The liquid deuterium moderator for TUCAN

See also:
M. McCrea, T2-6
S. Vanbergen, T4-6

TRIUMF Ultra-Cold Advanced Neutron collaboration

Jeff Martin

The University of Winnipeg

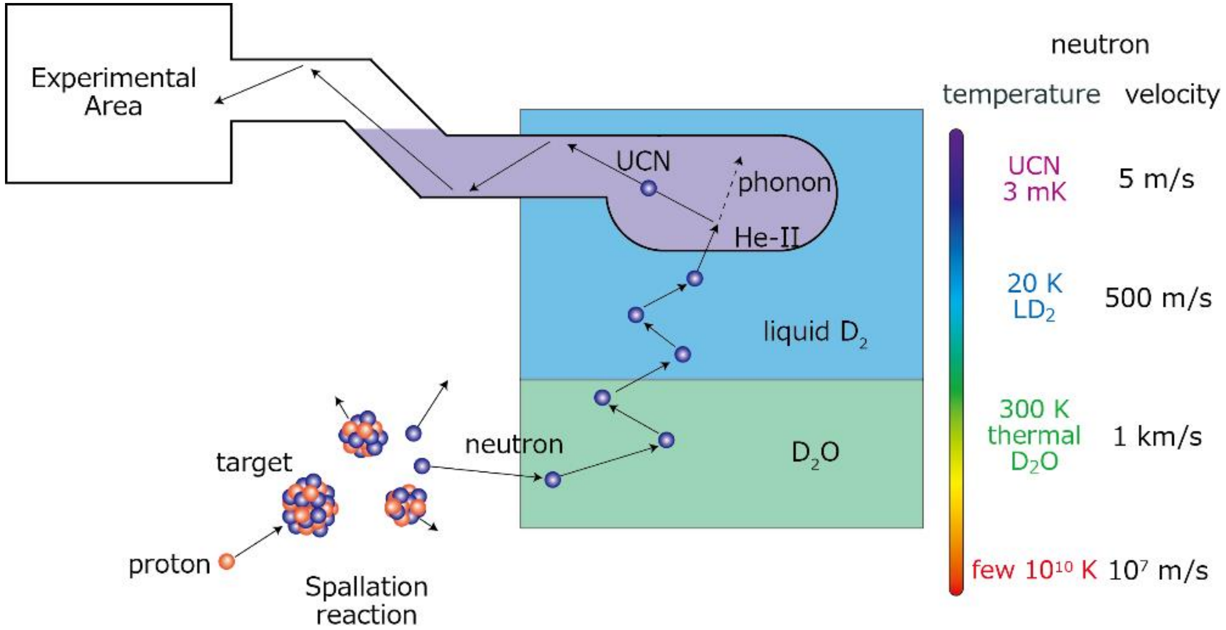
Land acknowledgement

We acknowledge that we are gathered 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

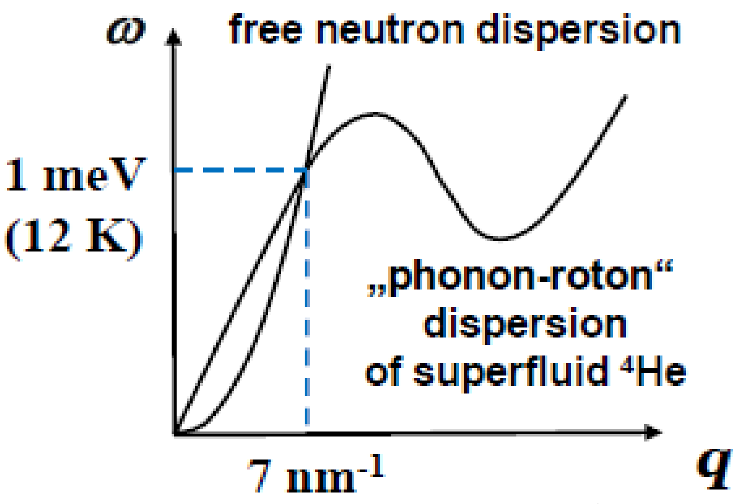
- Concept:
  - Use superfluid helium (He-II) to convert cold neutrons into **ultracold neutrons**.
  - Couple the He-II directly to a spallation source of neutrons and cold moderators that can be optimized fully.
  - Transport UCN to a room-temperature **neutron EDM experiment** located farther away 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**.



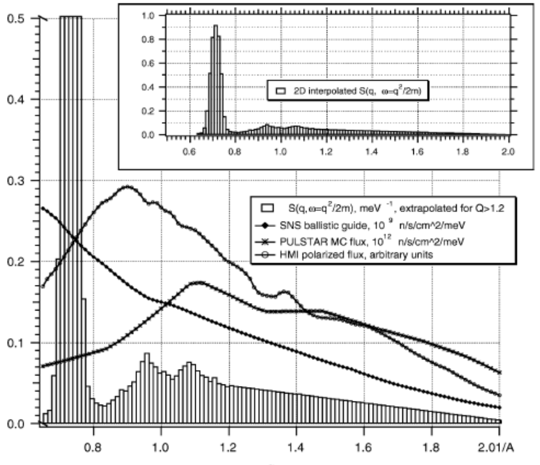
UCN production and losses in superfluid ^{4}He

- 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 τ_{UCN} = 64 s
  - We must keep the superfluid much colder than T_λ

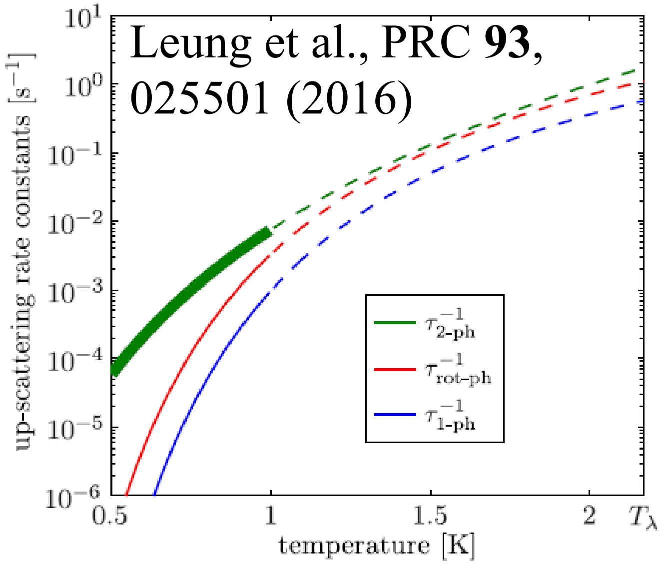
Maximize 1 meV neutrons;
Minimize losses, heat.



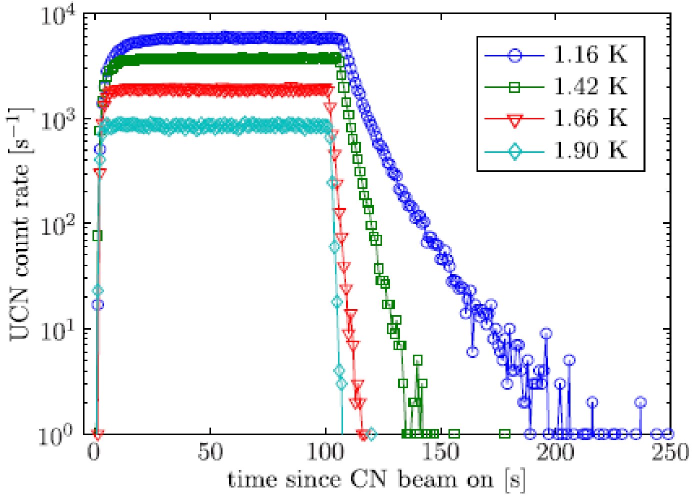
Courtesy O. Zimmer



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

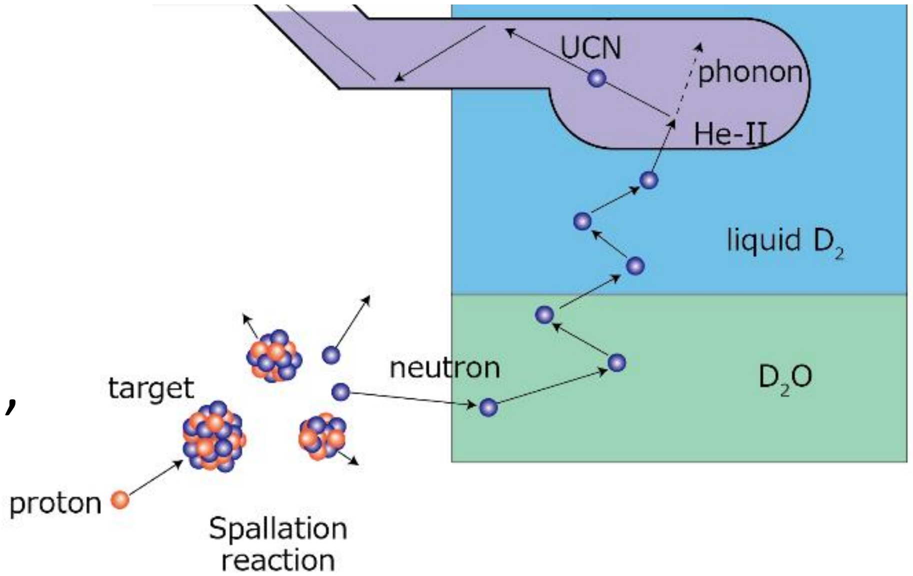


Leung et al., PRC **93**, 025501 (2016)

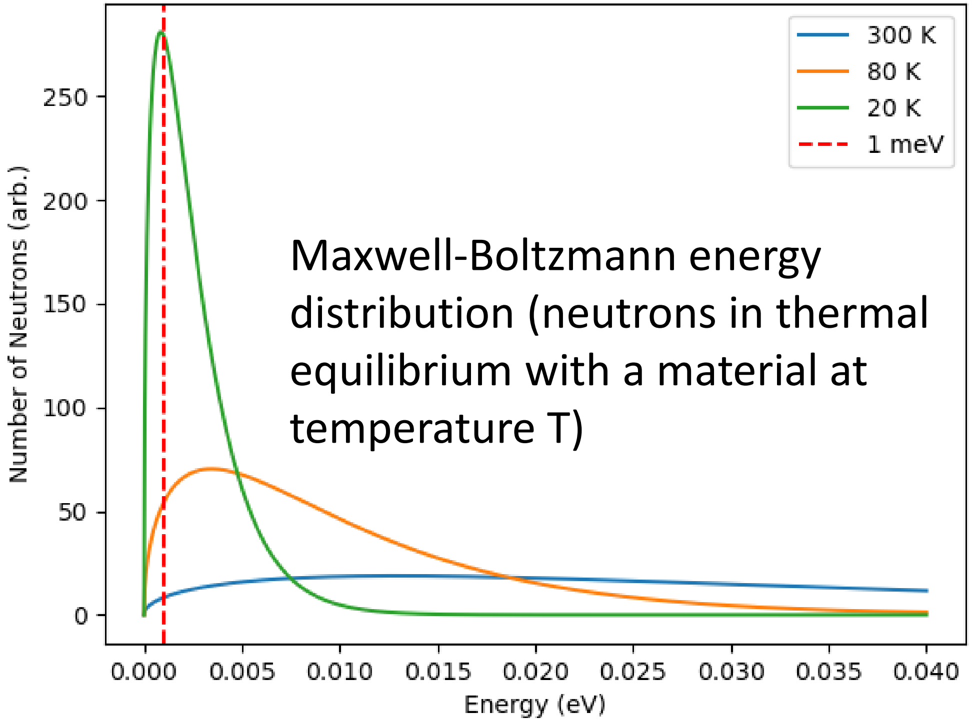


How to cool neutrons from 1 MeV to 1 meV?

- 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.



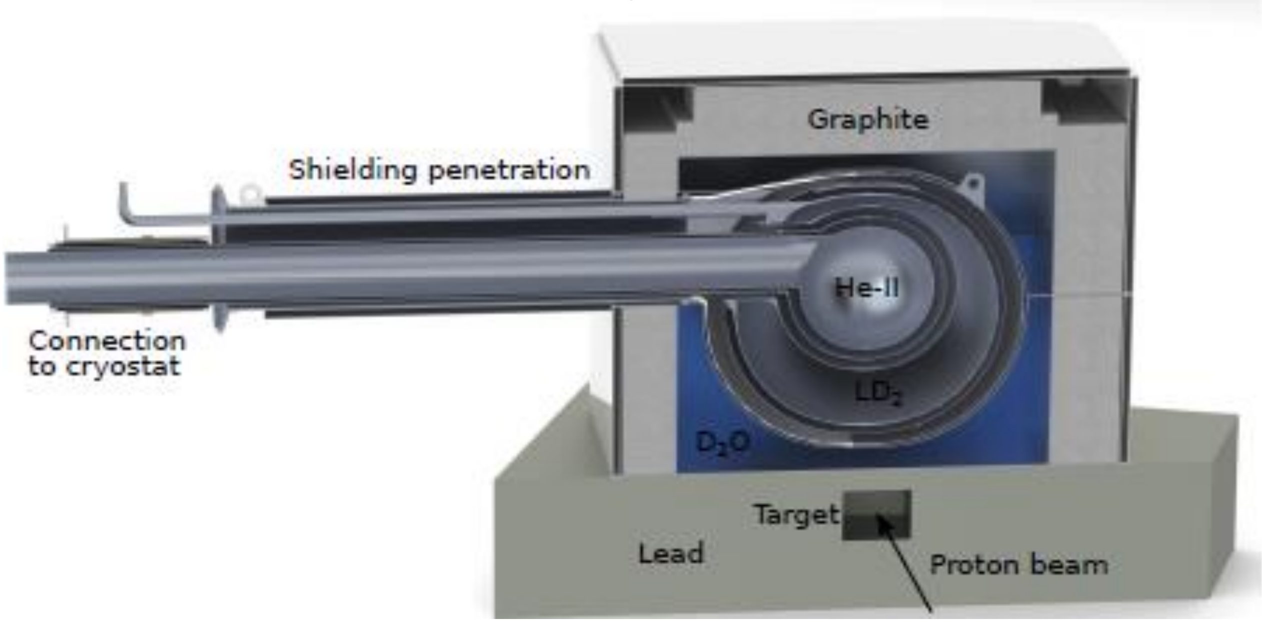
Why LD_2?

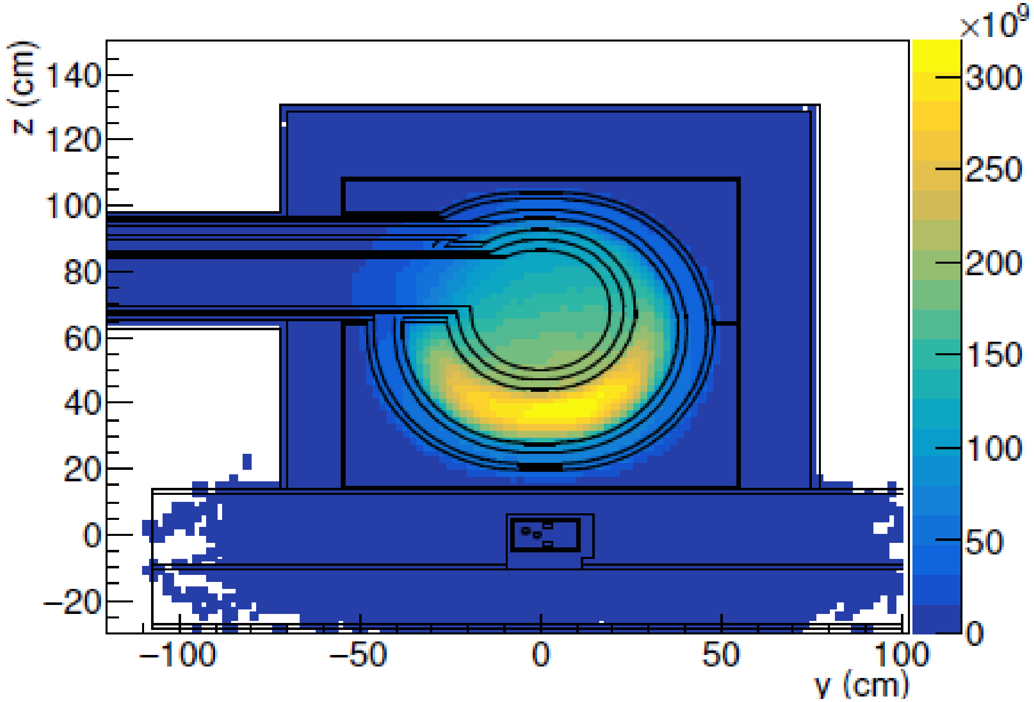


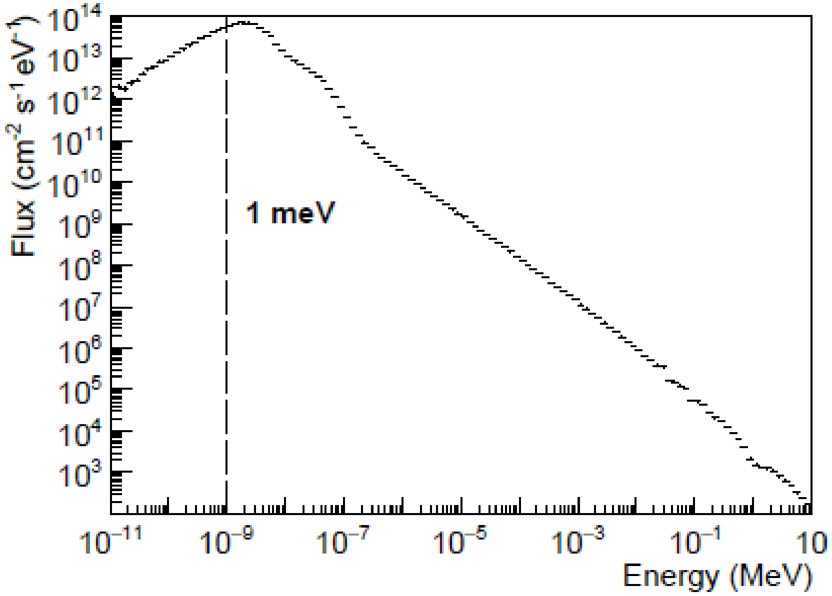
Maxwell-Boltzmann energy distribution (neutrons in thermal equilibrium with a material at temperature T)

- Relative to LH_2:
  - The scattering cross-section is smaller (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 in much colder D_2O.
  - 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!

Neutron production and heat load requirements





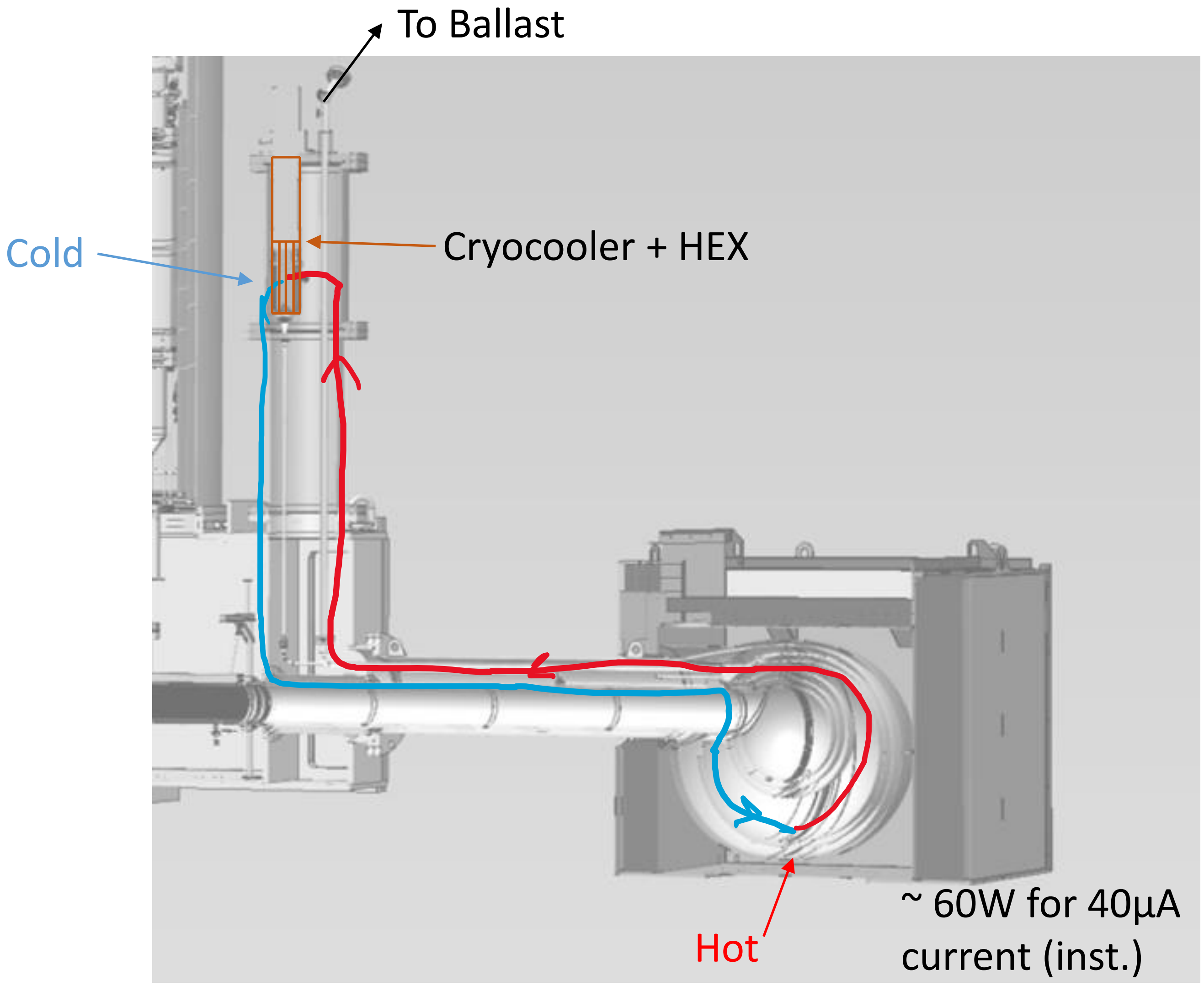


	Volume (L)	Heat load (W)	
		max.	average
UCN converter	27	8.1	2.8
Liquid deuterium	125	63	21
Heavy water	630	430	150

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

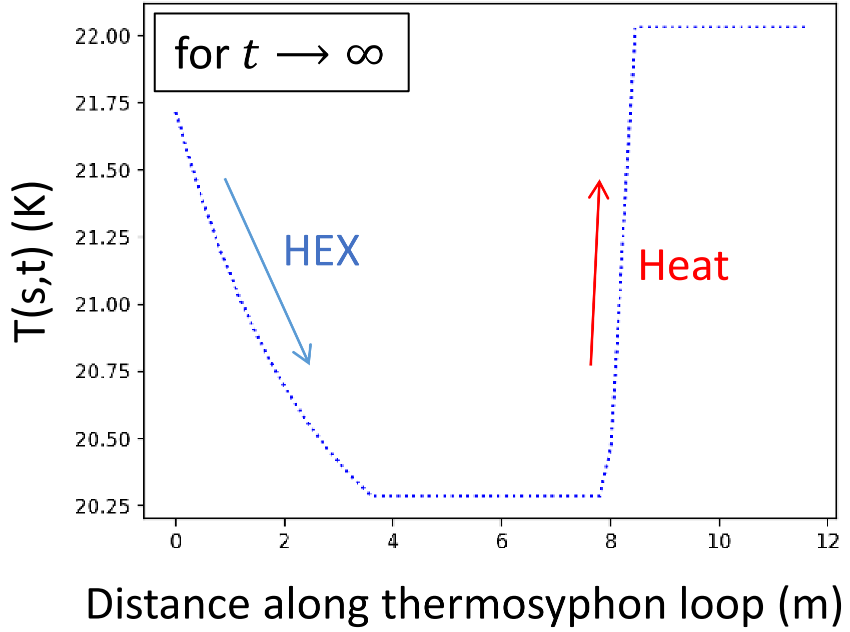
- Heat load to LD2 is 60 W instantaneously.

How to keep it cold?
LD$_2$ thermosyphon (natural circulation system)



~ 60W for 40µA current (inst.)

- Features: single-phase, no moving parts



Time-dependent thermodynamic model by Kiera Augusto and Shawn Stargardter

Construction Status

2219 Aluminum Domes

- Innermost vessel "Wall 1" completed (it has even been tested with ultracold neutrons!)
- Now preparing and assembling the layers of the other vessels; the next layer to be assembled is the LD_2 layer.

"Wall 1" in kapton super-insulation, all sensors installed

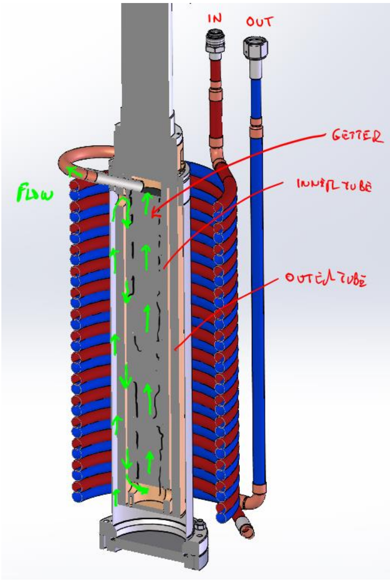
Thermal shock tests with LN2

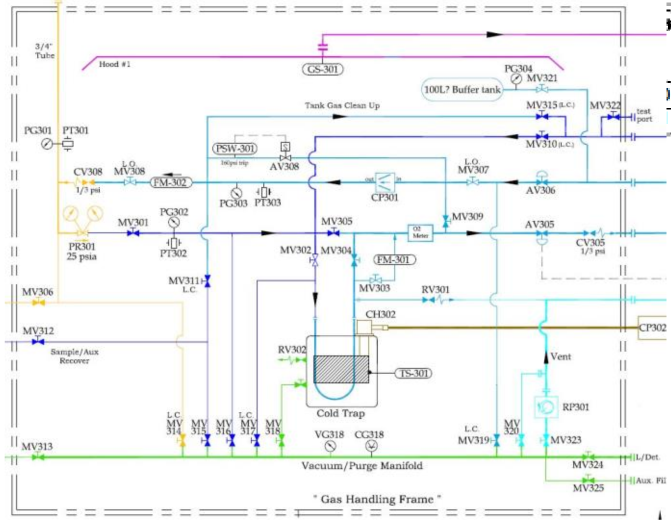
LD2 Cryostat – C. Marshall, et al. (TRIUMF)

- Expert review of the LD2 system - Completed **Oct 2022.**
- Detailed drawings are now complete.
- Many parts starting to come together.

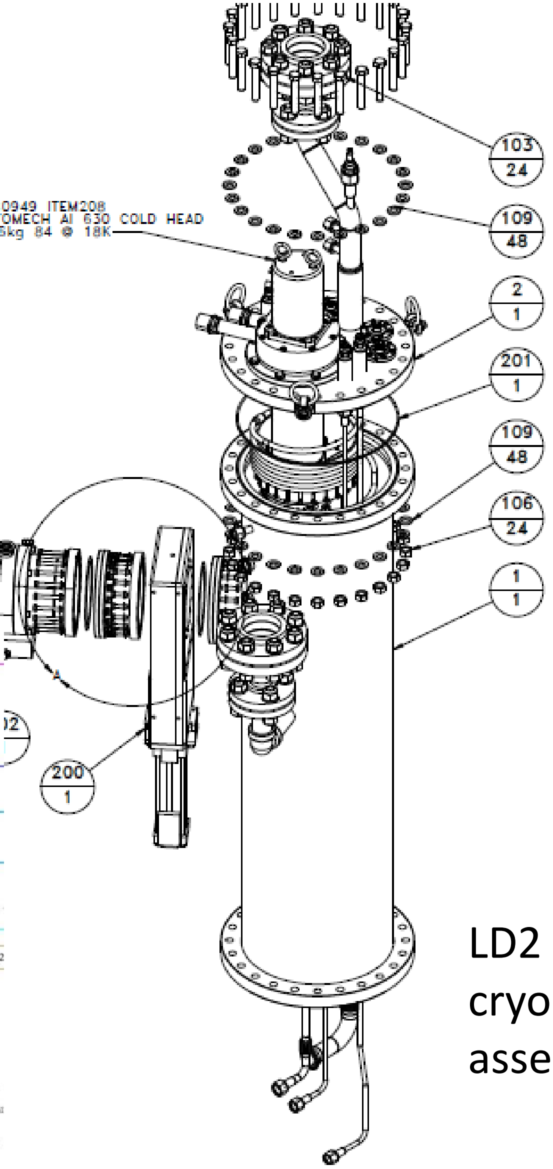
D2 storage tank installed October 2022

LD2 purifier design

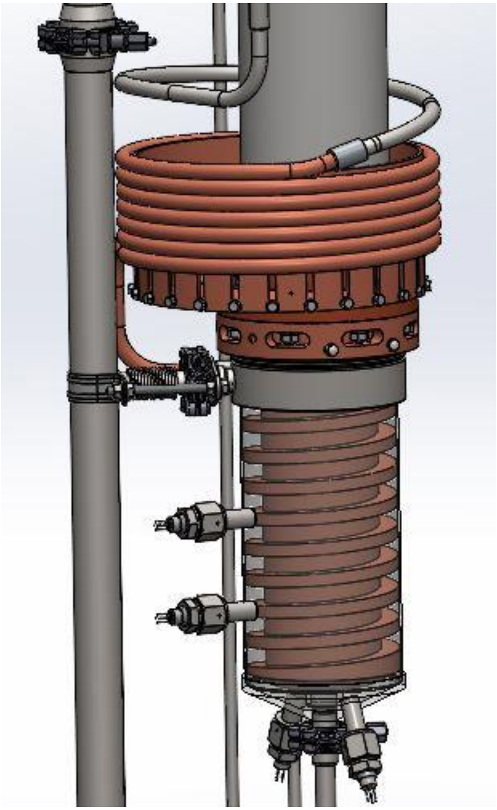




Gas handling design



LD2 cryostat assembly



LD2 Heat exchanger section

Summary and final thoughts

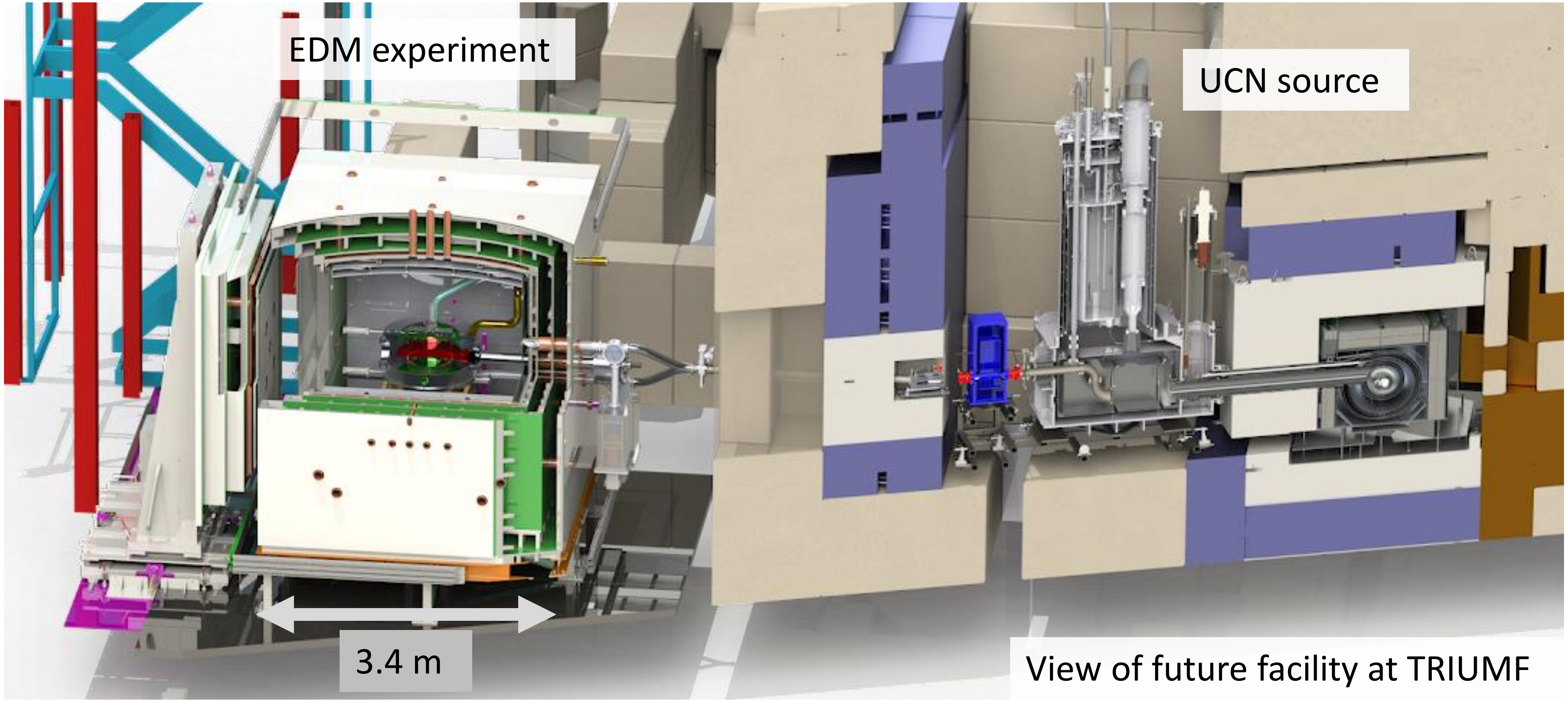
- The TUCAN source needs a large flux of 1 meV neutrons, so that they can downscatter in superfluid helium and become ultracold.
- An LD_2 moderator at 20 K has been optimized to provide the 1 meV neutrons.
- The system relies on a thermosyphon design to cool the LD_2.
- The technical design of the LD_2 moderator is nearing completion, with the component pieces (cryostat, heat exchanger, purifier, …) being prepared for construction.
- The LD_2 system will be completed in 2024.

Thank you!

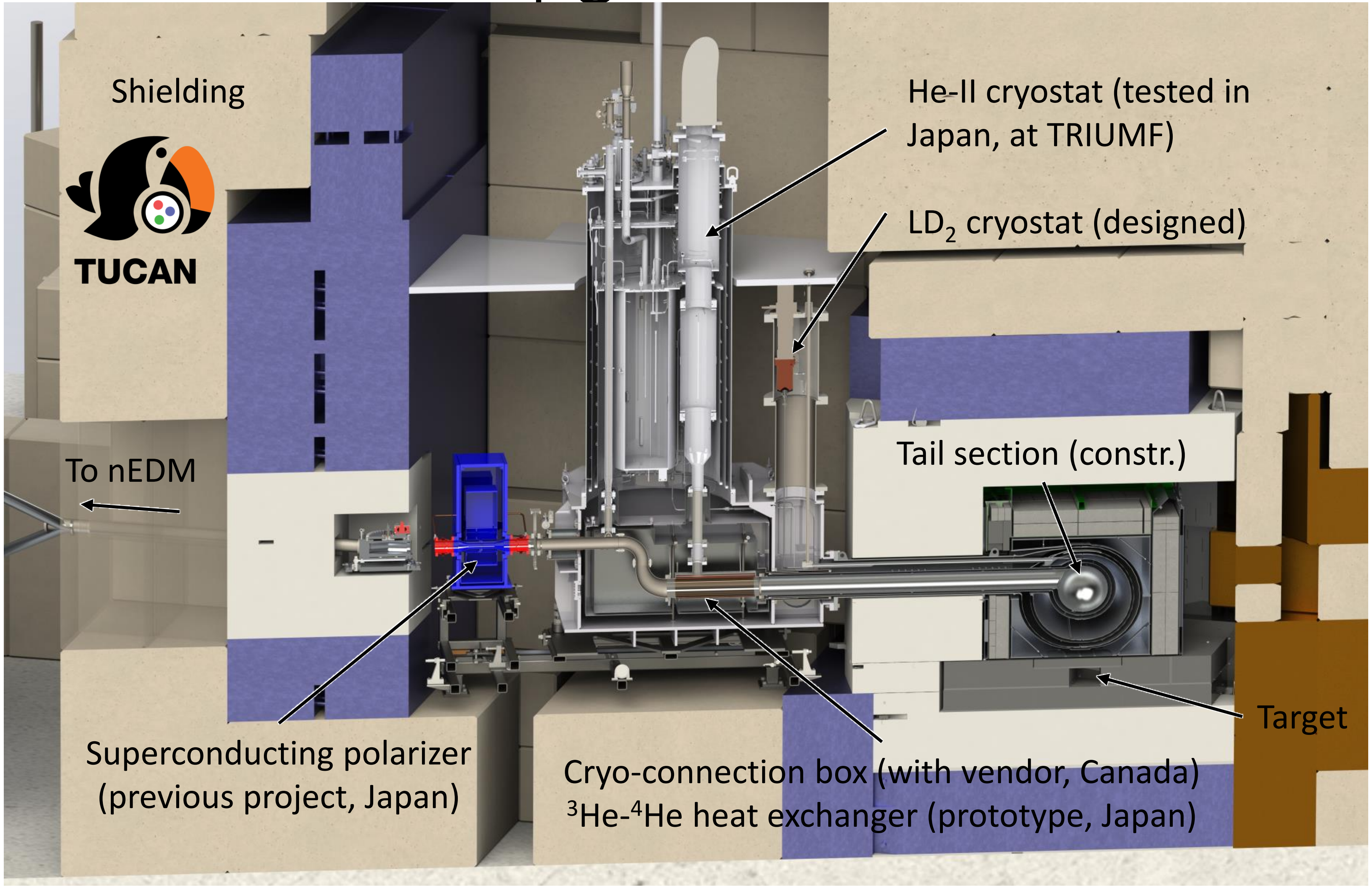
Collaboration meeting January 2023

TUCAN source and EDM Experiment

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



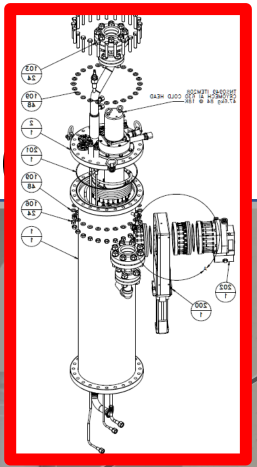
Horizontal source upgrade

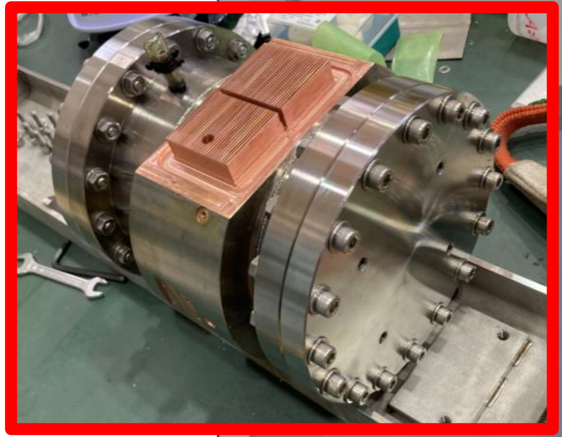


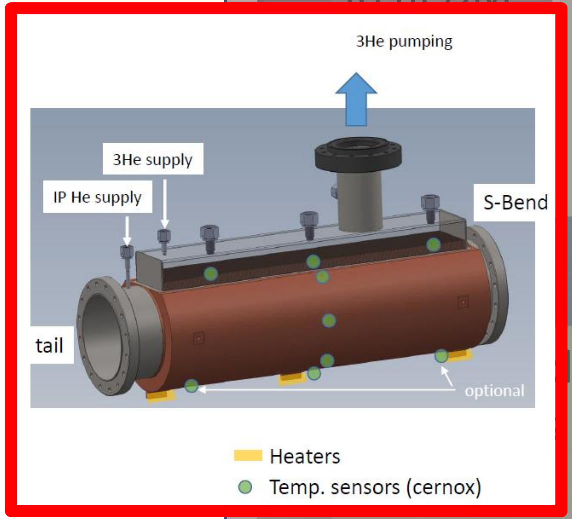
Horizontal s

Shielding

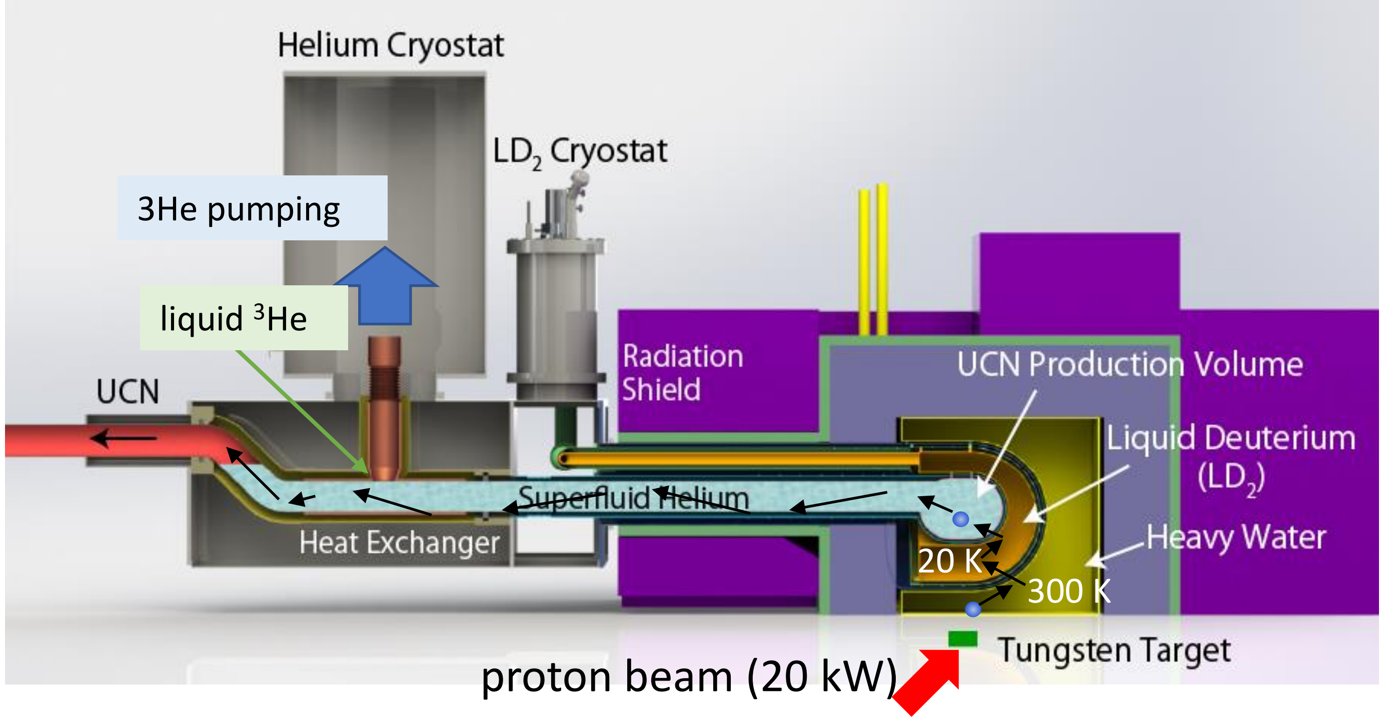
To nEDM





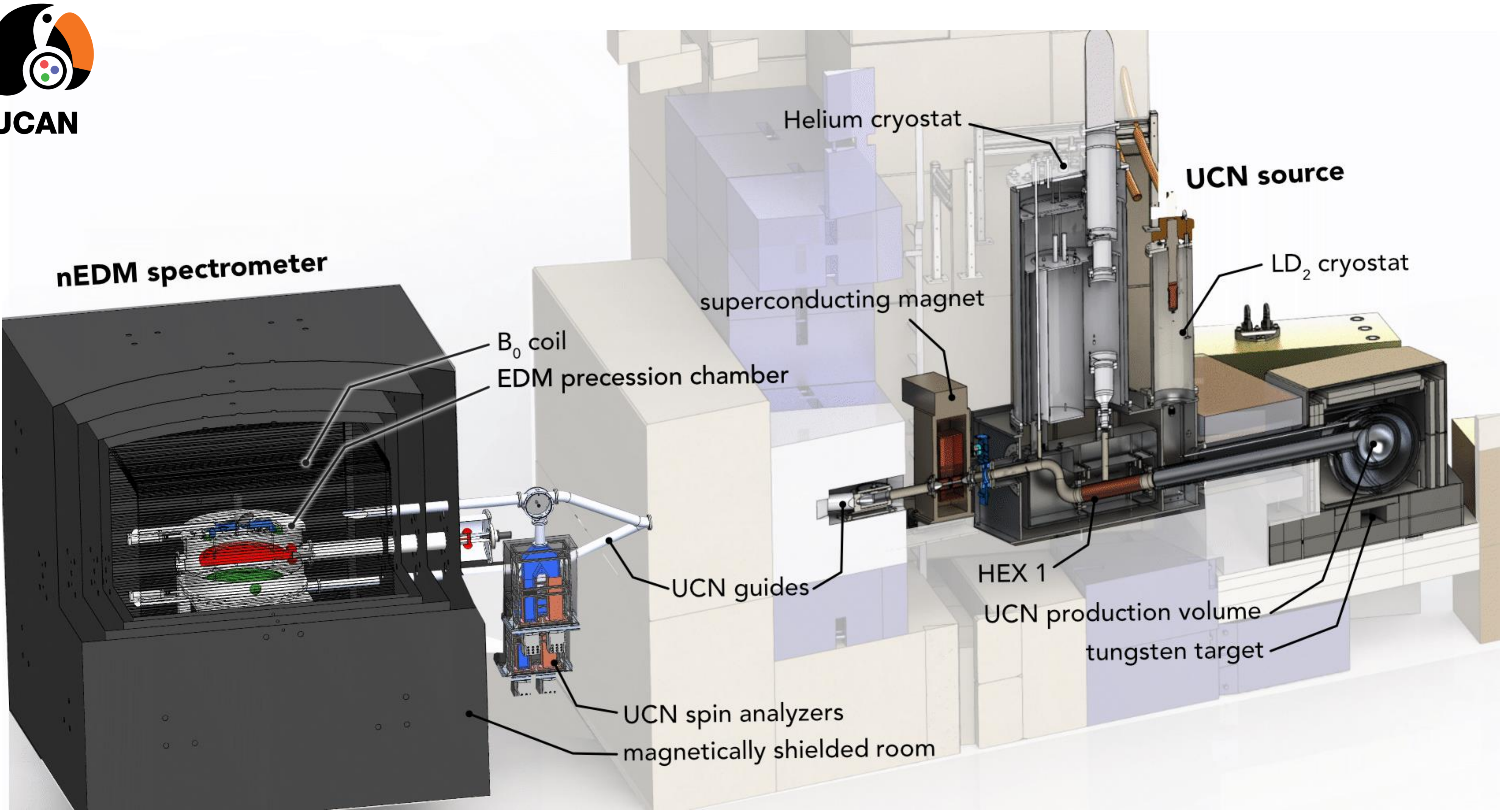


TUCAN Source Upgrade Concept and Goals



- 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: 1.4×10^7 UCN/s
  - UCN density
    - 6×10^3 UCN/cm^3 @ production
    - ～220 UCN/cm^3 @ measurement

TUCAN


Helium cryostat
UCN source
LD$_2$ cryostat
superconducting magnet
nEDM spectrometer
B$_0$ coil
EDM precession chamber
UCN guides
HEX 1
UCN production volume
tungsten target
UCN spin analyzers
magnetically shielded room

TUCAN Sensitivity Estimate

UCN production rate	1.4×10^7 UCN/sec	
UCN loaded into EDM cell	220 pol. UCN/cm^3	14M UCN
UCN detected at end of cycle	23 pol. UCN/cm^3	**1.4M UCN**

S. Sidhu, et al. arXiv:2212.04958

Compare to typ **15,000 UCN** detected at previous best expt. (ILL/PSI), and **121,000 UCN** projected for n2EDM

N. Ayres, et al. arXiv:2101.08730

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

E = 12.5 kV/cm
t_c = 188 s
α = 0.6 (visibility)

$\sigma_d = 2 \times 10^{-25}$ *ecm/cycle*

To reach statistical sensitivity of $\sigma_d = 1 \times 10^{-27}$ ecm
400 days of running required