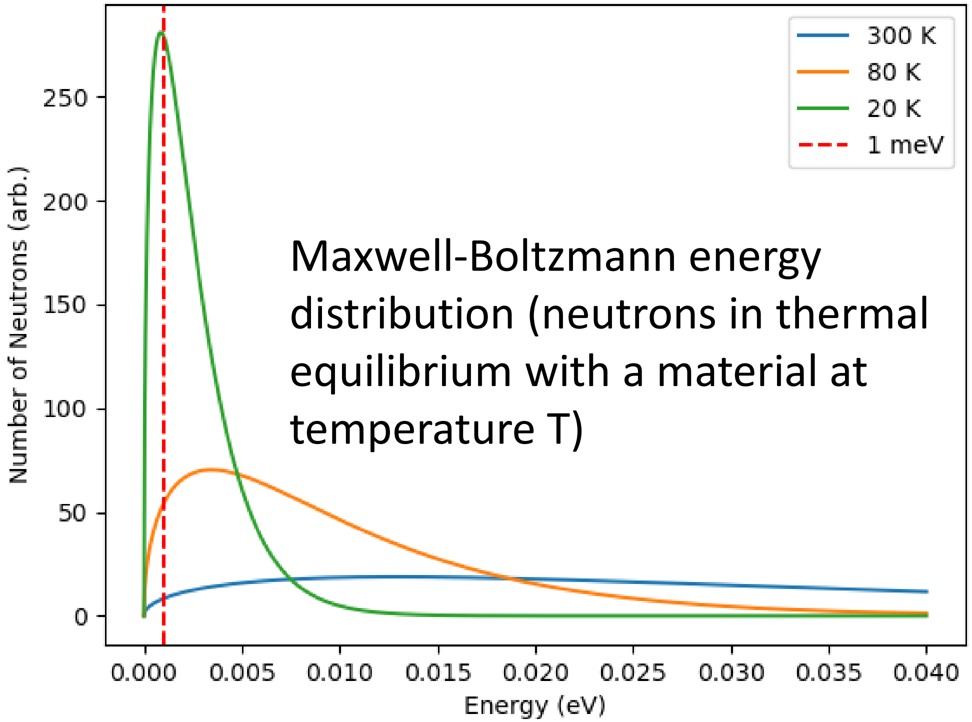
# How to cool neutrons from 1 MeV to 1 meV?

- It is easy to cool neutrons from 1 MeV to 1/40 eV = 25 meV. Let them bounce off nuclei at room temperature T = 300 K.
- e.g. a neutron moderator based on hydrogen
  - Neutrons scatter off protons elastically with $\sigma(E) = \text{const.}$ Their mfp is $\bar{\ell}_s = \frac{1}{n\sigma}$
  - After *N* collisions $\langle E \rangle_N = \left(\frac{1}{2}\right)^N E_0$, so in order to reach 25 meV, you need about 25 collisions.
  - Assuming random walk $\langle D^2 \rangle = \left(\bar{\ell}_s\right)^2 N$; *D* is roughly the thickness of material needed to thermalize.
- If you want colder neutrons, just use a colder material, like liquid hydrogen! Then *T* = 20 K or $\langle E \rangle_N$ = 2 meV.
- In general, light materials that don't absorb neutrons are best thermal moderators.
- Deuterium captures fewer neutrons, and as a result there is less gamma heating.



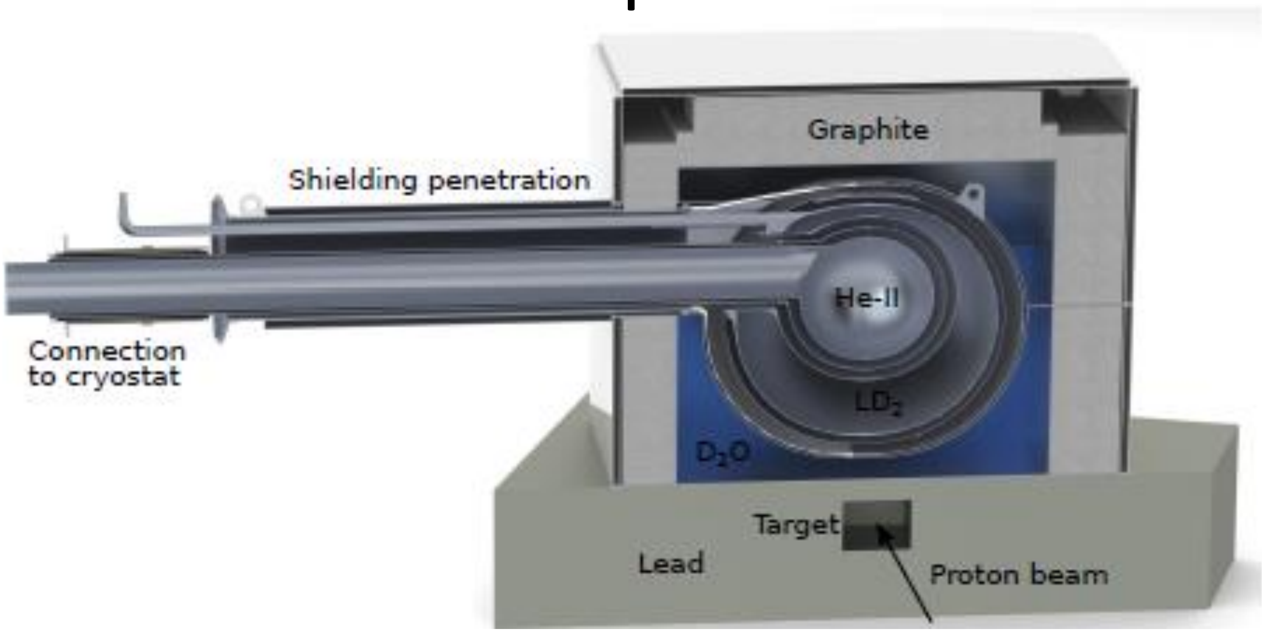
# Why $LD_2$?

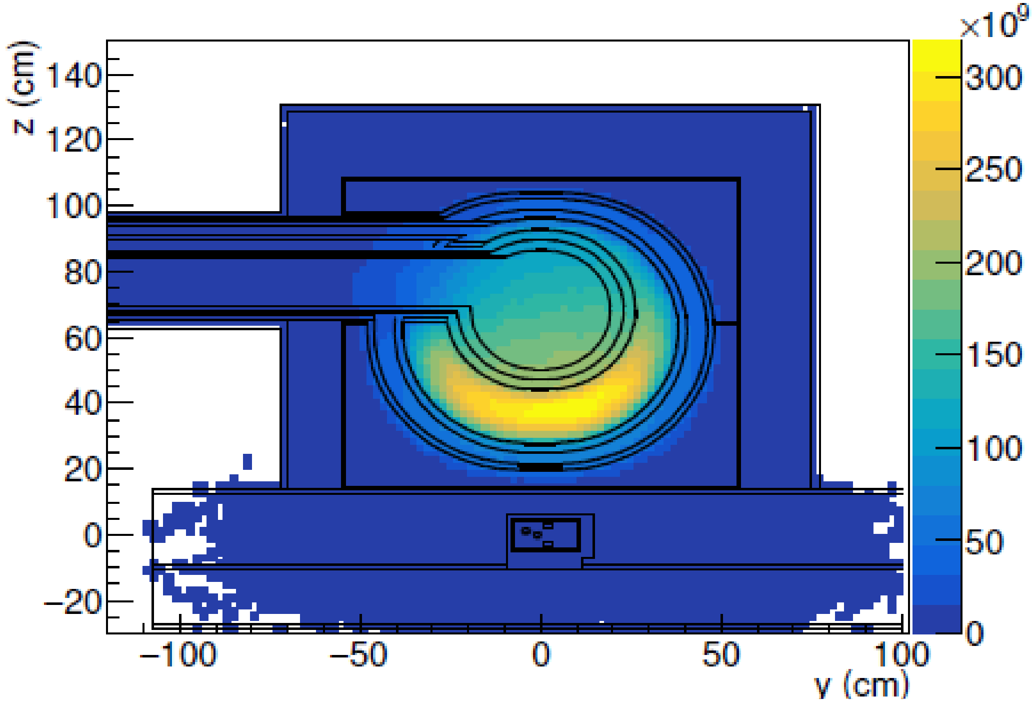
- Relative to $LH_2$:
  - The scattering cross-section is smaller (bad)
  - It's twice as heavy (bad)
  - The absorption cross-section is MUCH smaller (great!) leading to fewer losses and less gamma heating of the nearby superfluid.
- Relative to $D_2O$:
  - No problem with the oxygen in $D_2O$.
  - Crystal structure makes $D_2O$ vibrate, even at low temperatures. In previous experiments, we deduced that T = 80 K for neutrons even for much colder $D_2O$ (10 K).
  - Burping is a problem for $D_2O$. Progressive radiation damage to the crystal stores energy eventually leading to a catastrophic warm-up.
- Issues for $LD_2$:
  - Cryogenics, safety: engineering!

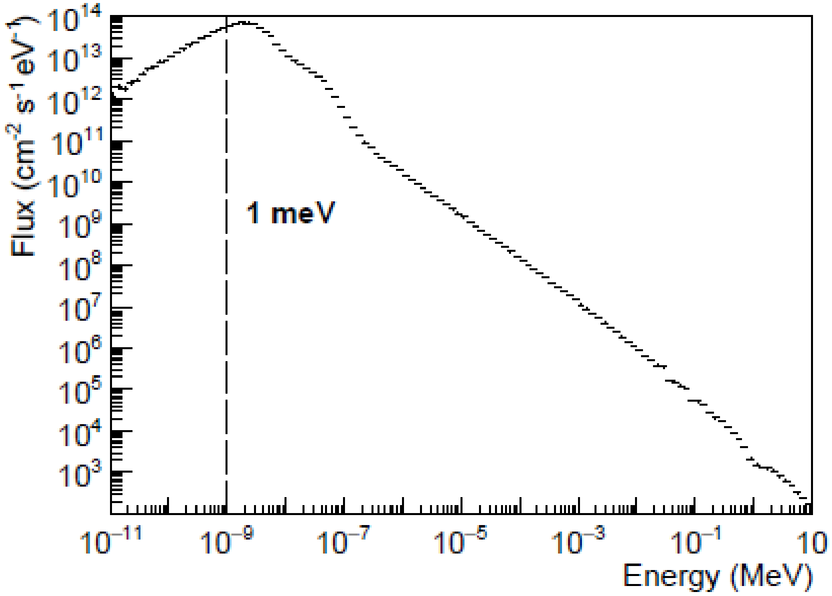



Maxwell-Boltzmann energy distribution (neutrons in thermal equilibrium with a material at temperature T)

# Neutron production and heat load requirements



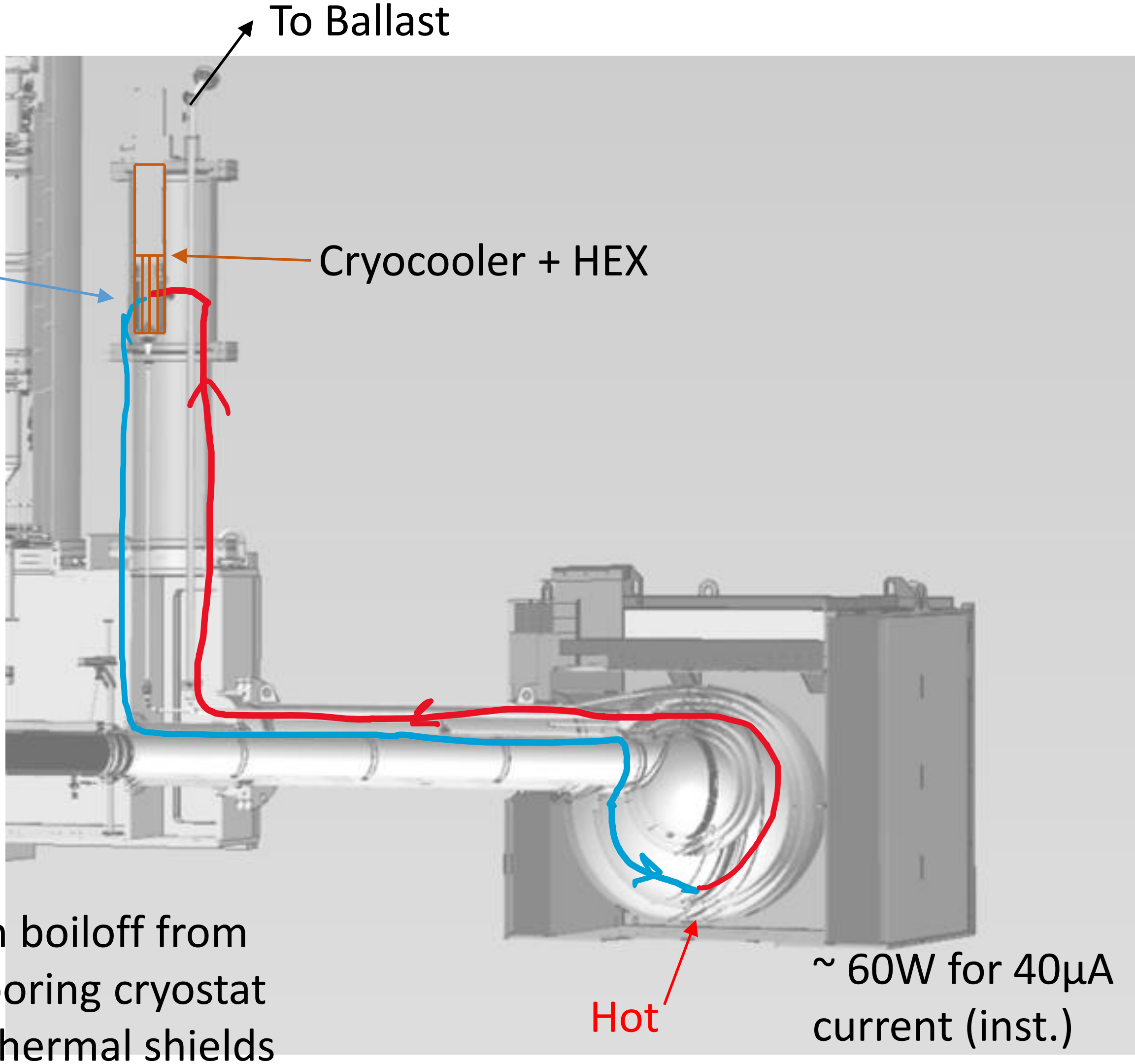




| | | Heat load (W) | |
|---|---|---|---|
| | Volume (L) | max. | average |
| UCN converter | 27 | 8.1 | 2.8 |
| Liquid deuterium | 125 | 63 | 21 |
| Heavy water | 630 | 430 | 150 |

W. Schreyer, et al., NIM A 959 (2020) 163525.

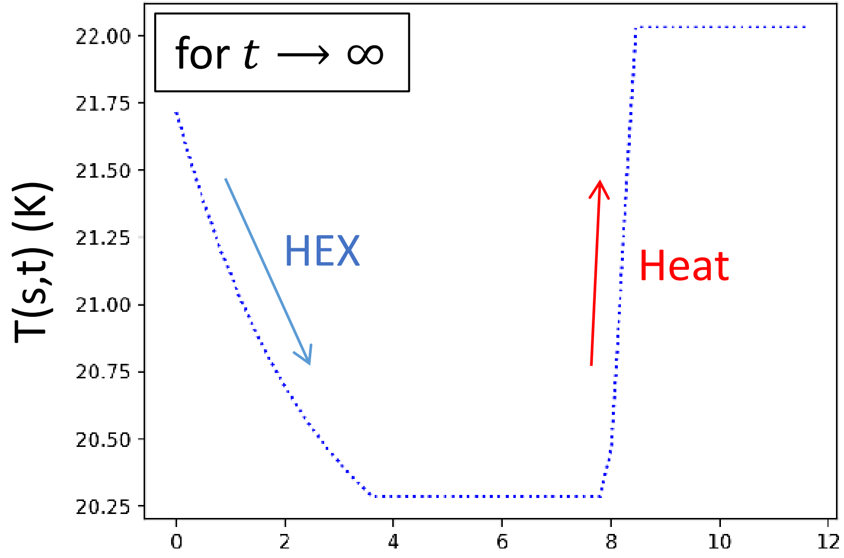
- Heat load to $LD_2$ is 60 W instantaneously.

# How to keep it cold?
# $LD_2$ thermosyphon (natural circulation system)




Helium boiloff from neighboring cryostat cools thermal shields

- Features: single-phase, no moving parts

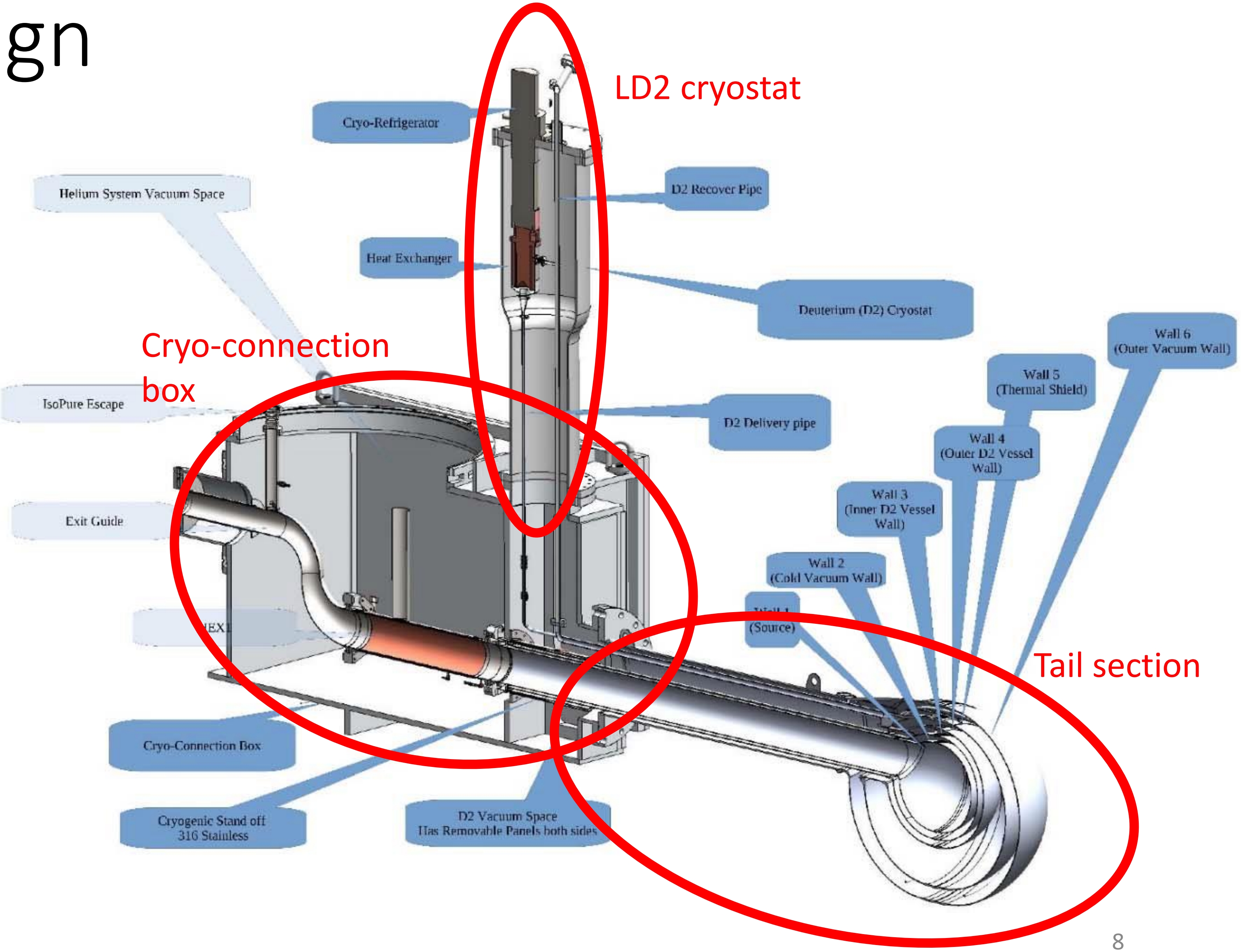



Distance along thermosyphon loop (m)

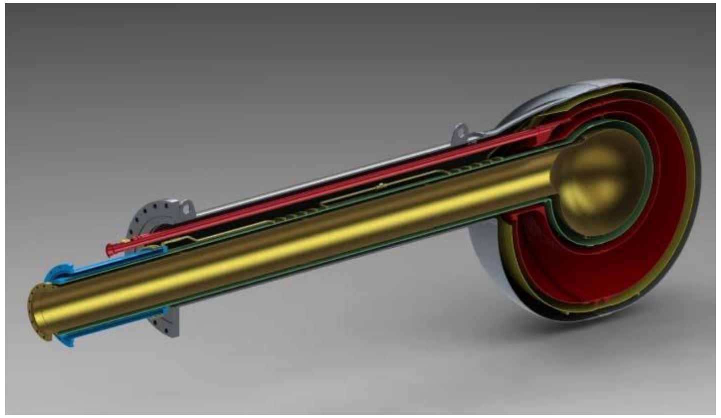
Time-dependent thermodynamic model by Kiera Augusto and Shawn Stargardter

# $LD_2$ system design

- $LD_2$ cryostat
- Cryo-connection box
- Tail section
- Also:
  - $LD_2$ gas panel
  - $LD_2$ purifier
  - $LD_2$ reservoir tank
  - Piping
  - Ventilation and safety systems



# Tail section

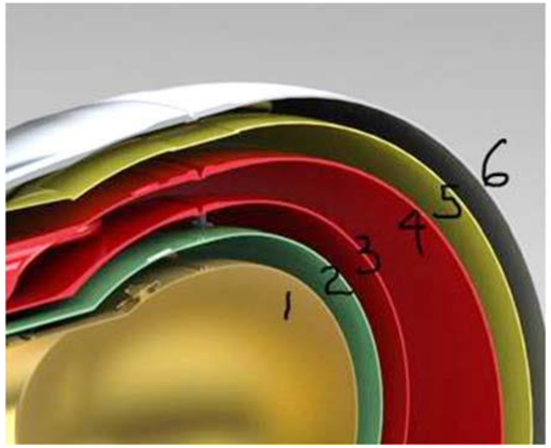


- Is absolutely in our critical path to get UCN next year!
- Innermost vessel "Wall 1" completed (it was tested with UCN at LANL!) and was leak-checked extensively.
- We have been seeking approval by the regulators in the province of BC, before proceeding with construction of other walls.
- 2021-22: welding and qualification procedures developed at TRIUMF with ASME-certified welder.
- 2023: vessel designs registered with Tech. Safety BC (CRN received)
- October 2023: documented approval to proceed with construction at TRIUMF, pending final paperwork with Tech. Safety BC.
- Welding of layer 2 has now commenced (vacuum separation wall to isolate $LD_2$ from He-II vacuum).
- Cryo-connection box installed at TRIUMF: stamped and design also registered with TSBC – it provides the interface between the $LD_2$ cryostat and the tail section.

# Construction Status

2219 Aluminum Domes

Welding of wall 2 now in progress



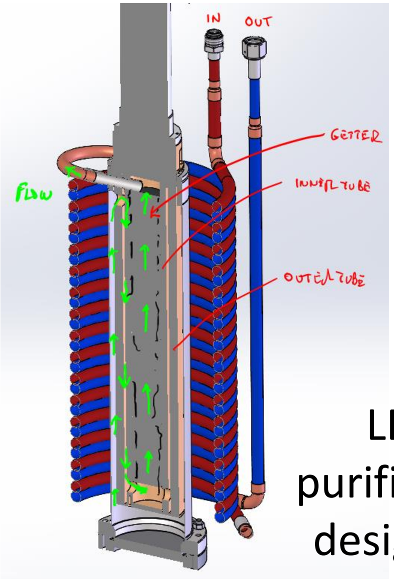


“Wall 1” in kapton super-insulation,
all sensors installed

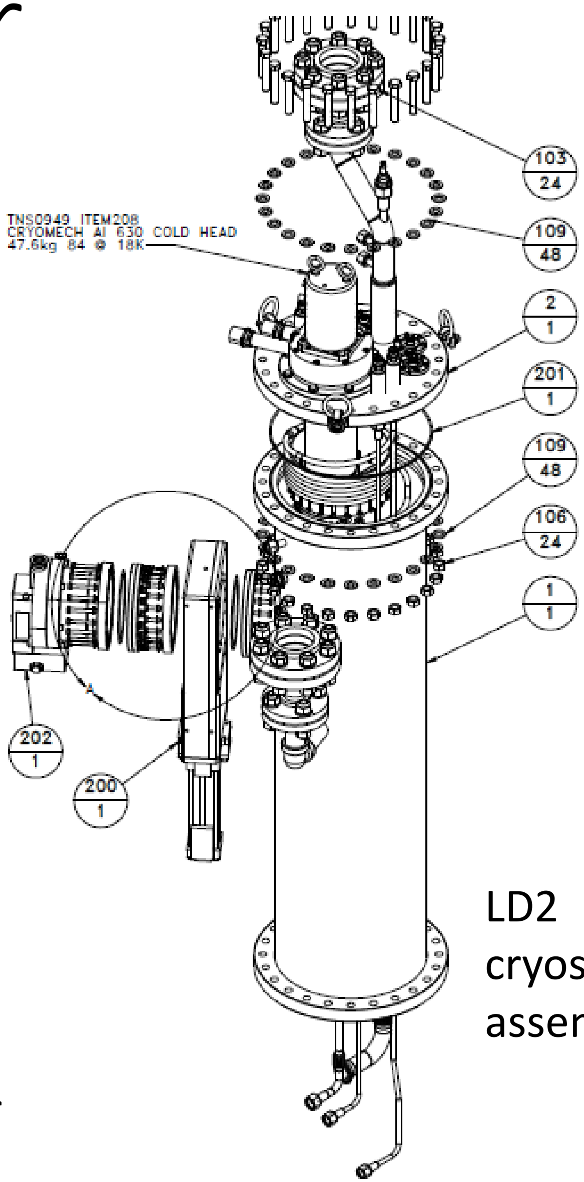
Thermal shock tests with $LN_2$

# $LD_2$ cryostat and $LD_2$ purifier

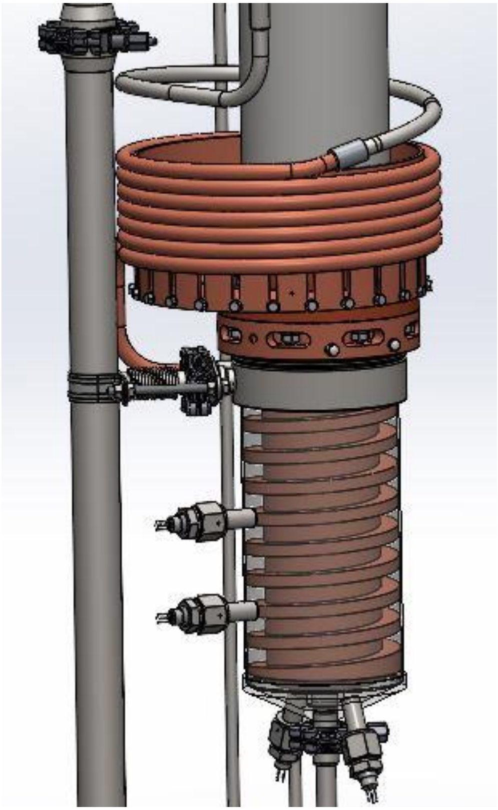
- Will be built by KEK, at JECC-Torisha, the same company that built our He-II cryostat.
- $LD_2$ purifier will be based on a similar helium purifier that is already being built by KEK/JECC-Torisha.
- $LD_2$ cryostat design completed at TRIUMF. Detailed design is being discussed with JECC-Torisha for manufacture.




LD2 purifier design



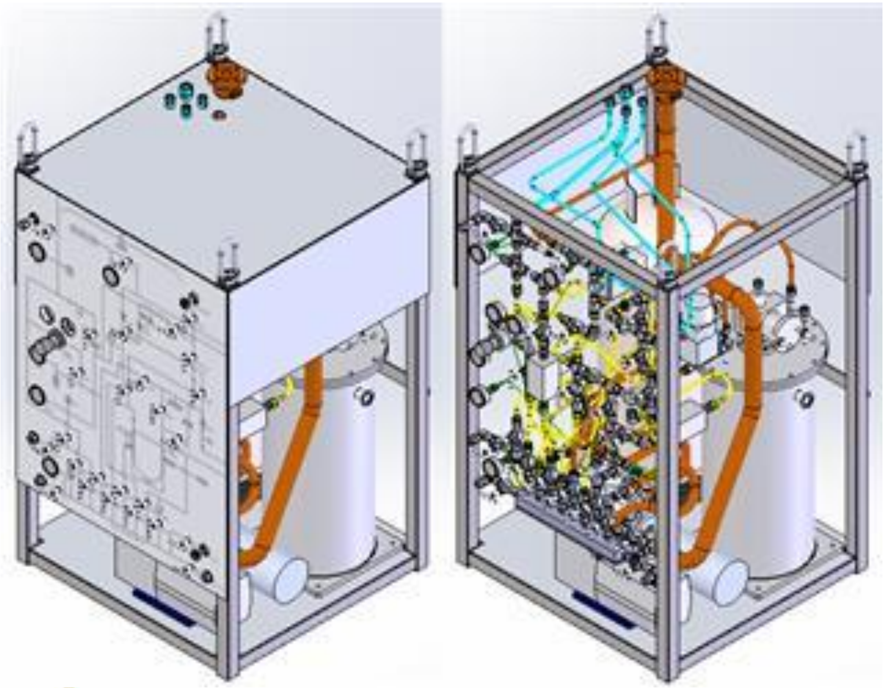

LD2 cryostat assembly

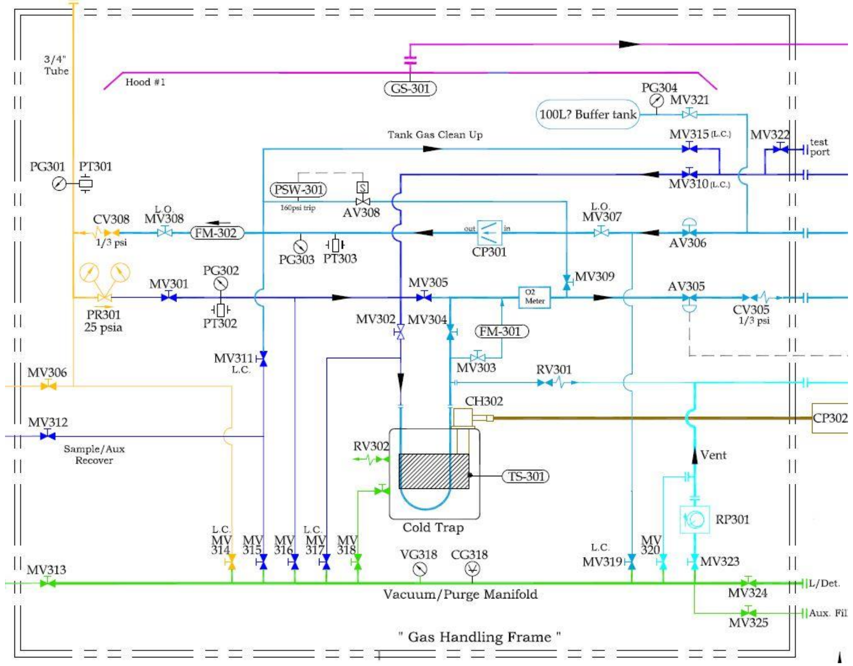


LD2 Heat exchanger section

# $LD_2$ gas panel

- Initial design complete.
- Most critical parts already received. Orders for standard parts are commencing.
- Is be built at TRIUMF (experience building $^3He/^4He$ gas panel), ready to begin building it.
- $LD_2$ piping and safety systems
  - Piping to be completed by certified welder.
  - Vent pipe design being completed by PhD student Shawn Stargardter
  - Ventilation requires two explosion-proof fans, $D_2$ gas sensors and alarms.
  - Various hazard scenarios have been addressed, such as BLEVE and ignition.





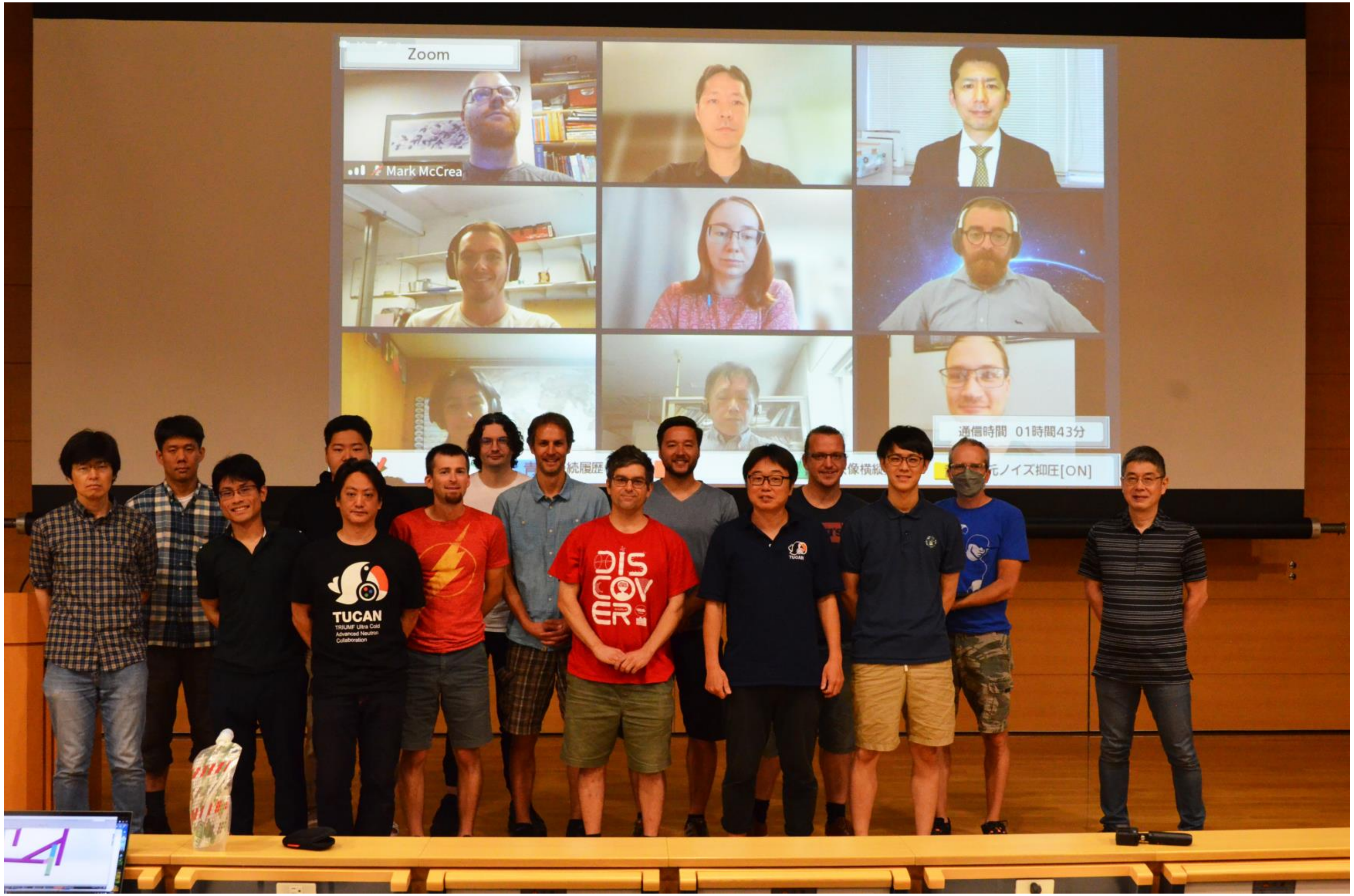
# Summary and final thoughts

TUCAN

- The TUCAN source needs a large flux of 1 meV neutrons, so that they can downscatter in superfluid helium and become ultracold.
- An $LD_2$ moderator at 20 K has been optimized to provide the 1 meV neutrons.
- The system relies on a thermosyphon design to cool the $LD_2$.
- The $LD_2$ system component pieces (tail section, cryostat, heat exchanger, purifier, …) are being built or prepared for construction.
- Goal to complete tail section so that it can be installed by May 2024 during the TRIUMF main shutdown.
- Other $LD_2$ system parts will be completed in 2024 and can be installed as a non-shutdown task in 2024/2025 when ready.

# Thank you!

Collaboration meeting at KEK, August 2023




TUCAN

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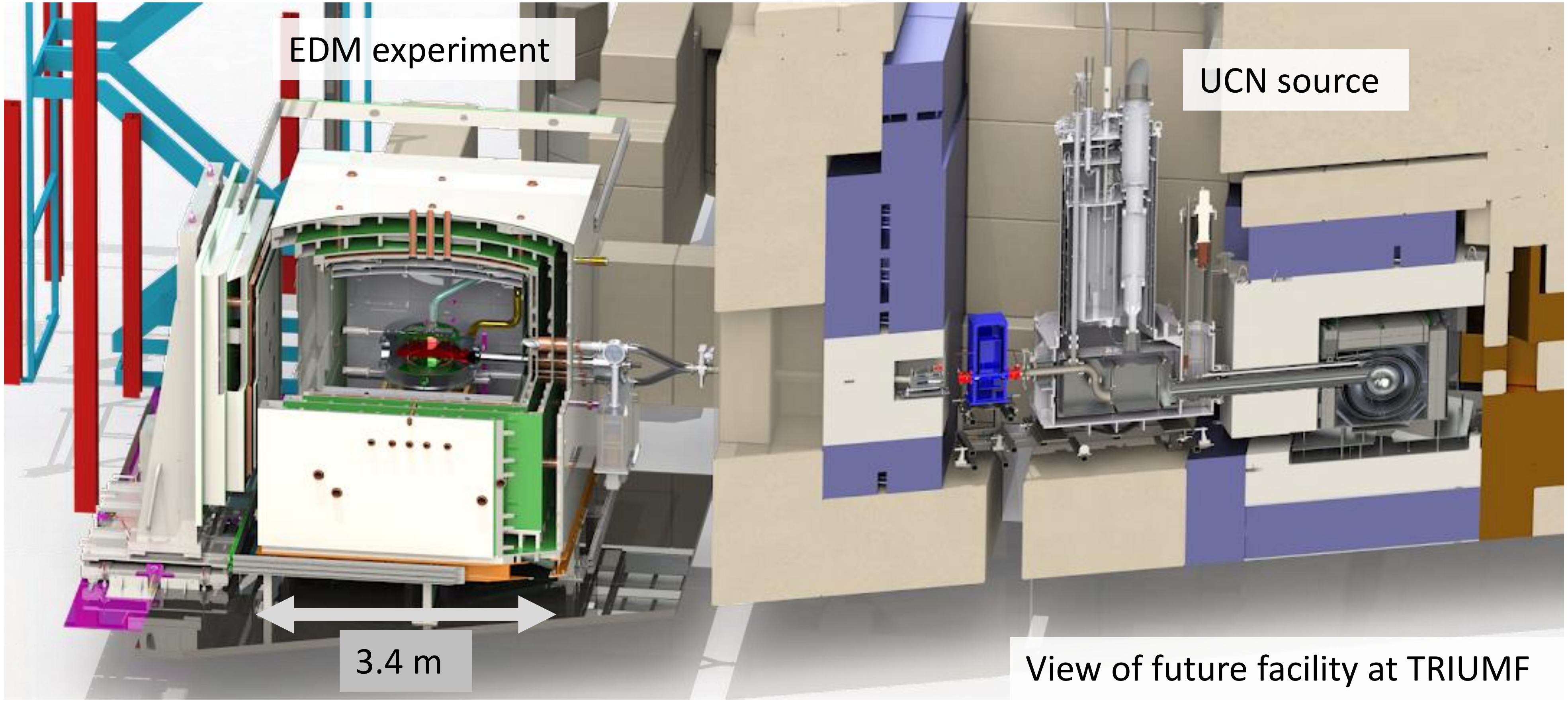
NSERC CRSNG

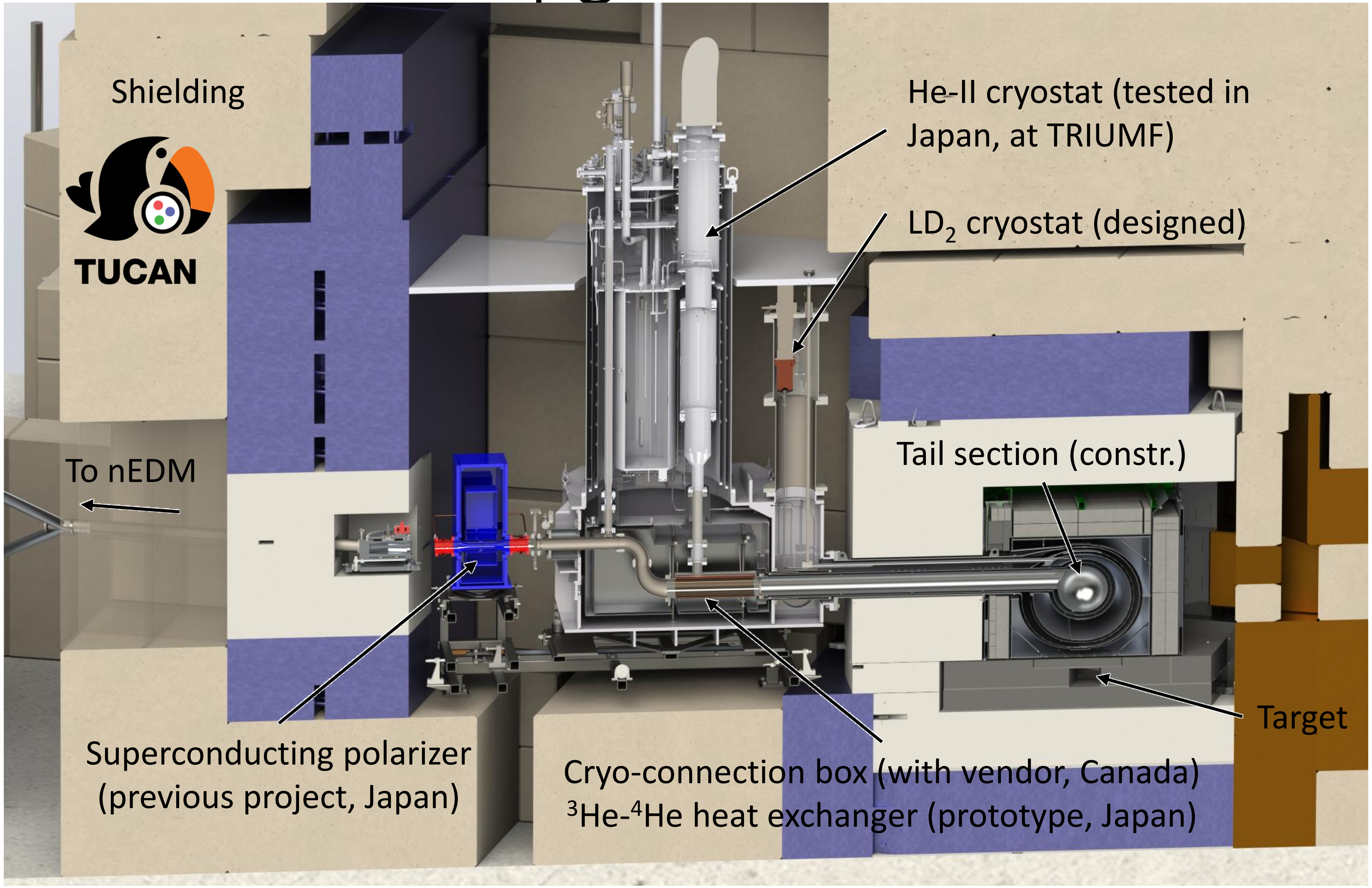
CANADA RESEARCH CHAIRS
CHAIRES DE RECHERCHE DU CANADA

# TUCAN source and EDM Experiment

- Enable search for neutron EDM with $1 \times 10^{-27}$ *e*cm precision.

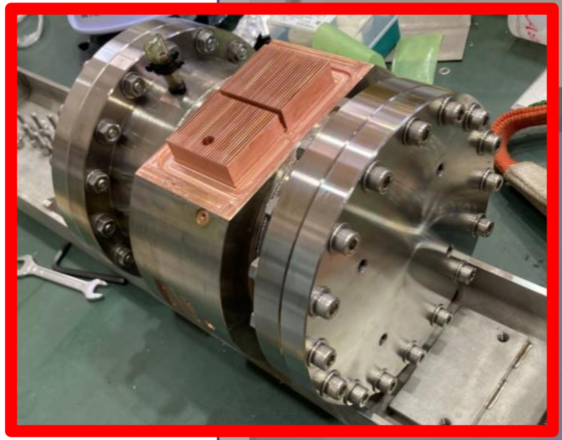


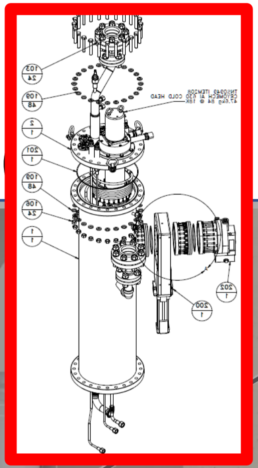
# Horizontal source upgrade



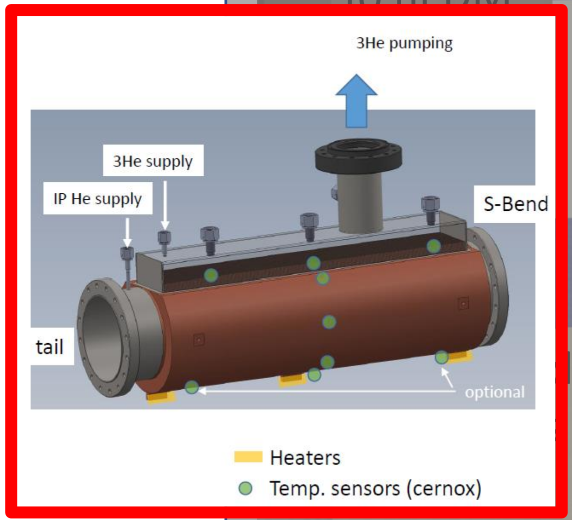
# Horizontal s

Shielding

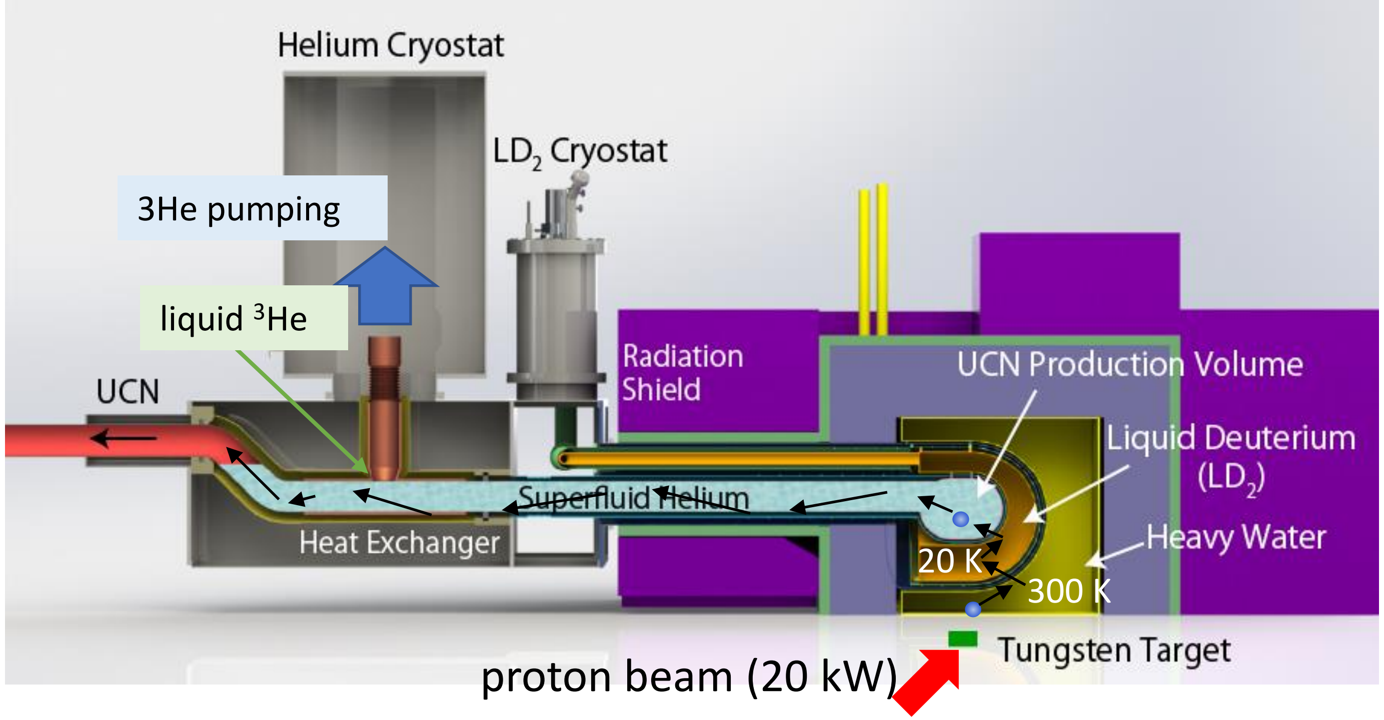


To nEDM

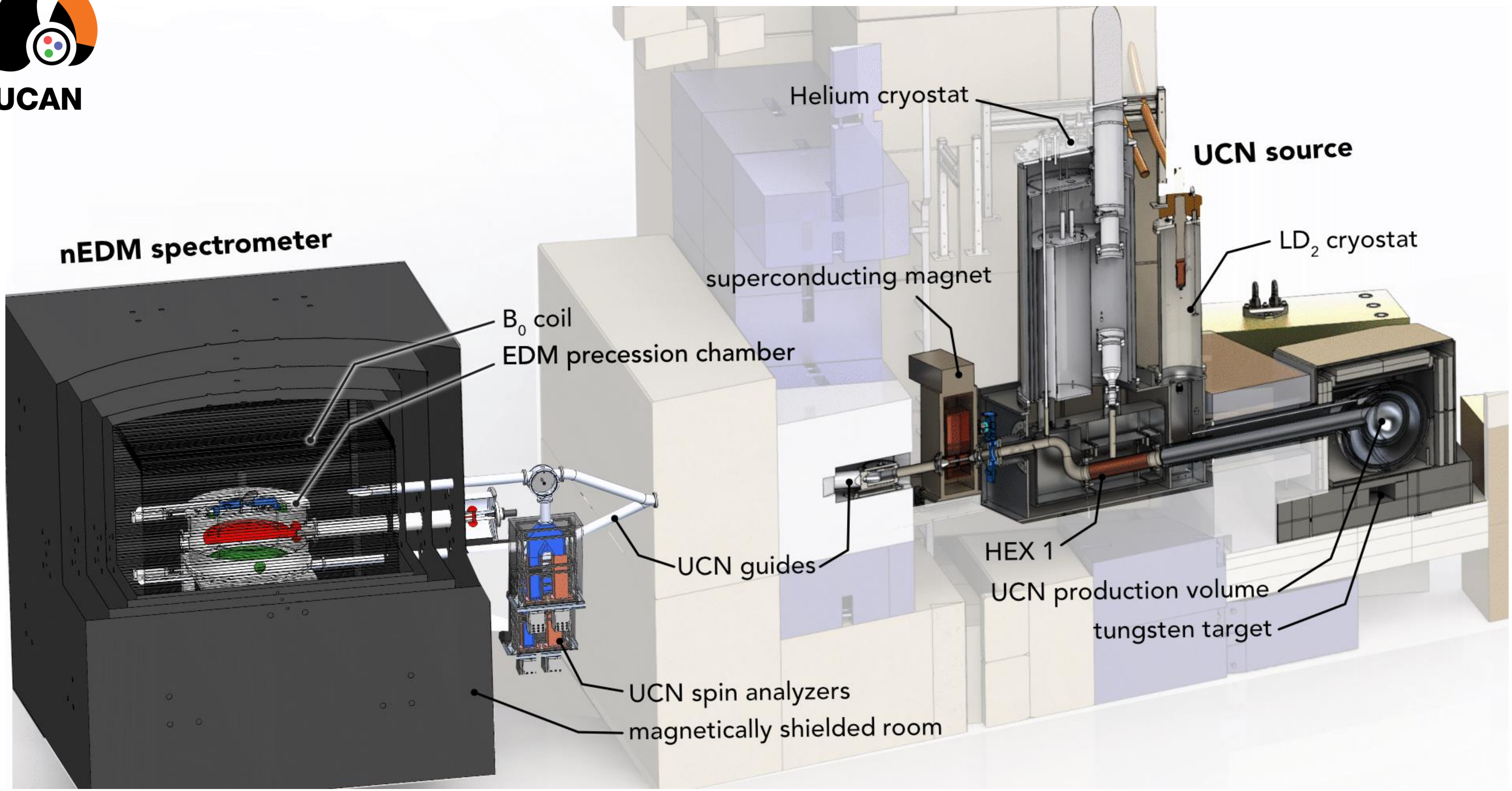



# TUCAN Source Upgrade Concept and Goals

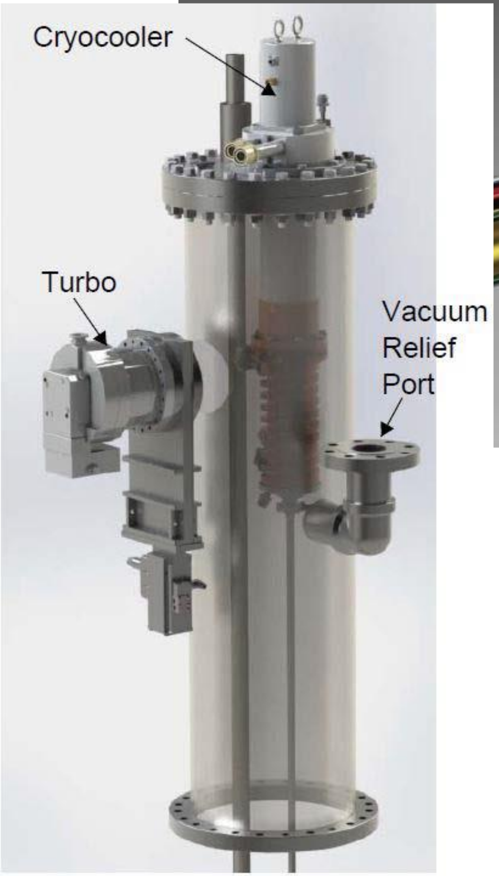


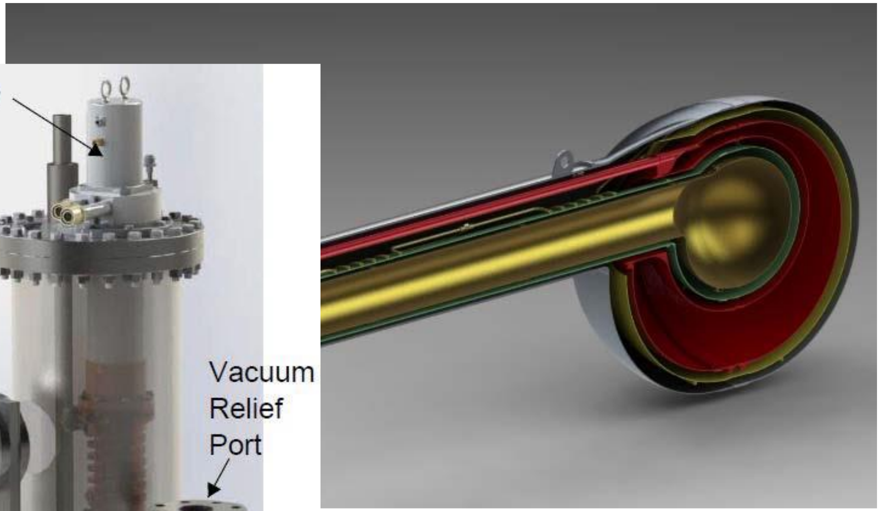

- $LD_2$ moderator
  - increase cold neutron flux at 1 meV (×2.5)
- Helium Cryostat with high cooling power
  - production volume (×3)
  - proton beam power (×50)
    - 0.5 kW -> 20 kW
    - heat load on superfluid : 8.1 W
      - include heat deposit on vessel
  - superfluid helium temperature (×1/3)
    - $T_{He\text{-}II}$ = 1.2 K (0.8 K@RCNP)
    - Storage lifetime : ～ 30 sec
- Estimated source performance
  - production rate: $1.4 \times 10^7$ UCN/s
  - UCN density
    - $6 \times 10^3$ UCN/cm$^3$ @ production
    - ～220 UCN/cm$^3$ @ measurement

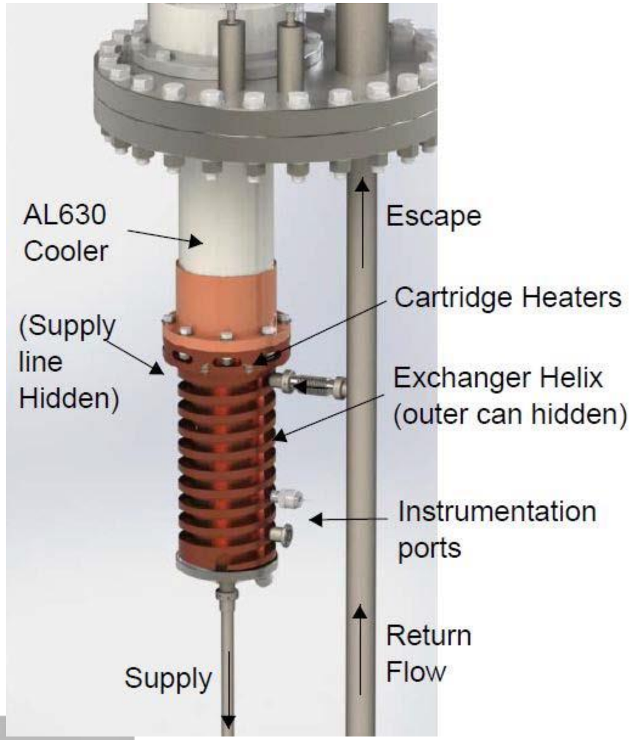
**TUCAN**



nEDM spectrometer
$B_0$ coil
EDM precession chamber
UCN guides
UCN spin analyzers
magnetically shielded room
Helium cryostat
superconducting magnet
UCN source
$LD_2$ cryostat
HEX 1
UCN production volume
tungsten target


Cryocooler
Turbo
Vacuum
Relief
Port




AL630
Cooler
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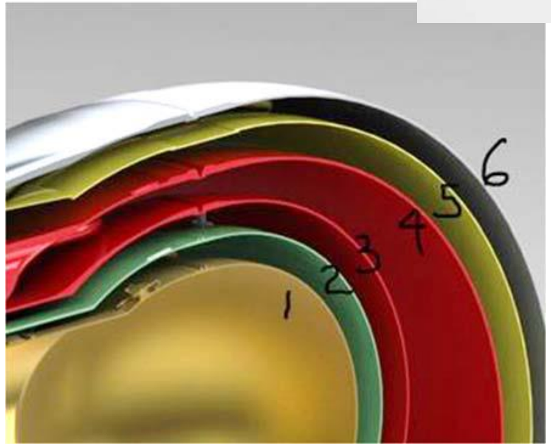
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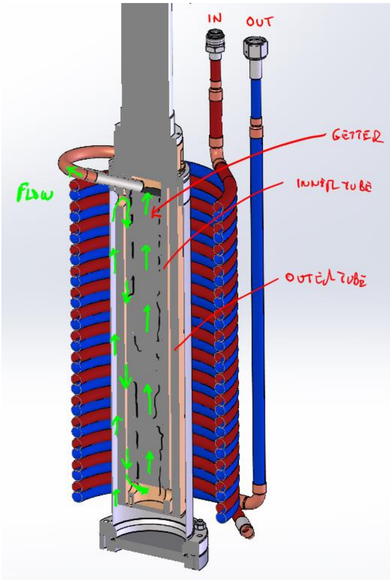
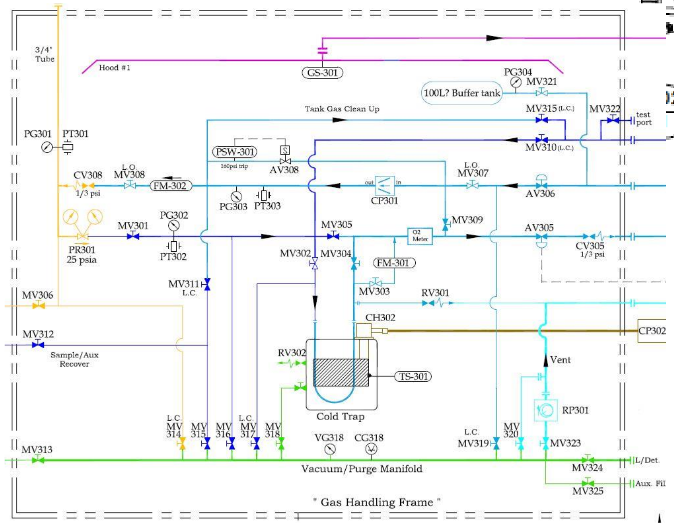
# LD2 cryostat system – C. Marshall, et al. (TRIUMF)

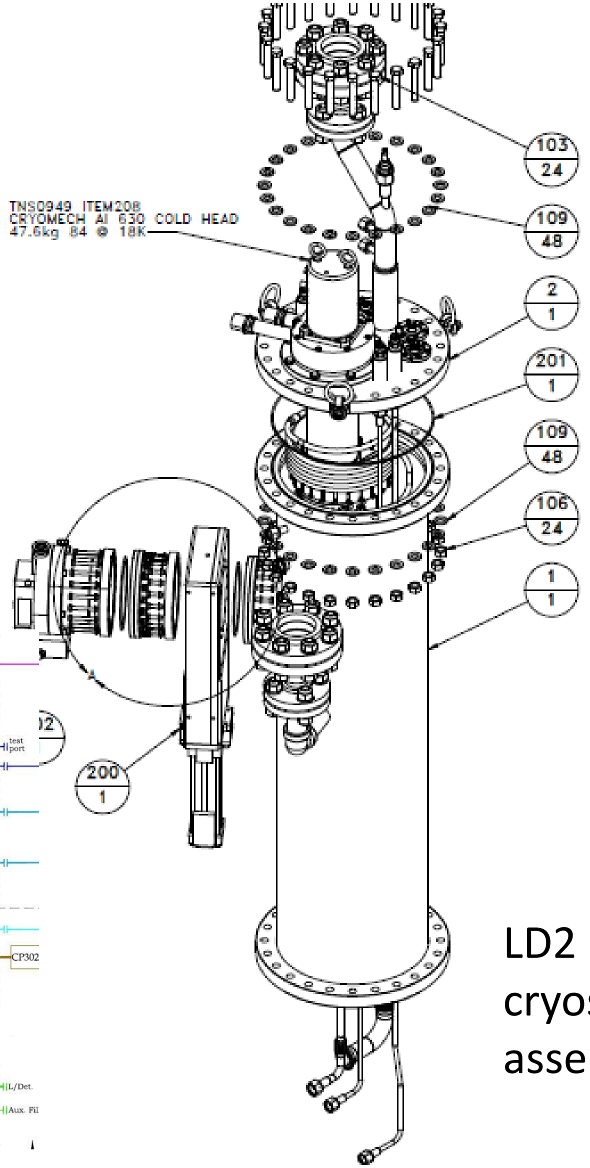
D2 storage tank installed October 2022


LD2 purifier design

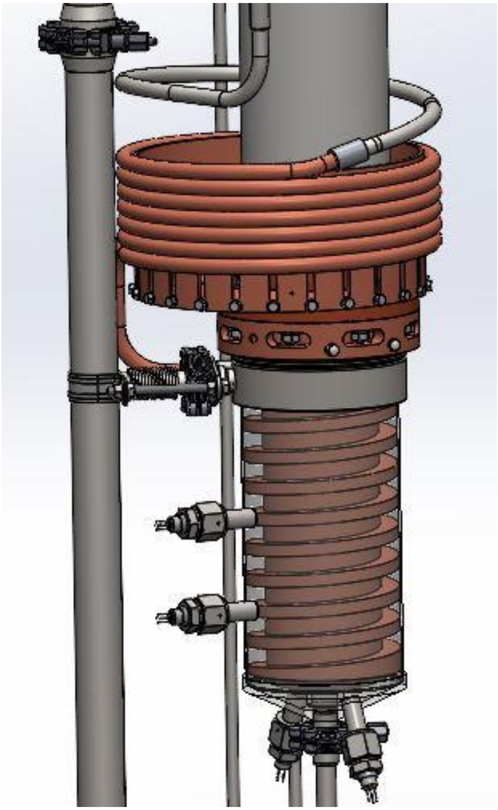



Gas handling design




LD2 cryostat assembly



LD2 Heat exchanger section