# TUCAN EDM Experiment

**TRIUMF Ultra-Cold Advanced Neutron Electric Dipole Moment Experiment**

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# Electric dipole moment, CP violation, and basic technique

- Hamiltonian of neutron in an EM field (non-relativistic limit)

$$H = -\mu_n \vec{\sigma} \cdot \vec{B} - \underline{d_n \vec{\sigma} \cdot \vec{E}}$$

$$\rightarrow \not{T} \rightarrow \not{CP}$$

- Experiment: precise measurement of neutron spin precession frequency to determine $d_n$

$$\hbar\omega = 2\mu_n B \pm 2 d_n E$$

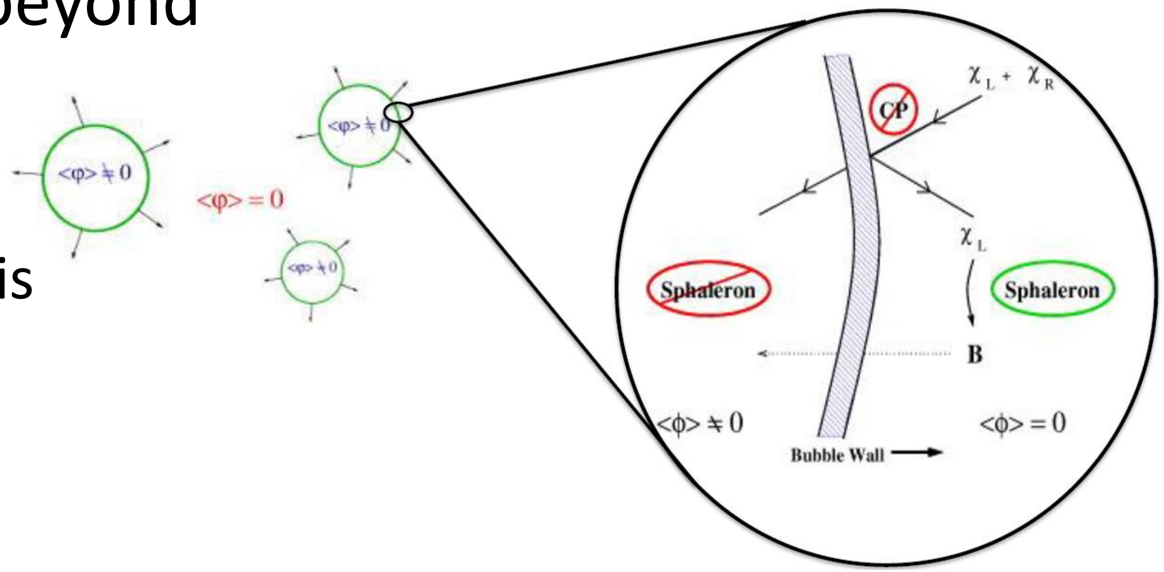
- Statistical uncertainty:

$$\sigma_{d_n} = \frac{\hbar}{2\alpha E T \sqrt{N}}$$

Precision frequency measurement requiring lots of neutrons

# Physics of Neutron Electric Dipole Moment

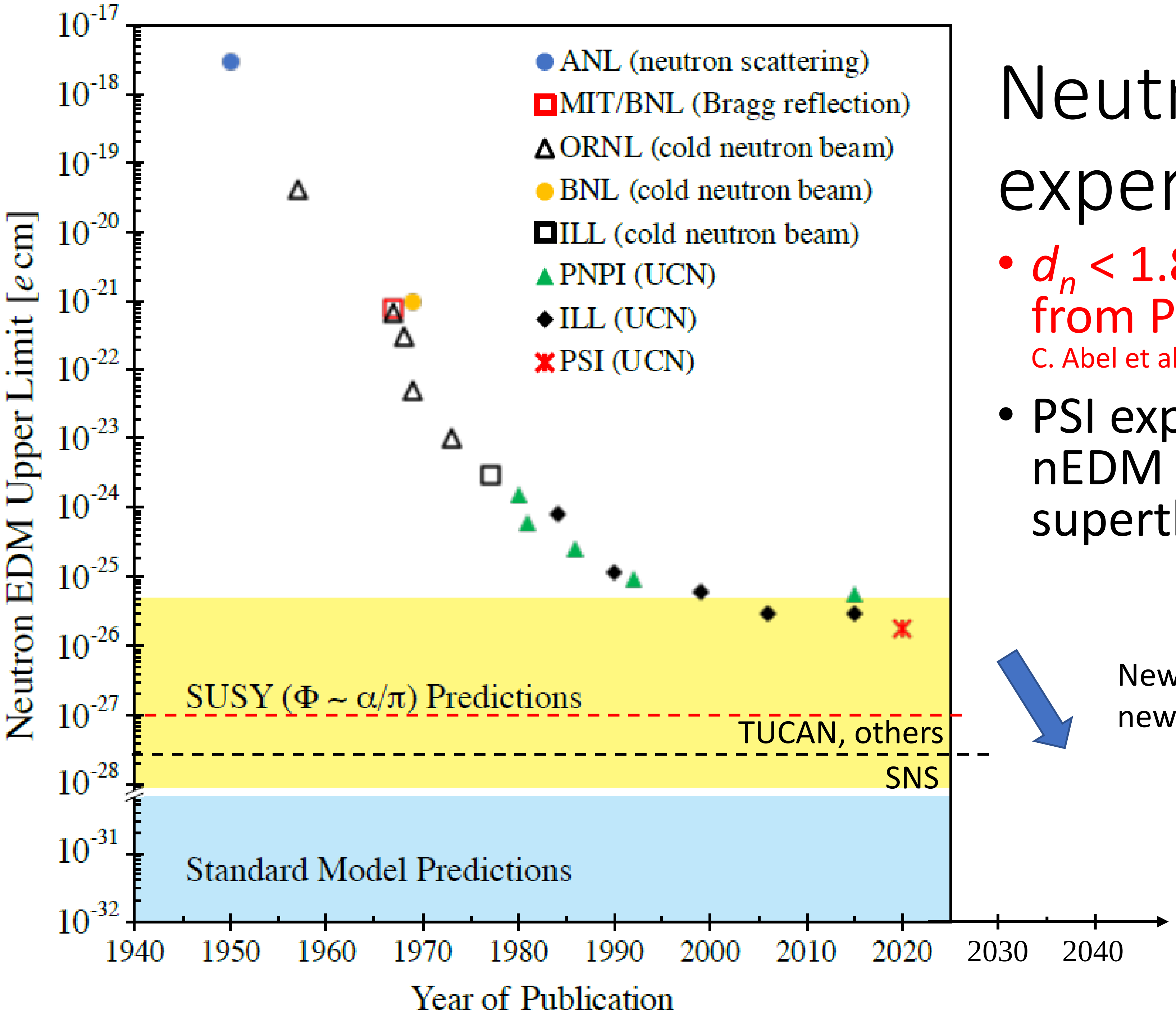
- Search for new sources of CP violation beyond the standard model.
- Motivated by:
  - New physics for (electroweak) baryogenesis
  - SUSY CP problem / new TeV-scale physics
  - Strong CP problem / Peccei-Quinn, axions
  - Other new physics scenarios




Adapted from Morrissey & Ramsey-Musolf New J. Phys. 2012

# Neutron EDM – experimental status

- $d_n < 1.8 \times 10^{-26}$ *e* cm (90% C.L.) from PSI experiment
  C. Abel et al., PRL 124, 081803 (2020)
- PSI experiment was the first nEDM measurement to use a superthermal UCN source




New UCN source technology, new techniques

Many groups pursuing $10^{-27}$ *e* cm measurement as next step, including TUCAN

# PP-EEC 2022 report

## S1722: UCN/TUCAN Status Report

The committee heard about the progress during the past year towards realizing the ultra-cold neutron source, which would enable TUCAN to measure the neutron electric dipole moment (EDM) with world leading precision, and thereby achieve sensitivity to subtle effects expected from new physics. Despite delays and increased costs due to the COVID pandemic, significant progress has been made. The project is working on a descope plan to deal with the budget shortfall. These plans will be reviewed by an External Advisory Committee in May. **We look forward to seeing the recommendations of the EAC.** At our next meeting in one year we would also welcome **another update, including a detailed commissioning plan** and an **overview of the competitive landscape and the opportunities for world leading results.**

# Ongoing/Planned Neutron EDM Experiments

| Experiment | Source | Type |
|---|---|---|
| n2EDM@PSI | spallation so-$D_2$ | UCN |
| PanEDM (ILL/Munich) | reactor He-II | UCN |
| LANL nEDM | spallation so-$D_2$ | UCN |
| TUCAN (Japan/Canada) | spallation He-II | UCN |
| ILL/PNPI/Gatchina | reactor He-II | UCN |
| nEDM@SNS | He-II source/experiment | UCN |
| BeamEDM at ILL/ESS | intense neutron beam | CN |
| J-PARC crystal | high E in crystal | CN |

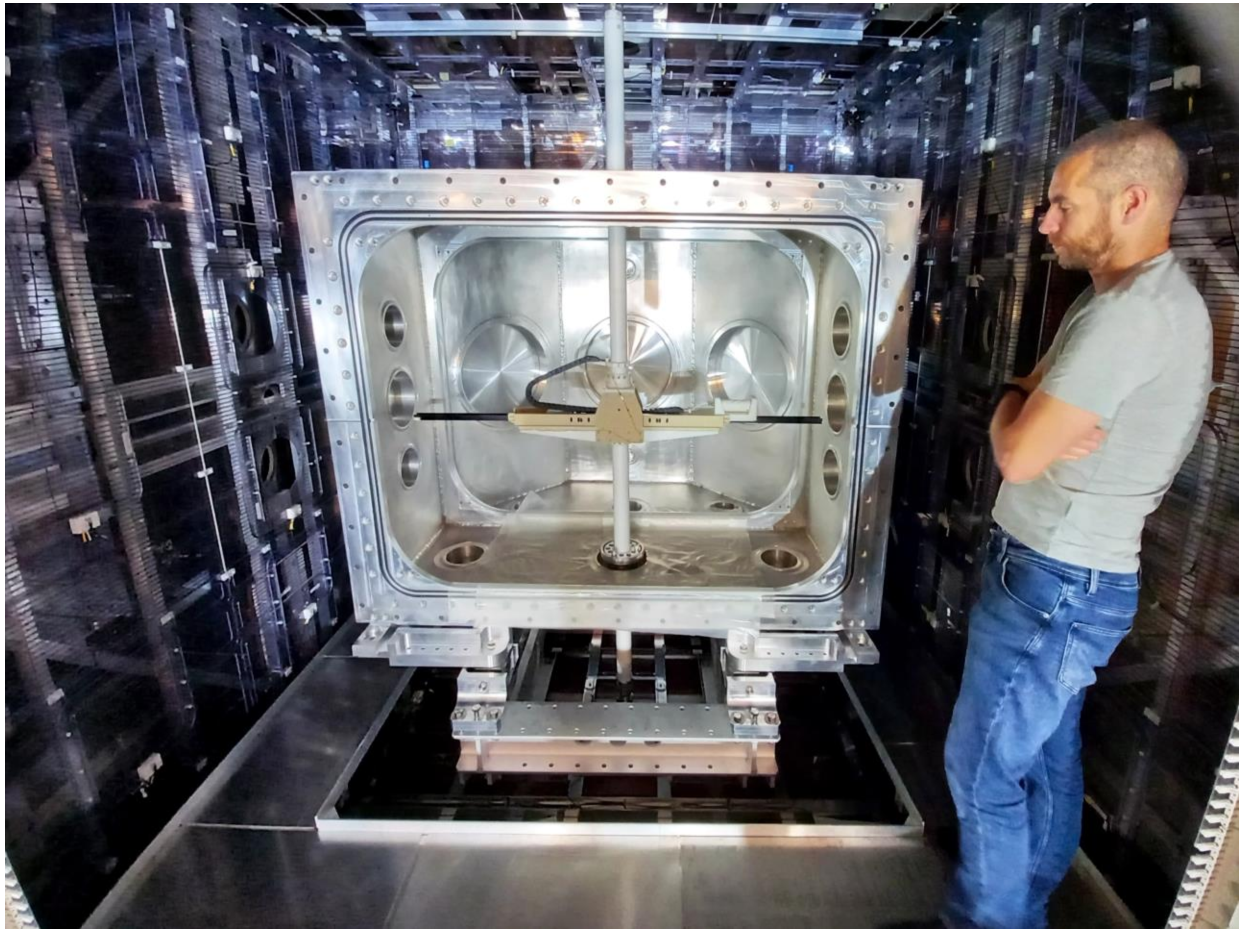
# n2EDM progress and schedule

n2EDM@PSI

2020: Commissioning of the MSR
[The very large n2EDM magnetically shielded room, nEDM collaboration, Rev. Sci. Instrum. (2022)]

2021-2022: Magnetic commissioning
B0 coil installation, field mapping

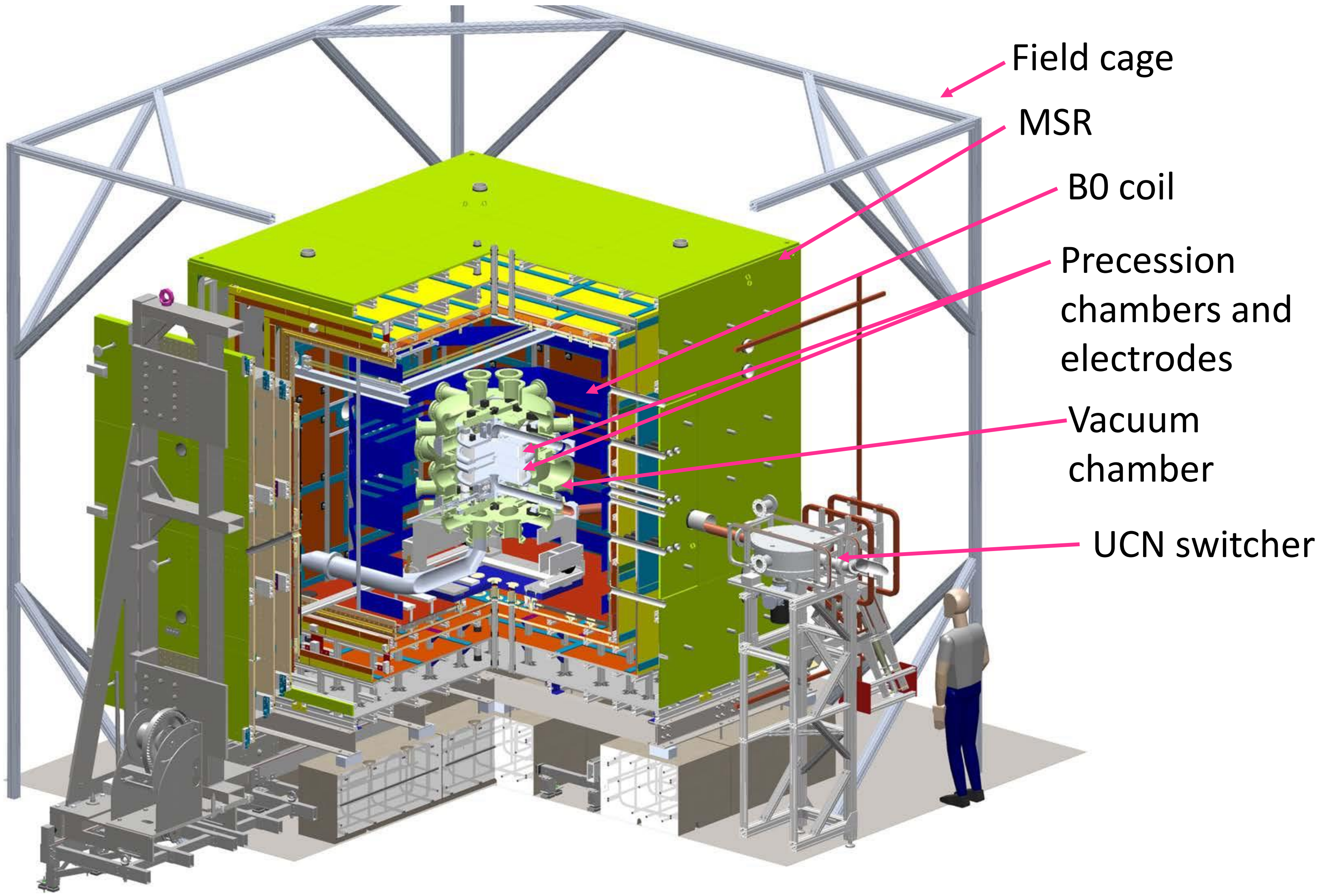
2022-2023: UCN commissioning
Detectors, UCN transport, Ramsey chambers, high voltage
=> apparatus ready for data taking



View inside the n2EDM magnetically shielded room during the installation of the field mapper in the vacuum vessel

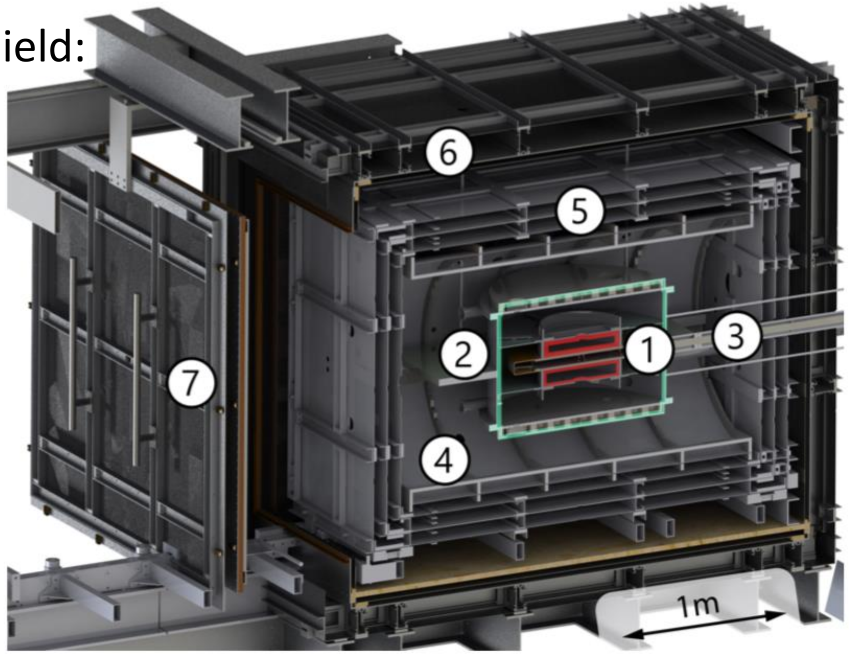
# LANL nEDM experiment

- MSR has been installed. It has been shown to meet the specs on both the shielding factor ($10^5$ @ 0.01 Hz) and the residual field ($\lesssim$ 0.5 nT).
- In fall 2022, assembled the precession chambers and UCN valves.
- Engineering run in December 2022 with UCN guided to lower cell.

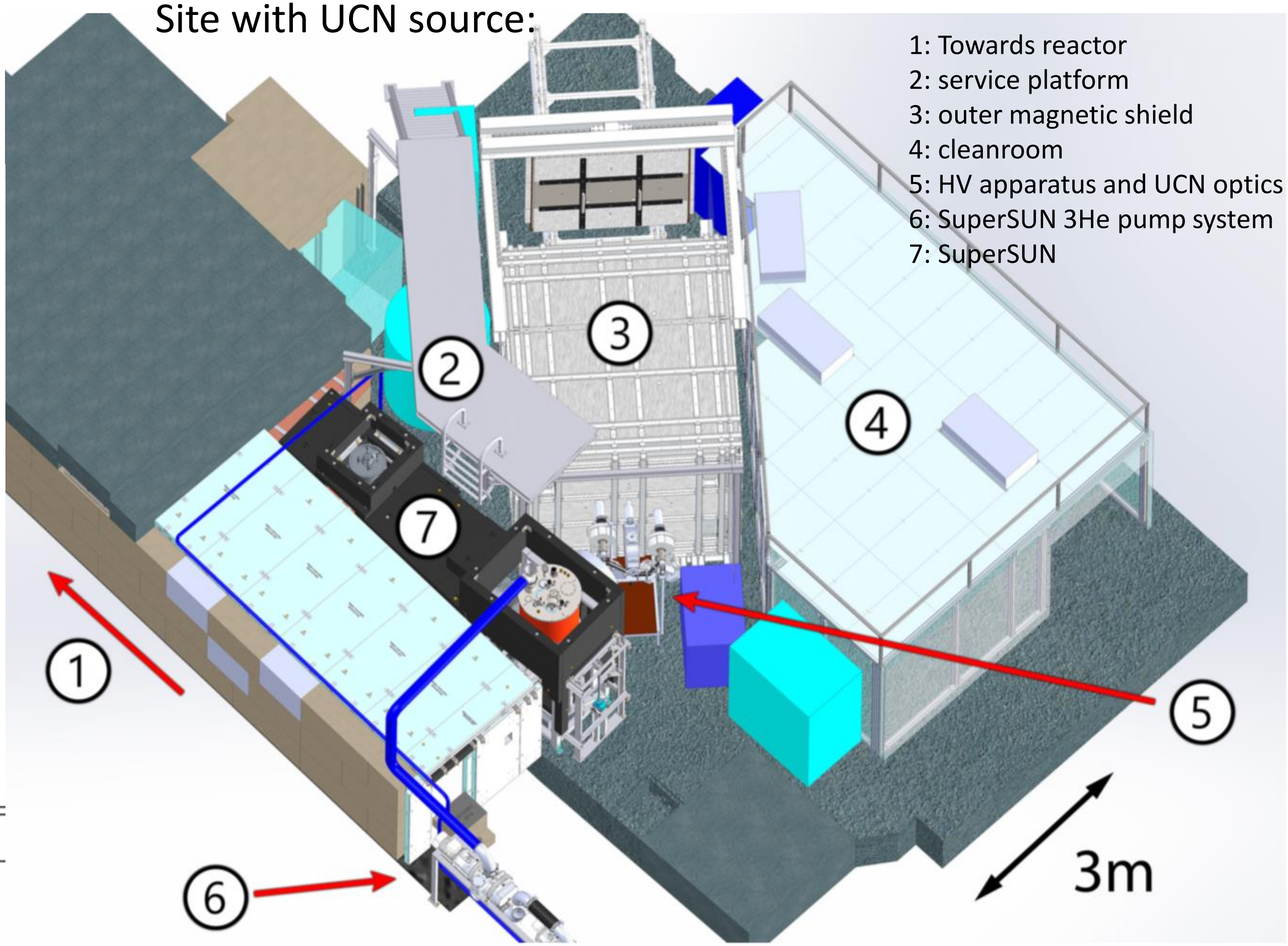


ILL/Munich
PanEDM

Magnetic shield:




Site with UCN source:




Statistical sensitivity:

| **SuperSUN** | **Phase I** |
|---|---|
| Saturated source density [$cm^{-3}$] | 330 |
| Diluted density [$cm^{-3}$] | 63 |
| Density in cells [$cm^{-3}$] | 3.9 |
| **PanEDM Sensitivity** [$1\sigma$, $e$ cm] | |
| Per run | $5.5 \times 10^{-25}$ |
| Per day | $3.8 \times 10^{-26}$ |
| Per 100 days | $3.8 \times 10^{-27}$ |

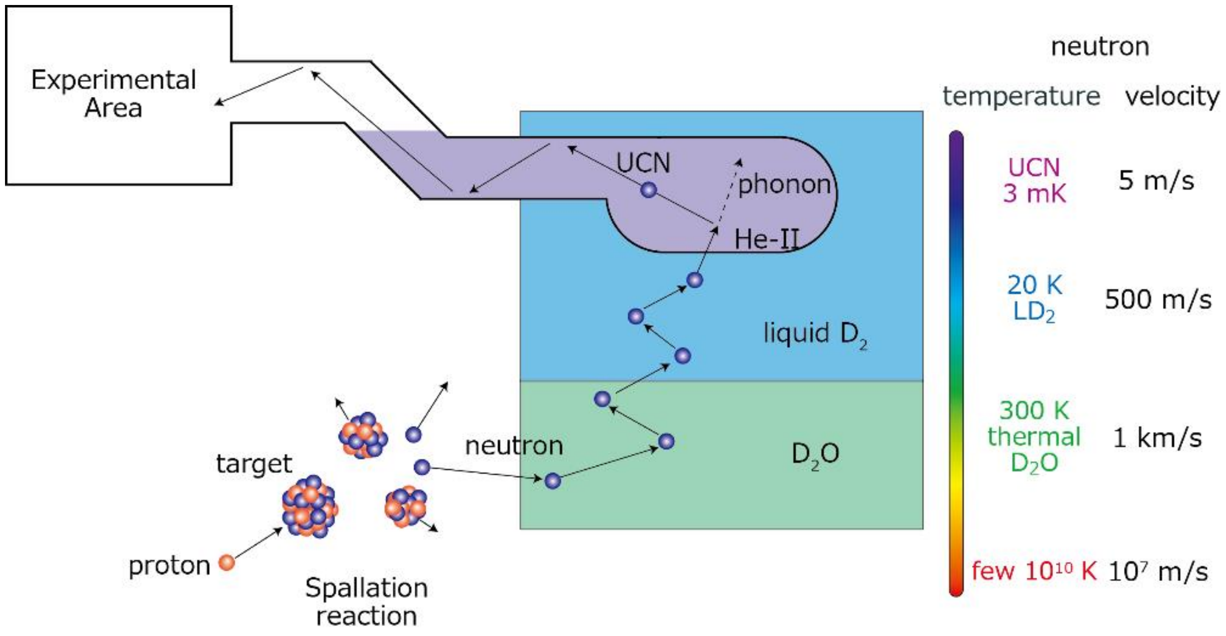
Idea of status (from Jeff's outsider view):

- Assembled at ILL
- Challenges in getting UCN out of source, and to experiment

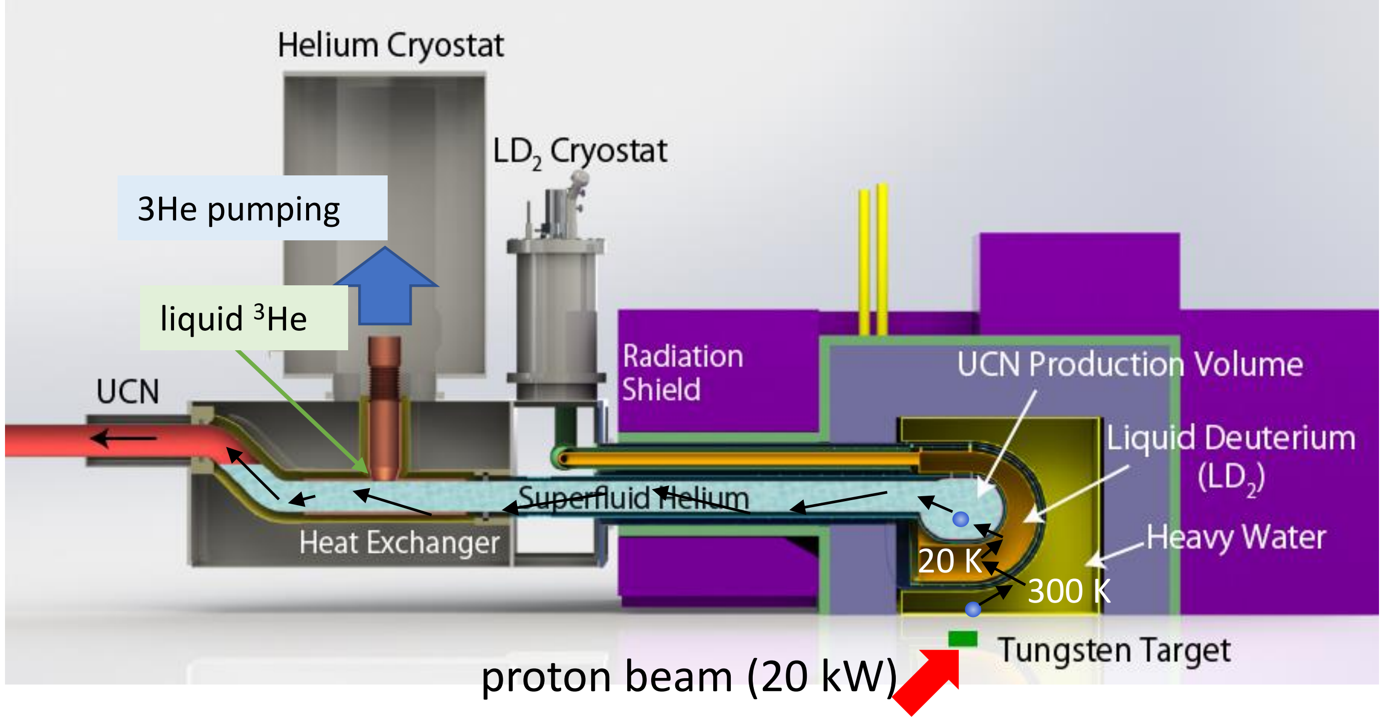
# TRIUMF Ultracold Advanced Neutron (TUCAN) Source

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.



# 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 Sensitivity Estimate

| | | |
|---|---|---|
| UCN production rate | $1.4 \times 10^{7}$ 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 (SSP 2022 conf. proc.)

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

N. Ayres, et al., Eur. Phys. J. C 81, 512 (2021)

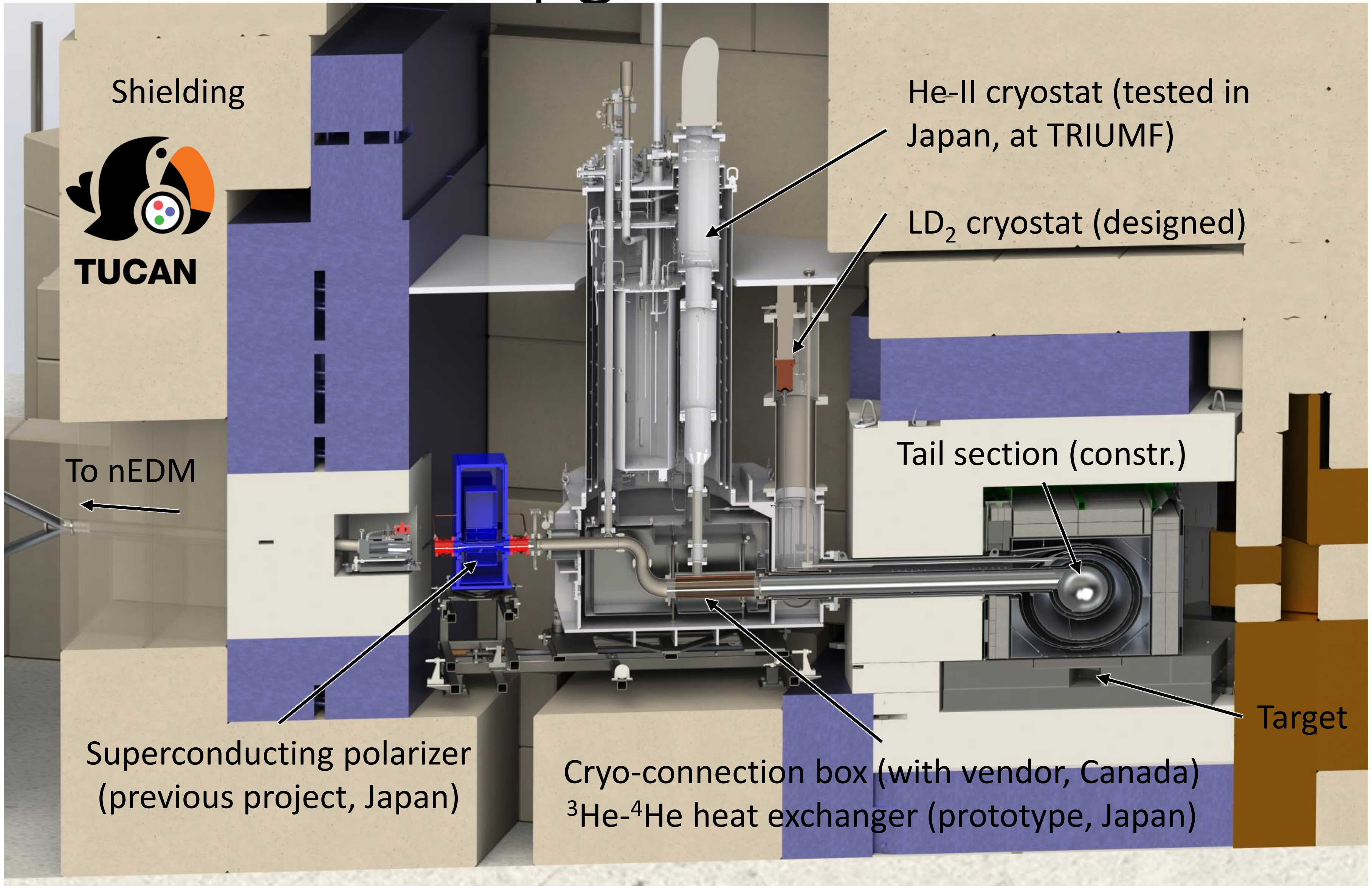
$$\sigma_d = \frac{\hbar}{2\alpha E t_c \sqrt{N}}$$

E = 12.5 kV/cm
$t_c$ = 188 s
$\alpha$ = 0.6 (visibility)

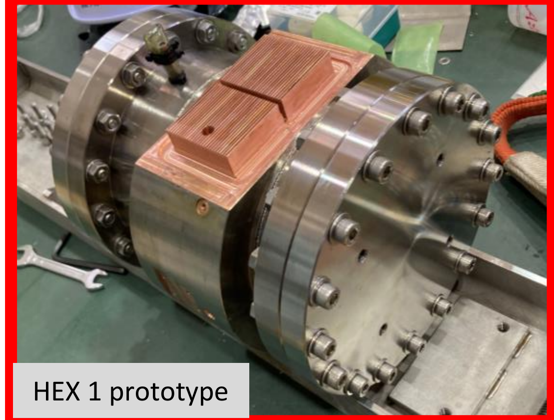
$\sigma_d = 2 \times 10^{-25}$ *e*cm/cycle

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

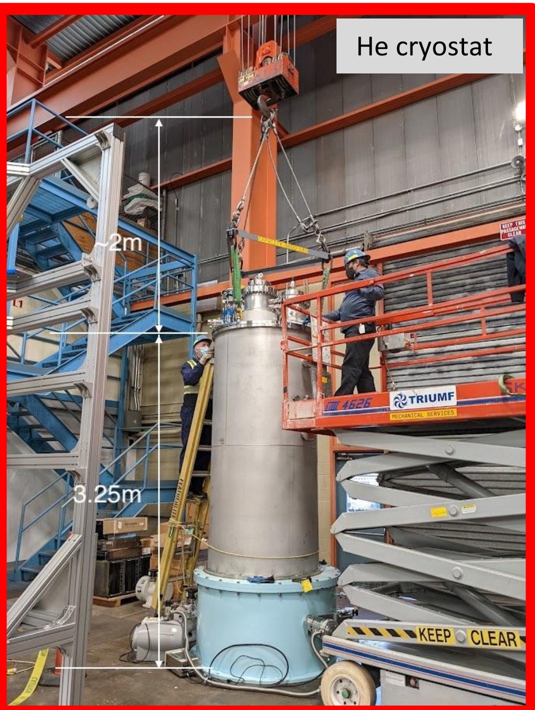
# Horizontal source upgrade



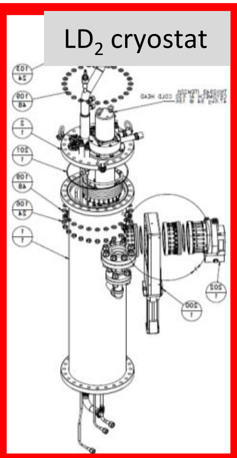
# Horizontal s



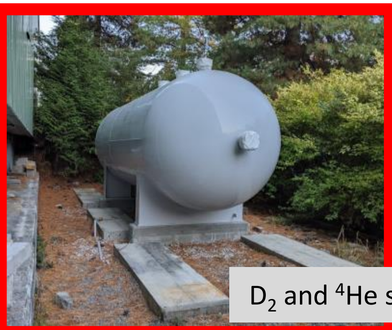
HEX 1 prototype




He cryostat

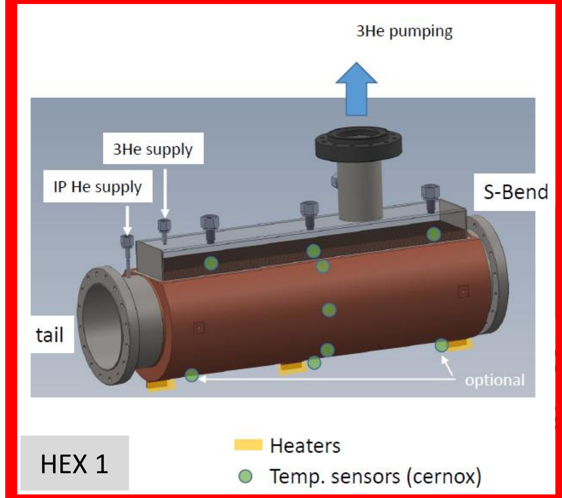


$LD_2$ cryostat

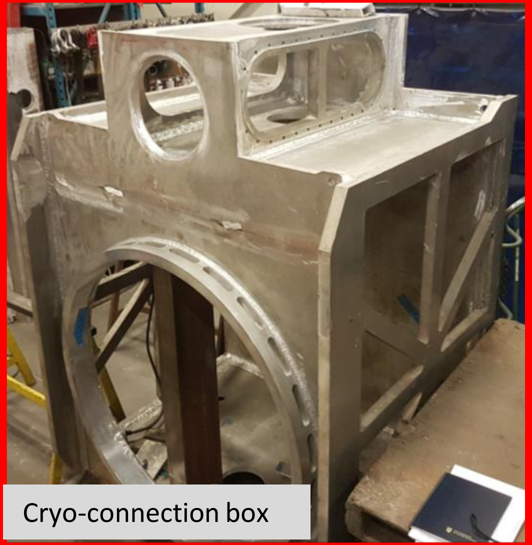


$D_2$ and $^4He$ storage tanks

Tail section layers



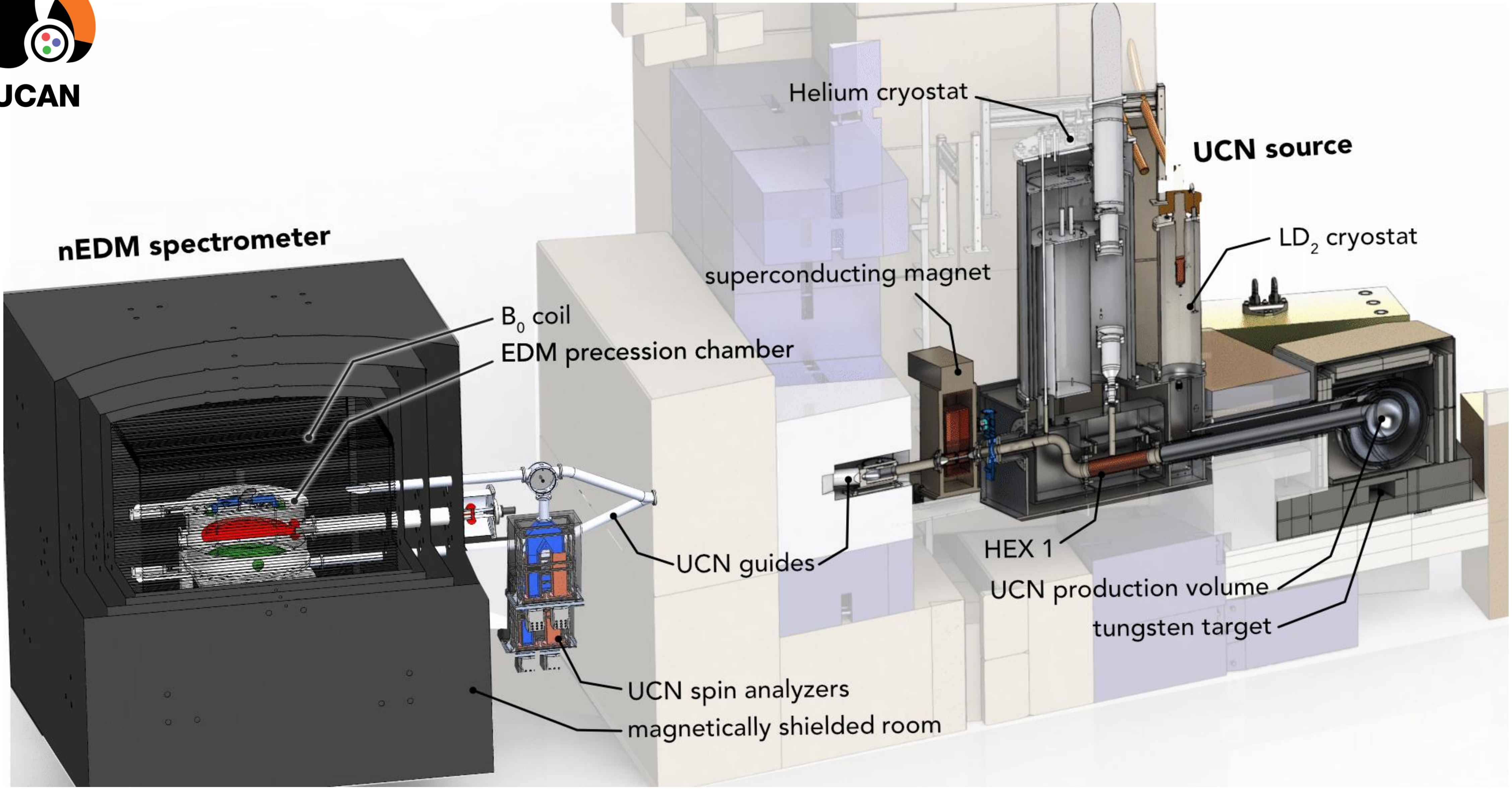

HEX 1



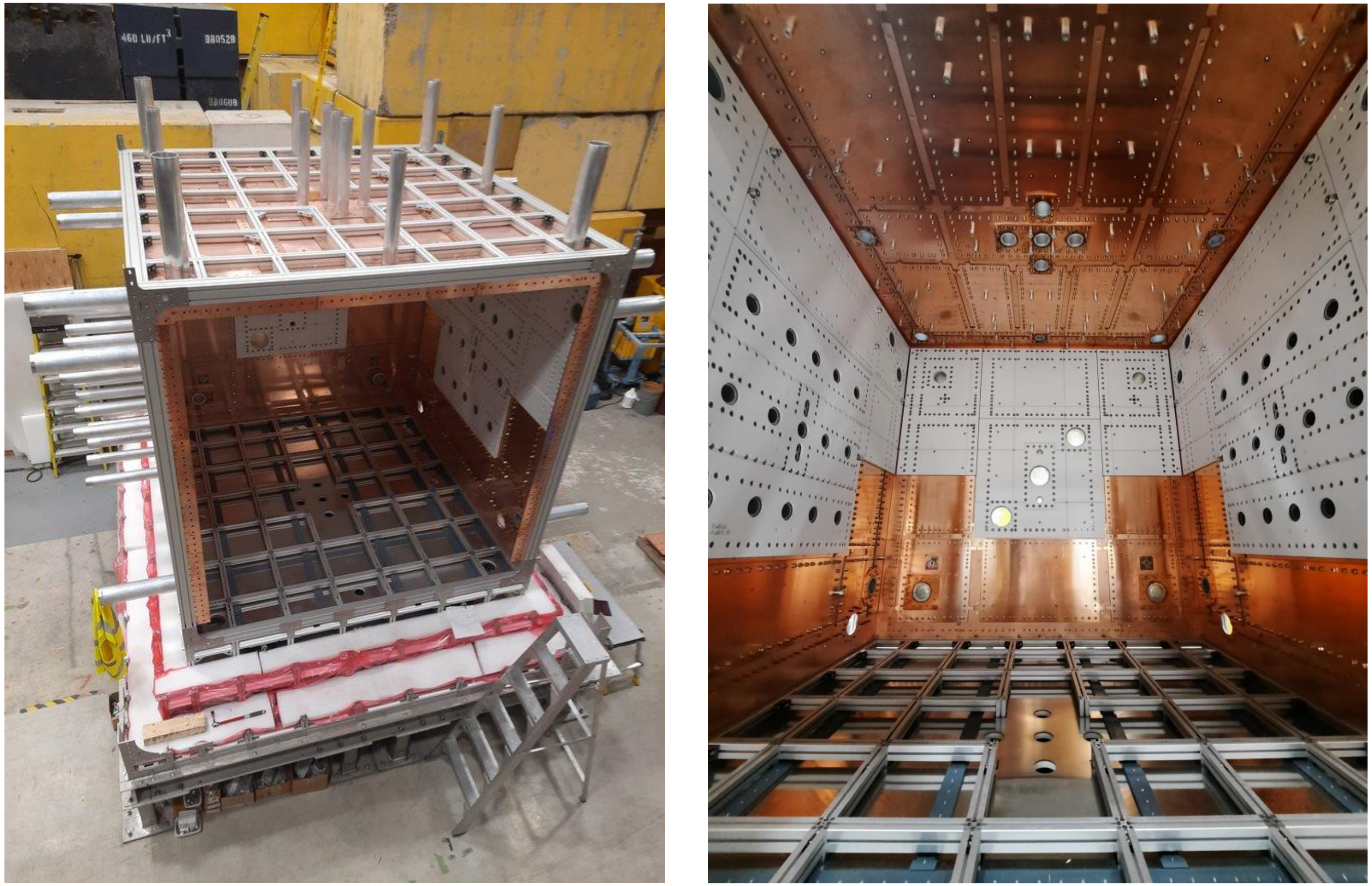
Cryo-connection box

Tail section innermost layer (production volume)

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

# Magnetically Shielded Room



Copper shield and structure (Feb. 2023 status)

- Construction at TRIUMF well underway.
- Completion in fall 2023.
- Magnetic verification and testing fall 2023 – 2024
    - Plan of installations being developed by B. Franke

# Commissioning Plans (UCN source)

- Installation and commissioning plan Document-189414 was provided to the PP-EEC. The installation order and plan is still current.
- More detailed plans of the cryogenic commissioning leading to first UCN production have been developed, checks of equipment needed to execute each step in the plan.
- Next slide details the upcoming plans, divided into 6 phases.
- *A critical milestone is to produce UCN in 2024. If we do not achieve this, Japanese funding and future CFI funding would be in serious jeopardy.*
- *For example, we consider doing UCN production during phase 5 without $LD_2$ moderator, as a demonstration.*

TUCAN
TRIUMF Ultra Cold Advanced Neutron source

# Cryogenic testing detailed plan

TRIUMF

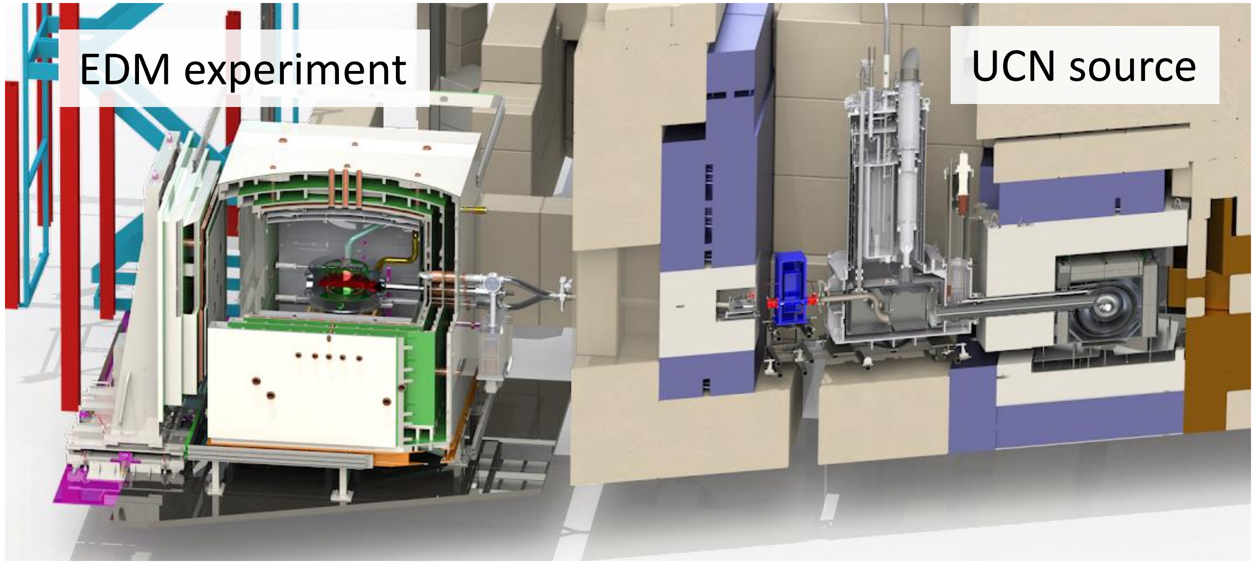
| Date | Test | Goals | Duration | People required |
|---|---|---|---|---|
| Summer 2022 | Pump tests (Phase 1) | VFD setup, pump curve | 1 day per pump set x 3 | 2 people (daytime) |
| | LHe transfer line | Cool down, loss, pressure drop | < 1 week | 1 person 24 h (offsite monitoring possible) |
| Spring 2023 | He cryostat 4K cooldown (Phase 2A) | Cold leaks, pressure drop, cooldown time, shield flow setup | 3 days cooldown, 2 days tests, 2 days warm-up evaporation | 2 people daytime, 1 person night for 1 week |
| Summer 2023 | Pumping on 1K and 3He pot (natural He) (Ph. 2B) | Superleak tests, HEX1 4He boiling curve | 5 days cooldown, 3 days tests, 2 days warm-up evaporation | 2 people daytime, 1 person night for 1 week |
| Fall 2023 | Full 3He cooldown (Phase 3) | Test of 3He system, full heat load at 1K, HEX1 3He boiling curve | 5 days cooldown, 5 days tests, 2 days warm-up evaporation | 2 people daytime, 1 person night for 2 weeks |
| Spring 2024 | He cryostat + tail + pumps + gradient measurement (Phase 5) | Condensation of “isopure” helium, gradient measurement | 5 days cooldown, 5 days condensation, 3 days tests, 2 days warm-up evaporation | 2 people daytime, 1 person night for 2 weeks |
| Summer 2024 | LD2 cooldown (Phase 4) | D2 condensation plus thermosyphon test | 2 days cooldown, 3 days condensation, 3 days test, 5 days evaporation | 2 people daytime, 1 person night for 2 weeks |
| Summer 2024 | UCN production (Phase 6) | UCN prod, lifetime as function of I, Q, T | 5 days cooldown, 5 days condensation, 7 days tests, 2 days warm-up evaporation | 2 people daytime, 1 person night for 3 weeks |

# Summary

- TUCAN source upgrade will enable a search for neutron EDM with 1 x $10^{-27}$ *e*cm precision.
- Neutron source upgrade completion 2024.
  - He-II cryostat built and tested in Japan 2020-2021. Now at TRIUMF and ready to install.
- Magnetically shielded room for EDM experiment installation 2022-2023.
- First UCN operations in 2024.

TUCAN

Future facility at TRIUMF



# Thank you!

Collaboration meeting January 2023