Status and Prospects of the TUCAN EDM Experiment

Sean Vanbergen, TRIUMF

EDMs2026 : WE-Heraeus Workshop

01/03/2026

The TUCAN Collaboration

TUCAN
TRIUMF Ultracold Advanced Neutron Collaboration

February 2026 collaboration meeting
National Autonomous University of Mexico

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

J-PARC J-PARC

RCNP

KYOTO UNIVERSITY

NAGOYA UNIVERSITY

NC STATE UNIVERSITY

KURNS

OAK RIDGE National Laboratory

INNOVATION.CA
CANADA FOUNDATION FOR INNOVATION | FONDATION CANADIENNE POUR L'INNOVATION
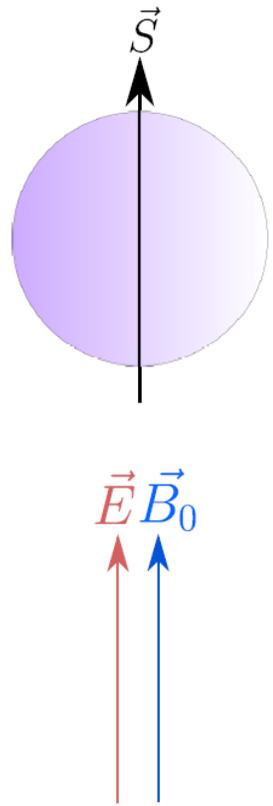
NSERC CRSNG

JST

JSPS

2

TUCAN's Goal

A measurement of the neutron EDM (nEDM) with statistical uncertainty $1\sigma = 10^{-27}\ e\mathrm{cm}$
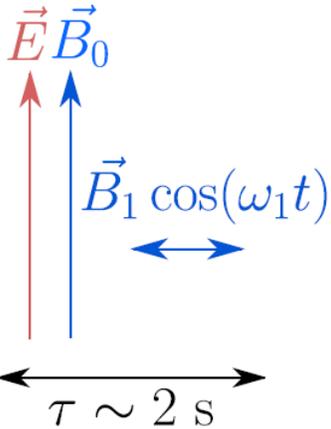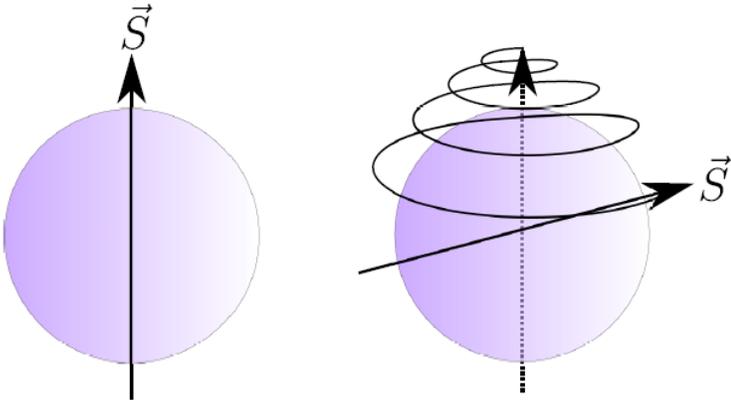
… plus, systematics.

And then what?

Measurements of the nEDM

1. Initial
state

Measuring the nEDM: Ramsey's Method of Separated Oscillating Magnetic Fields

$\vec{E}\ \vec{B}_0$

$\vec{E}\ \vec{B}_0$

$\vec{B}_1\cos(\omega_1 t)$
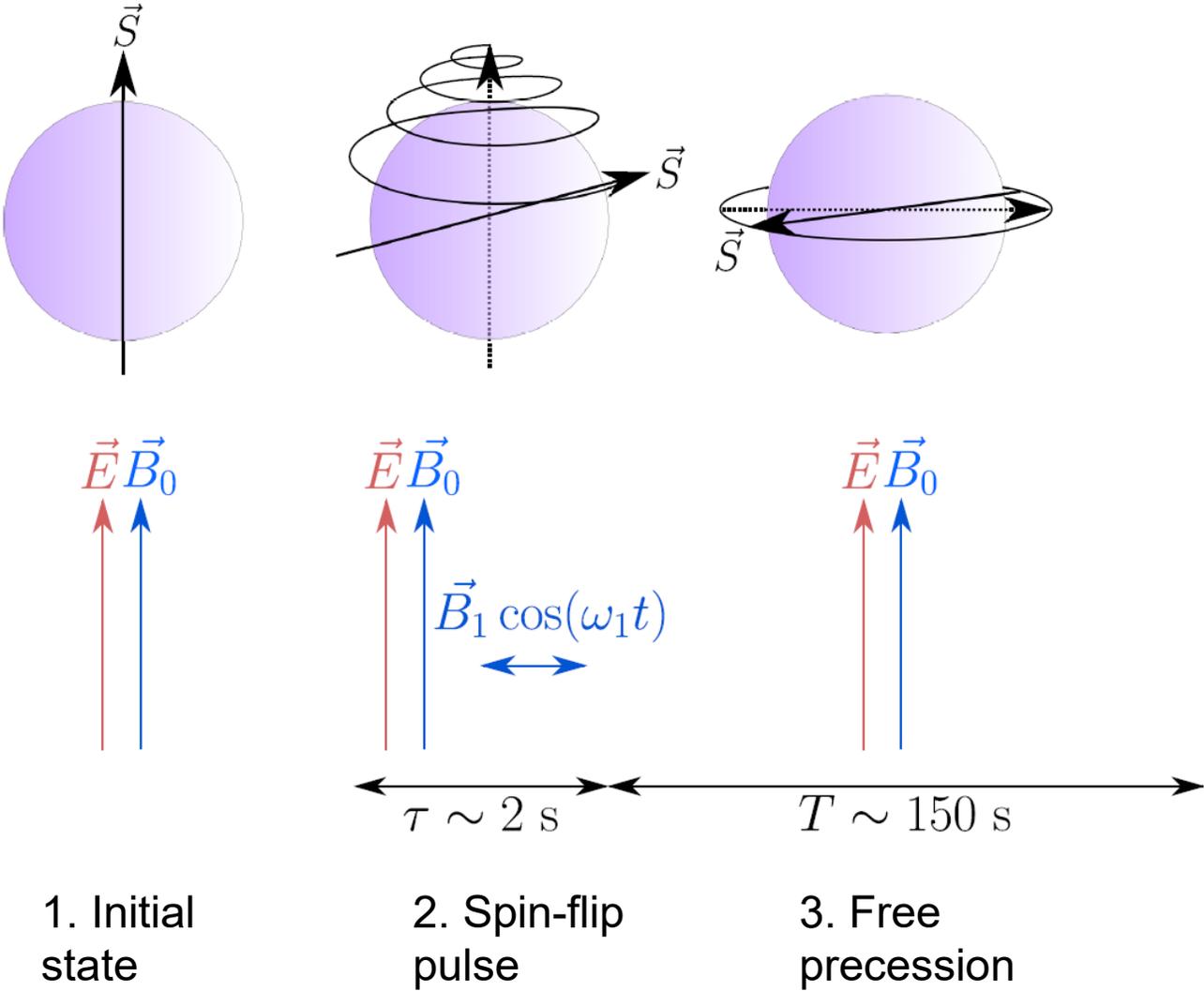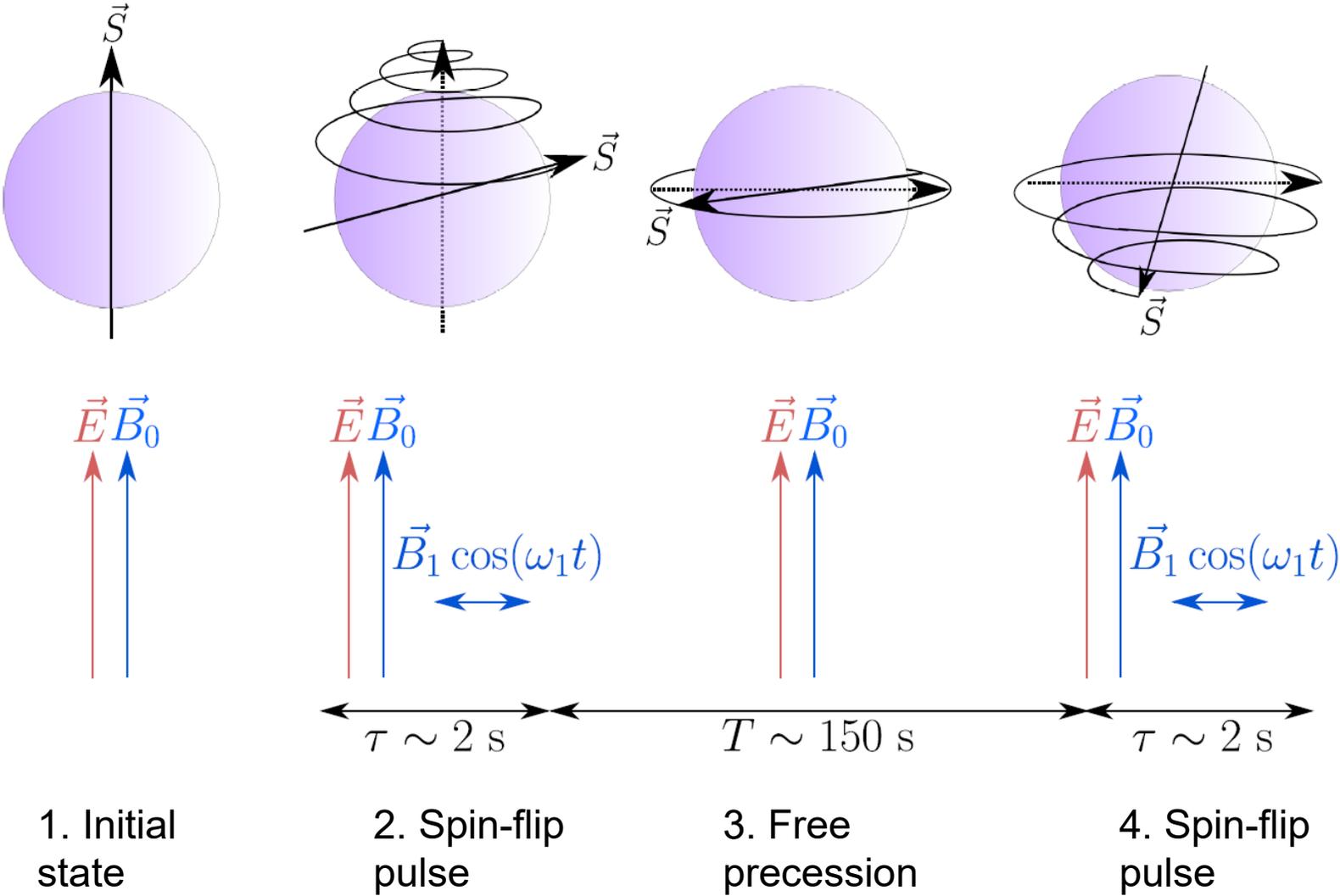
$\tau \sim 2\,\mathrm{s}$

1. Initial state

2. Spin-flip pulse

Measuring the nEDM: Ramsey's Method of Separated Oscillating Magnetic Fields

1. Initial state

2. Spin-flip pulse

3. Free precession

Measuring the nEDM: Ramsey's Method of Separated Oscillating Magnetic Fields
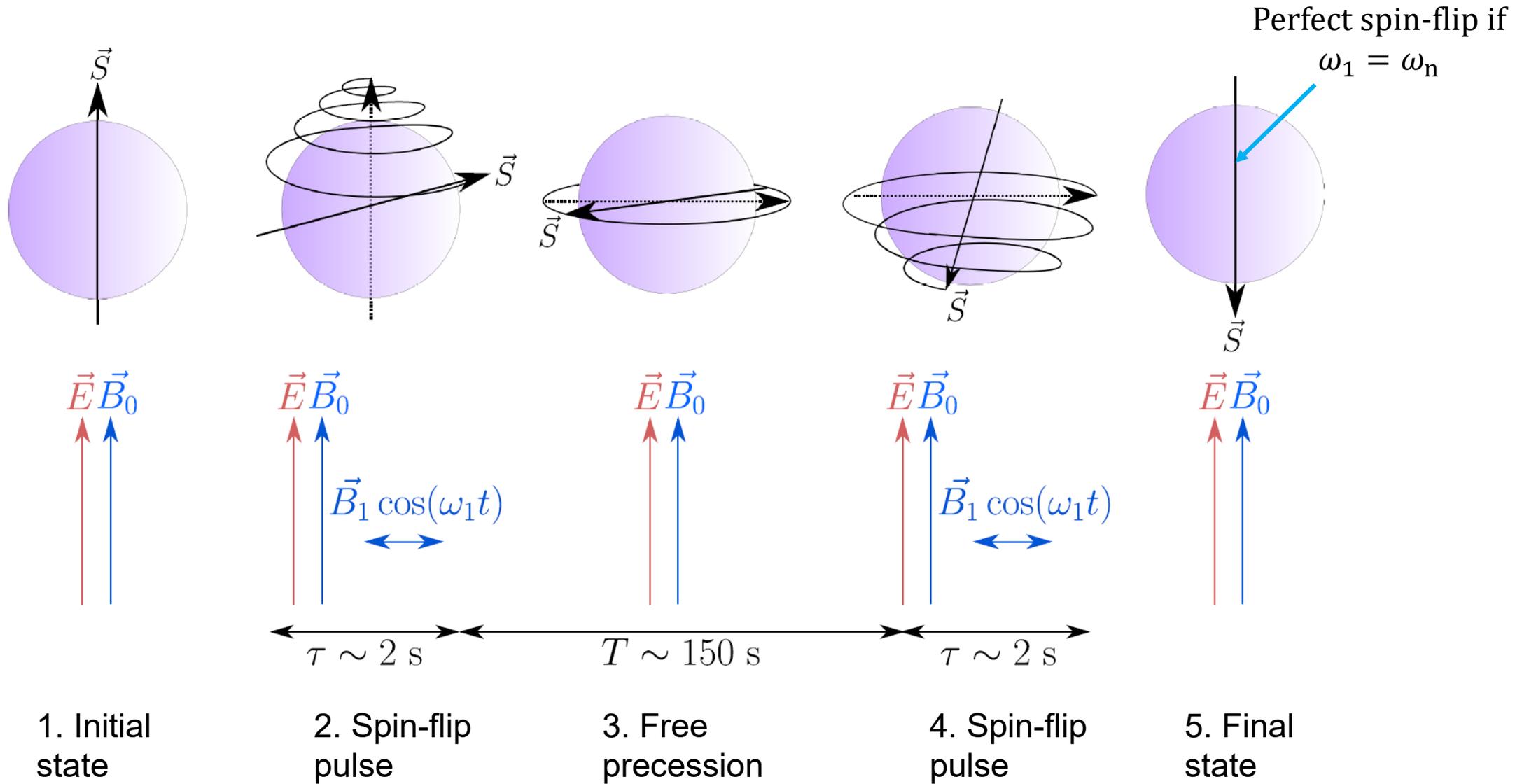

1. Initial state
2. Spin-flip pulse
3. Free precession
4. Spin-flip pulse

Measuring the nEDM: Ramsey's Method of Separated Oscillating Magnetic Fields

Perfect spin-flip if $\omega_1 = \omega_n$

$\vec{E}\,\vec{B}_0$ $\vec{E}\,\vec{B}_0$ $\vec{E}\,\vec{B}_0$ $\vec{E}\,\vec{B}_0$ $\vec{E}\,\vec{B}_0$

$\vec{B}_1 \cos(\omega_1 t)$ $\vec{B}_1 \cos(\omega_1 t)$

$\tau \sim 2\,\mathrm{s}$ $T \sim 150\,\mathrm{s}$ $\tau \sim 2\,\mathrm{s}$

1. Initial state

2. Spin-flip pulse

3. Free precession

4. Spin-flip pulse

5. Final state

$\omega_n \approx 30 \text{ Hz @ 1 } \mu\text{T}$

$\omega_n \approx 30 \text{ Hz @ } 1 \text{ μT}$

We count number of neutrons in each spin state

We measure at 4 "working point" frequencies

Spin flip probability

Applied frequency (Hz)
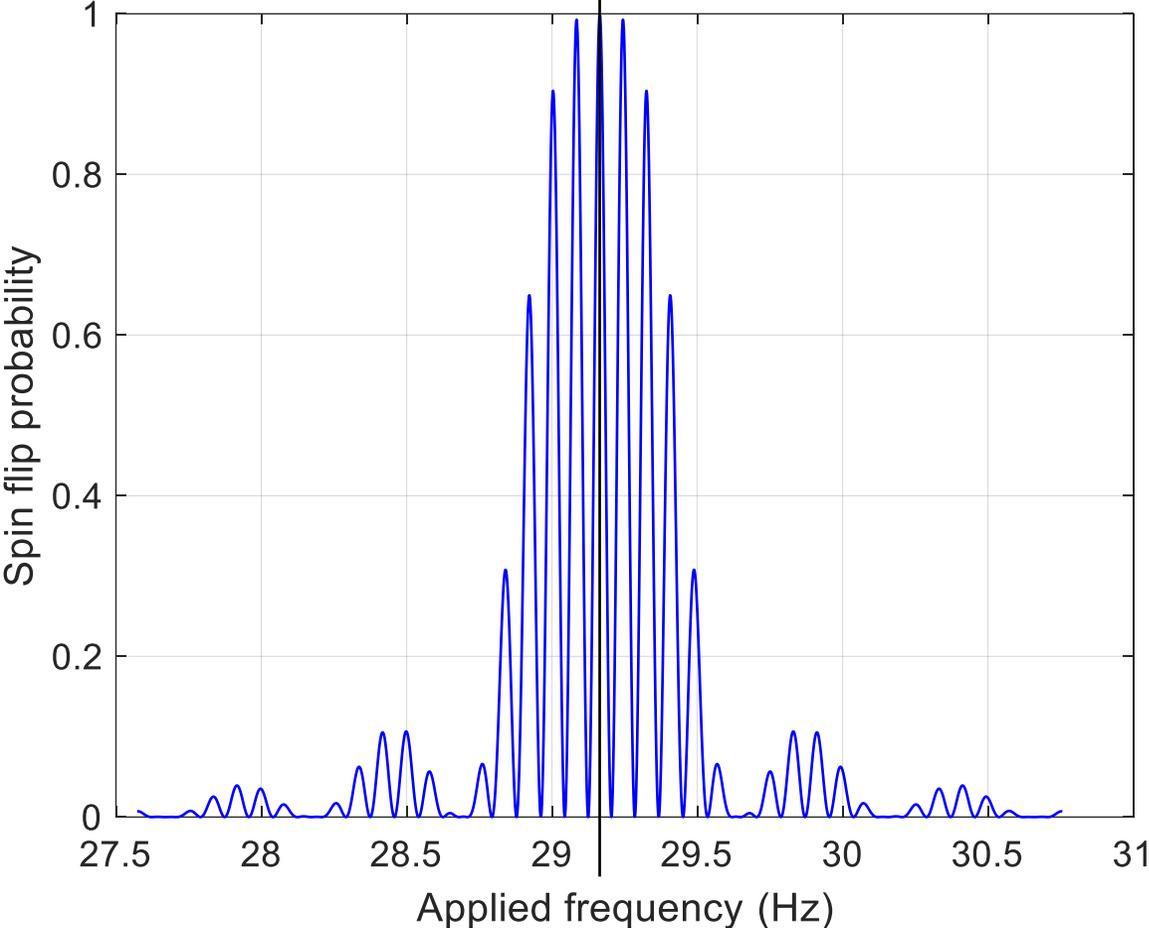
Measuring the nEDM: Ramsey's Method of Separated Oscillating Magnetic Fields

$\omega_n \approx 30$ Hz @ 1 μT

$$\hbar\omega_{n,\pm} = 2\mu_n|B_0| \pm 2d_n|E|$$

$$d_n = \frac{\hbar(\omega_{n,+} - \omega_{n,-})}{4|E|}$$

$$\sigma_{stat} \approx \frac{\hbar}{2\alpha(T + \frac{4\tau}{\pi})|E|\sqrt{N_{tot}}}$$

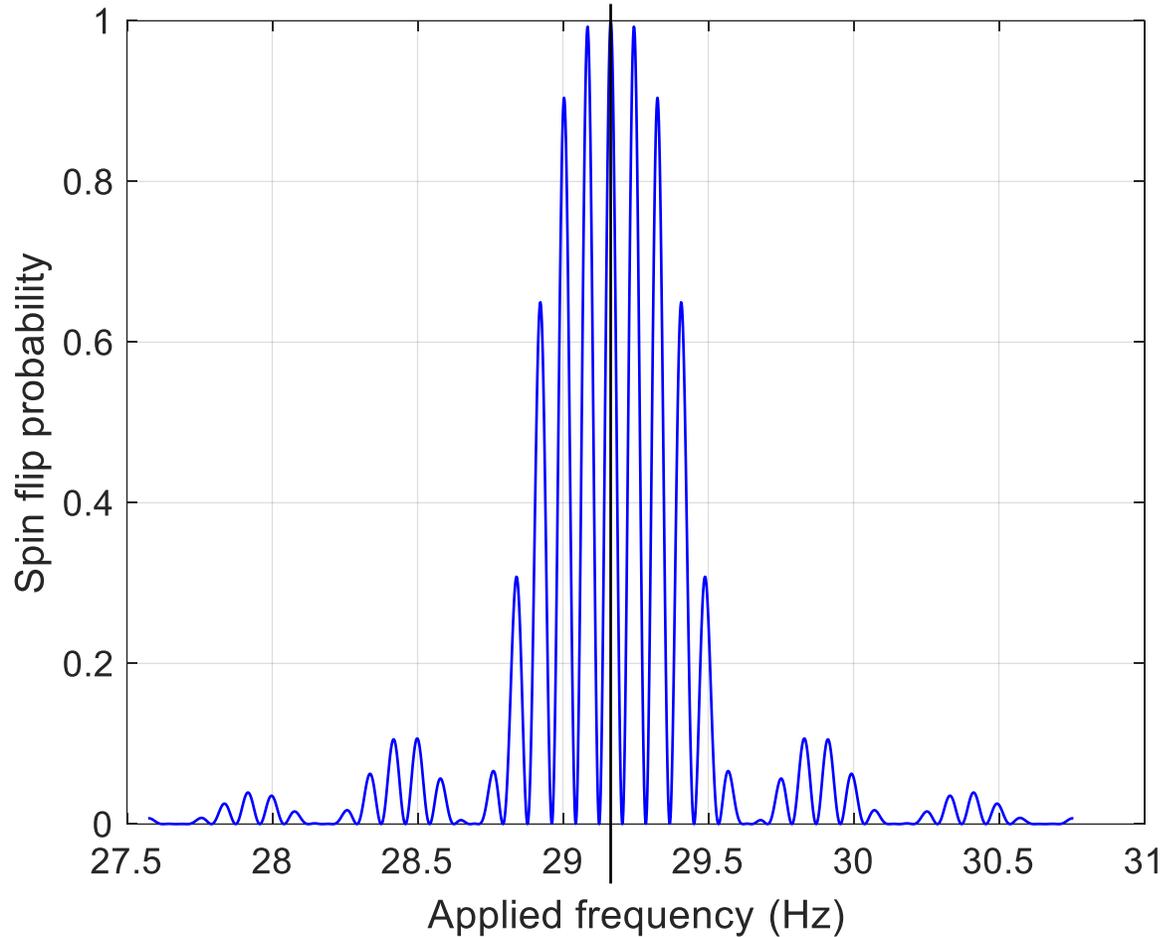Polarization of detected population

Free precession time

Electric field magnitude

Total neutrons

Measuring the nEDM: Ramsey's Method of Separated Oscillating Magnetic Fields

$\omega_n \approx 30 \text{ Hz @ } 1 \text{ μT}$
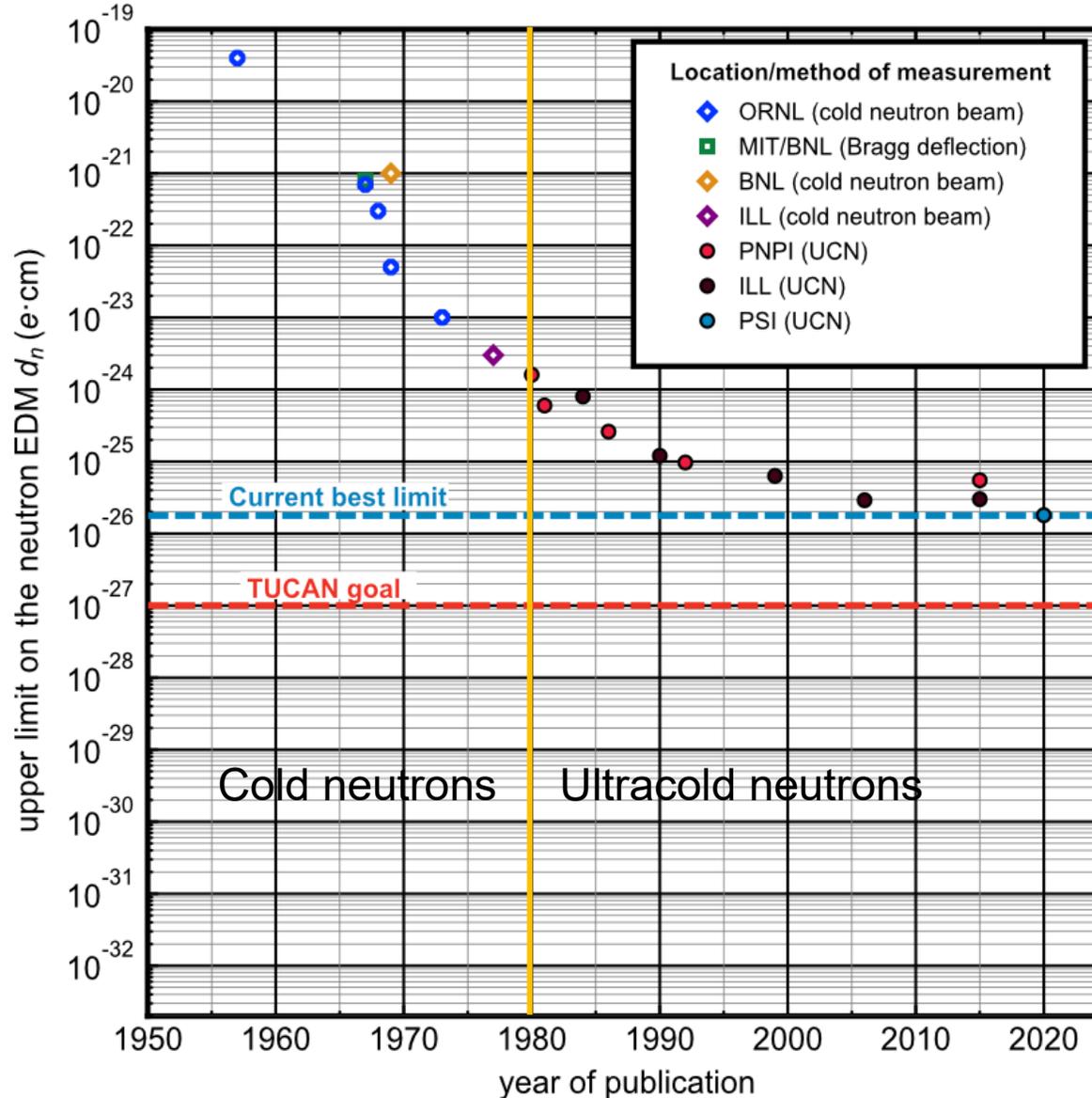

$$\hbar\omega_{n,\pm} = 2\mu_n|B_0| \pm 2d_n|E|$$

$$d_n = \frac{\hbar(\omega_{n,+} - \omega_{n,-})}{4|E|}$$

$\lesssim 20 \text{ nHz @} 10^{-27} \text{ ecm}$

$$\sigma_{\text{stat}} \approx \frac{\hbar}{2\alpha T|E|\sqrt{N_{\text{tot}}}}$$

$\sigma_{\text{syst}} \longrightarrow$ frequency shifts depending on E

Historical Development of nEDM Measurements


- Pre-1980 measurements used cold neutron beams:
  - High counts
  - Low interaction time
  - Problems with systematics

- Post-1980 measurements use ultracold neutrons
  - Long interaction time
  - Less problems with systematics
  - Challenging to get high counts

Ultracold Neutrons

Ultracold Neutrons (UCNs)

- UCNs have kinetic energies $\lesssim 350$ neV

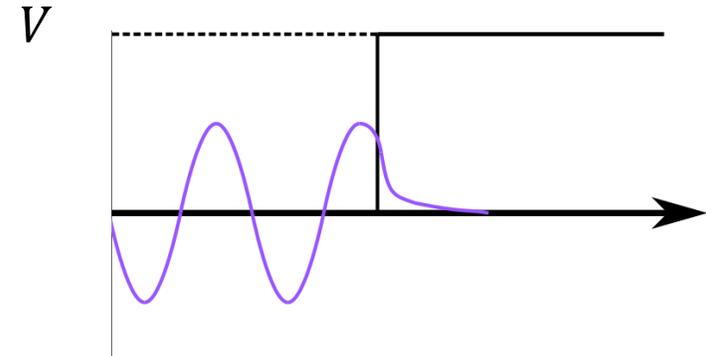- $\Rightarrow \lambda_{\mathrm{UCN}} > 50$ nm $\gg 0.4$ nm (typical interatomic spacing)

Steel ~0.28 nm
Diamond ~0.15 nm
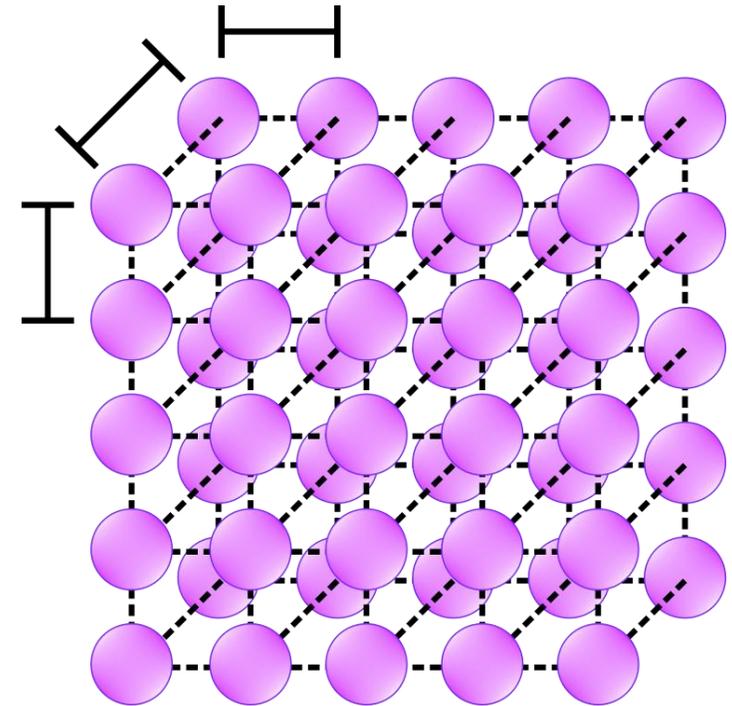
Ultracold Neutrons (UCNs)

- UCNs have kinetic energies $\lesssim 350$ neV

- $\Longrightarrow \lambda_{\mathrm{UCN}} > 50$ nm $\gg 0.4$ nm (typical interatomic spacing)

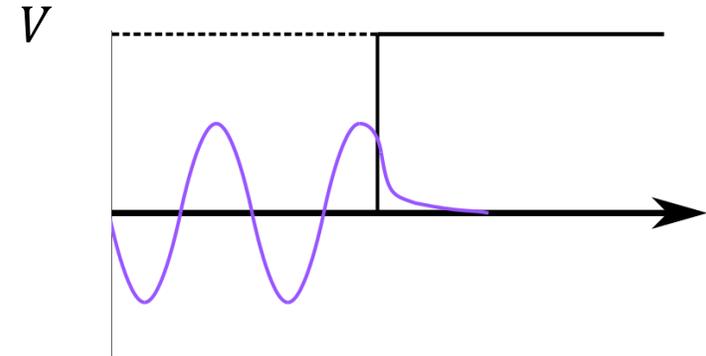- Bulk materials behave as a constant "Fermi potential"
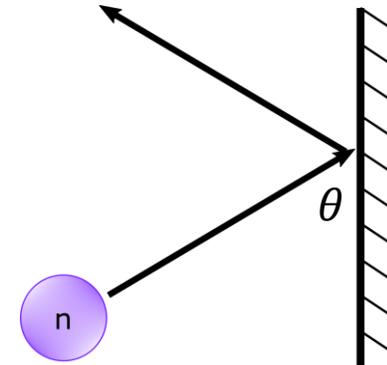
$$U = V + iW$$

Ultracold Neutrons (UCNs)

- UCNs have kinetic energies $\lesssim 350$ neV

- $\Longrightarrow \lambda_{\mathrm{UCN}} > 50$ nm $\gg 0.4$ nm (typical interatomic spacing)

- Bulk materials behave as a constant "Fermi potential"

$$U = V + iW$$

V

If $E_{\mathrm{kin}} < V$, then, for any θ
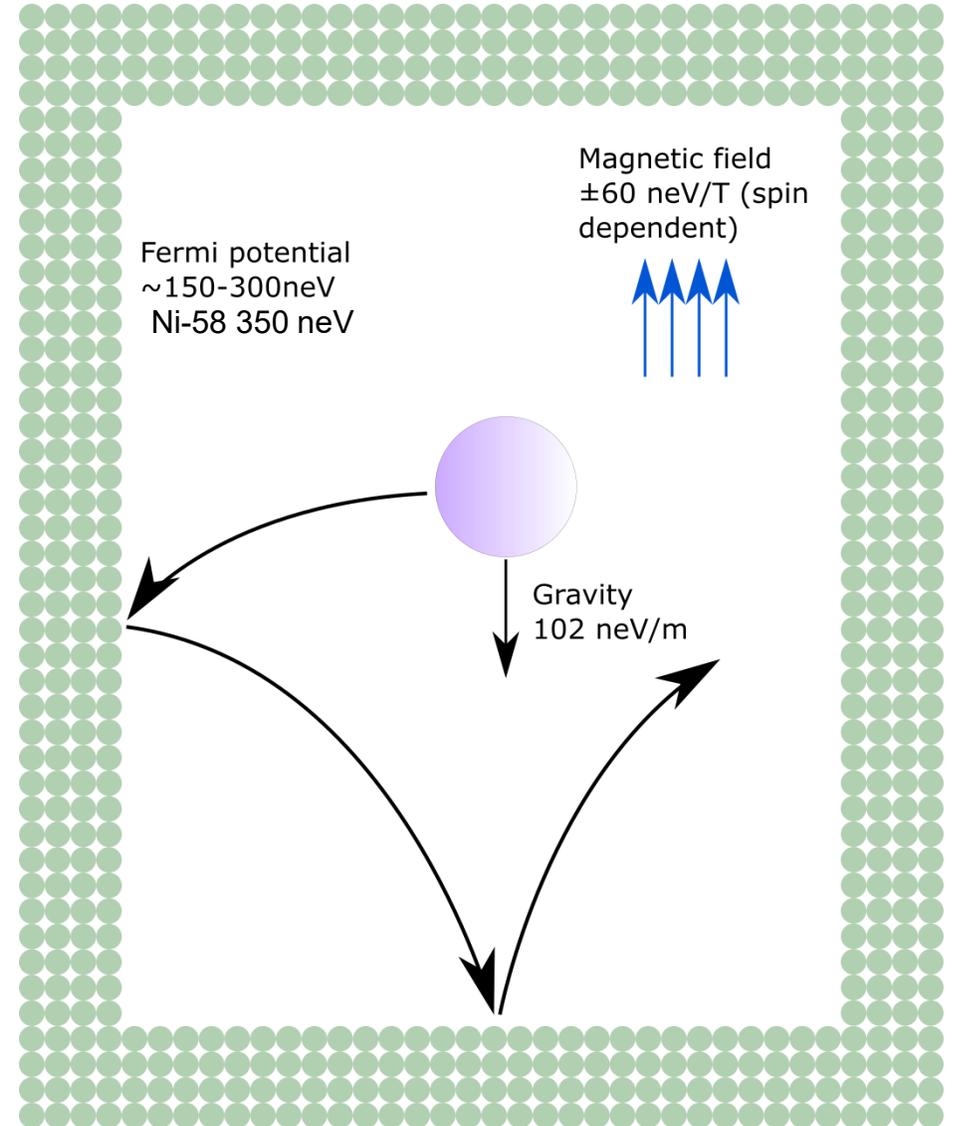
θ

n

Ultracold Neutrons (UCNs)

- UCNs have kinetic energies $\lesssim 350$ neV

- $\Rightarrow \lambda_{\text{UCN}} > 50$ nm $\gg 0.4$ nm (typical interatomic spacing)

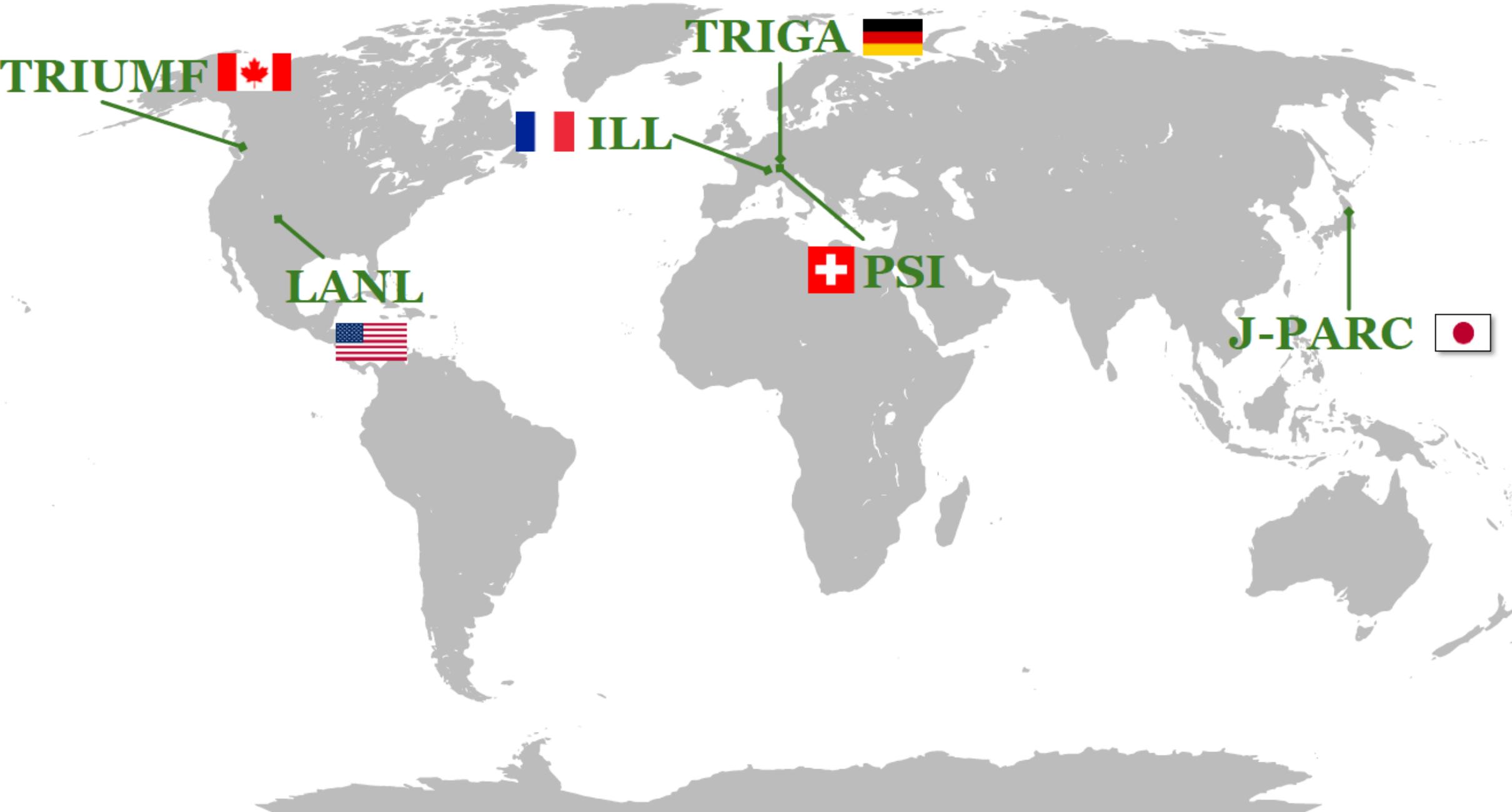- Bulk materials behave as a constant "Fermi potential"

$$U = V + iW$$

- Can be stored with material-dependent storage lifetimes $\tau_s \sim 100$ s (from losses on reflection)

$$N(t) \approx N_0 e^{-t/\tau_s}$$

Fermi potential
~150-300neV
Ni-58 350 neV

Magnetic field
±60 neV/T (spin dependent)

Gravity
102 neV/m

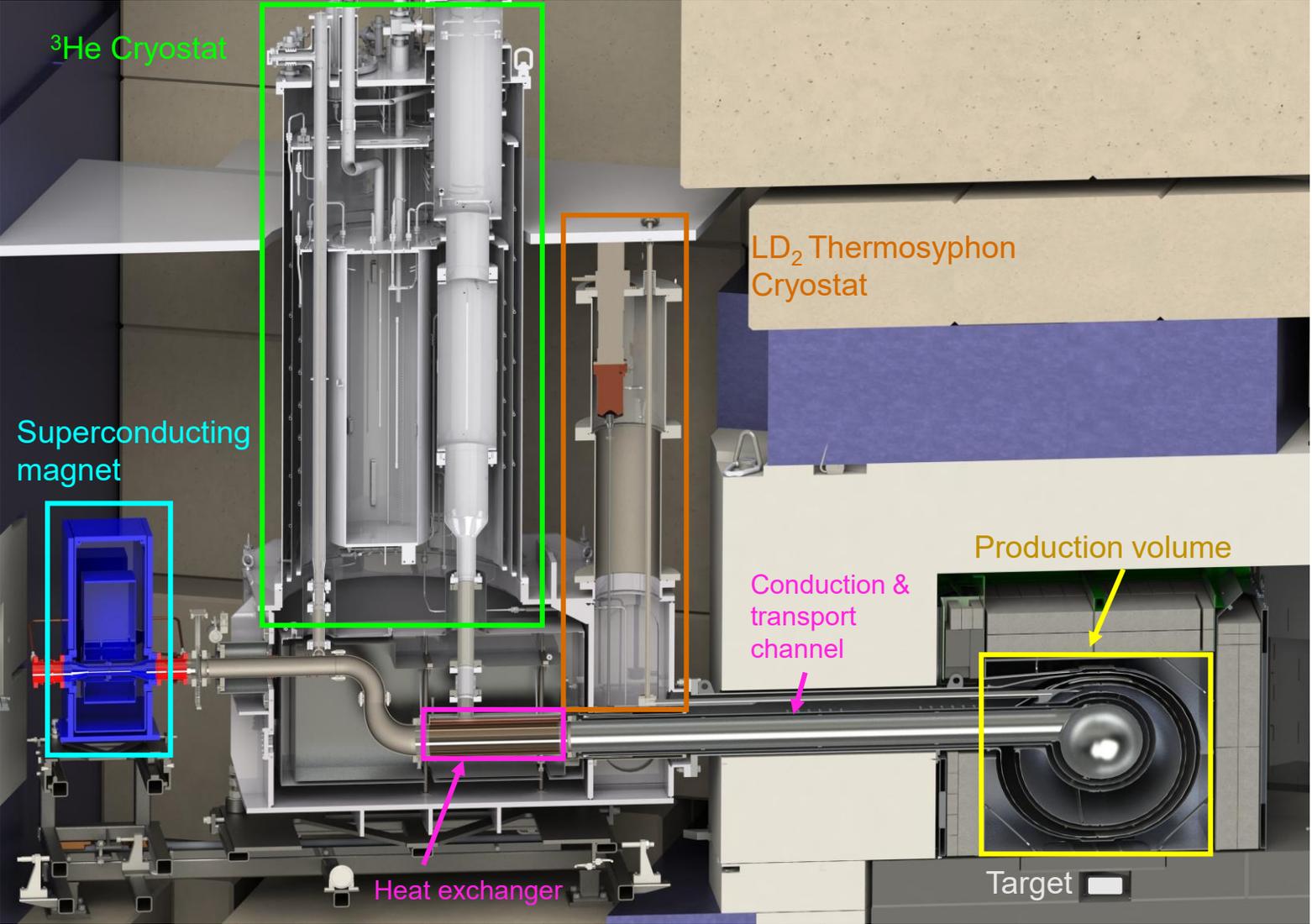**Active UCN Sources**
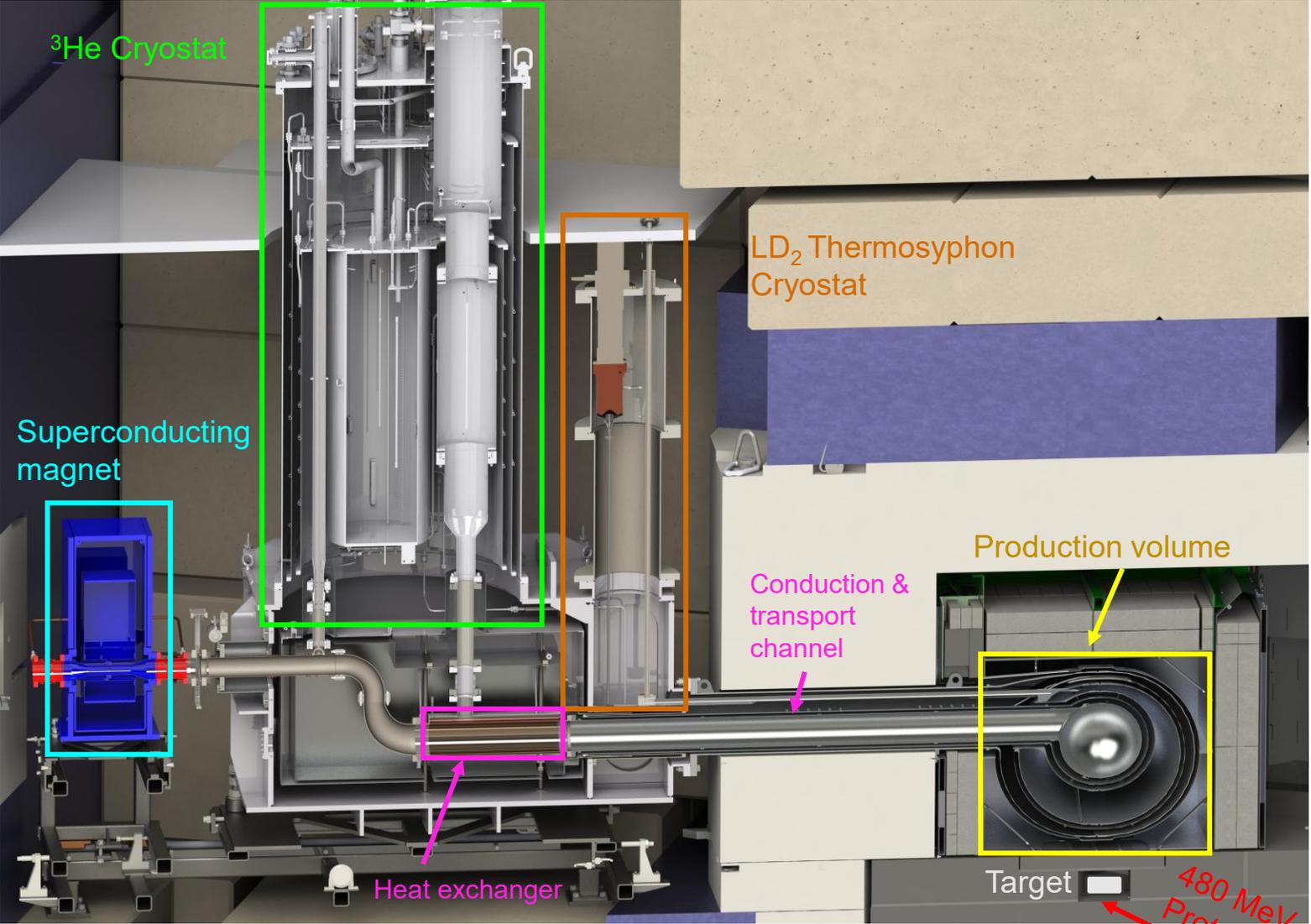
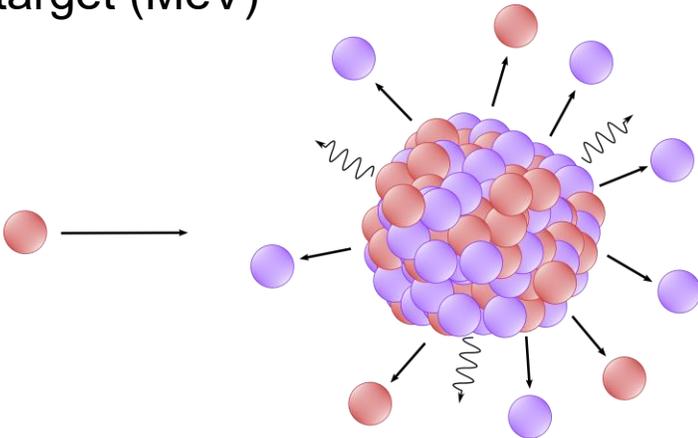**Active UCN Sources**

TRIUMF

TRIGA

ILL

PSI

LANL
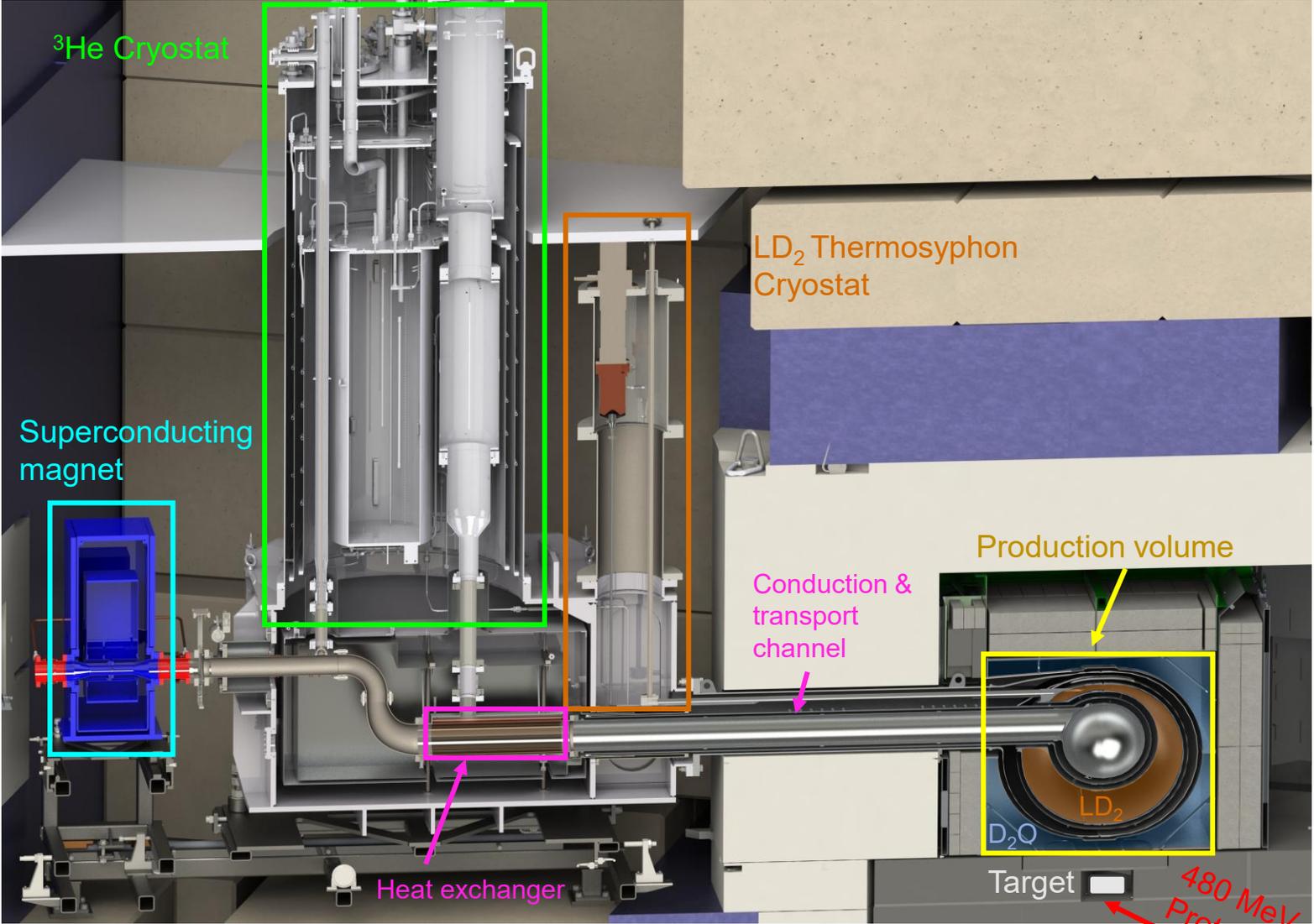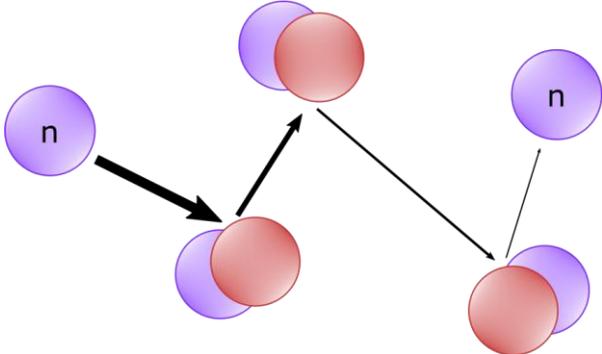
J-PARC
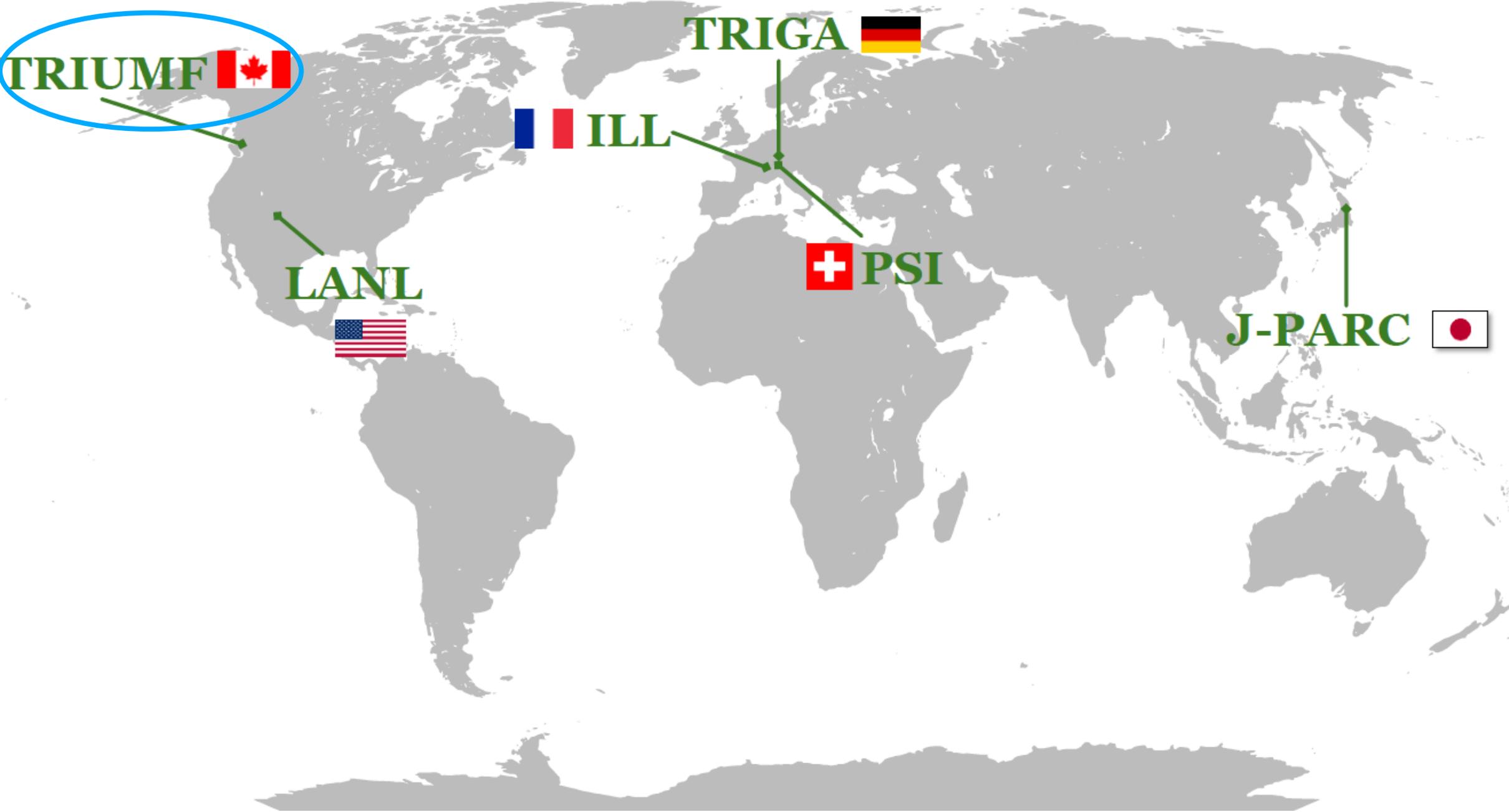
The TUCAN Source

The TUCAN Source

The TUCAN Source

1. Production of high energy neutrons by spallation of tungsten target (MeV)

The TUCAN Source
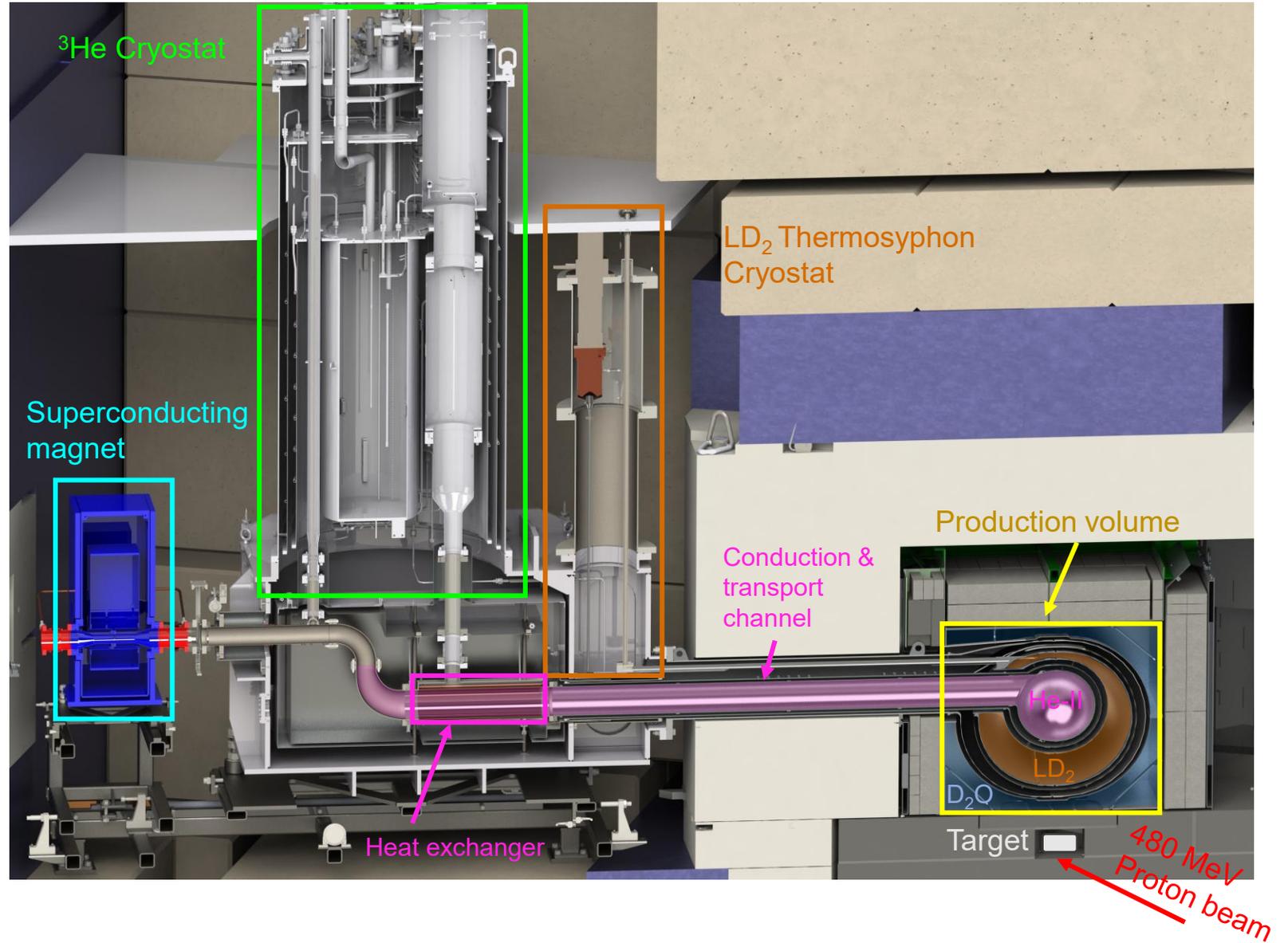
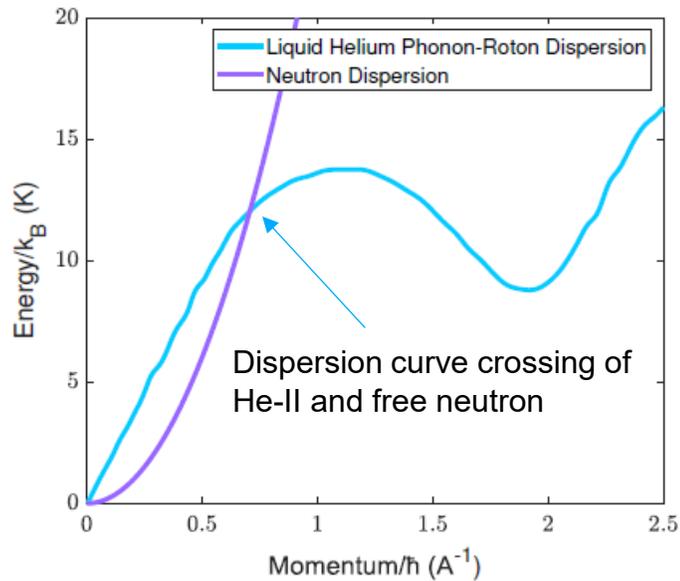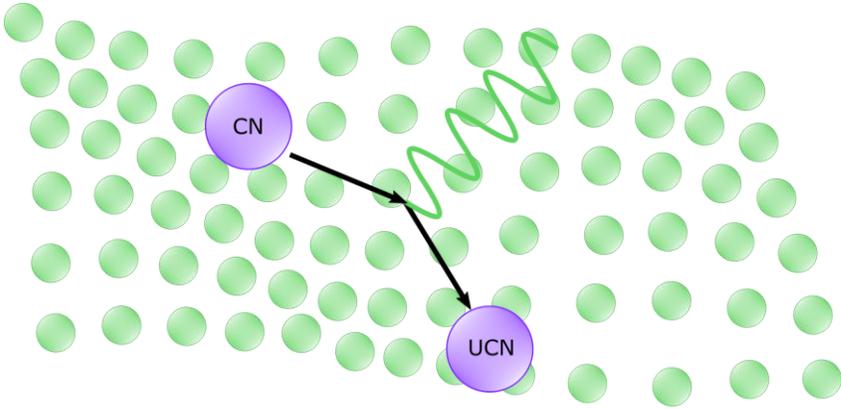2. Moderation to cold energies in 300 K D_2O and 24 K LD_2 (~meV)

The TUCAN Source

3. Superthermal conversion to UCNs (neV) by phonon emission in superfluid helium (He-II)

Dispersion curve crossing of He-II and free neutron

The TUCAN Source

4. Diffusion of UCNs out to experimental area

(superconducting magnet blocks one spin state to fill a polarized UCN population into experiments)
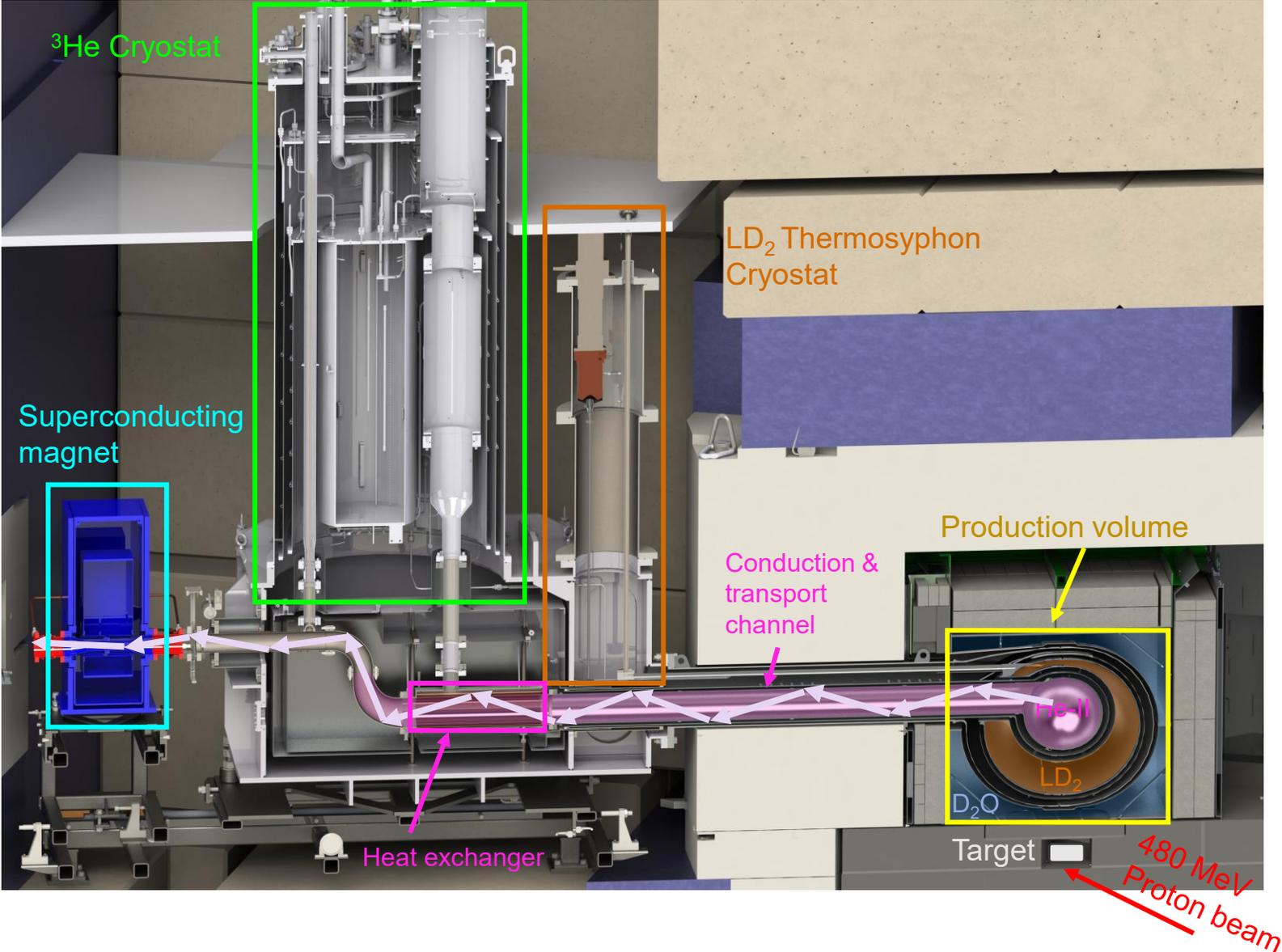
Timeline of the TUCAN Source
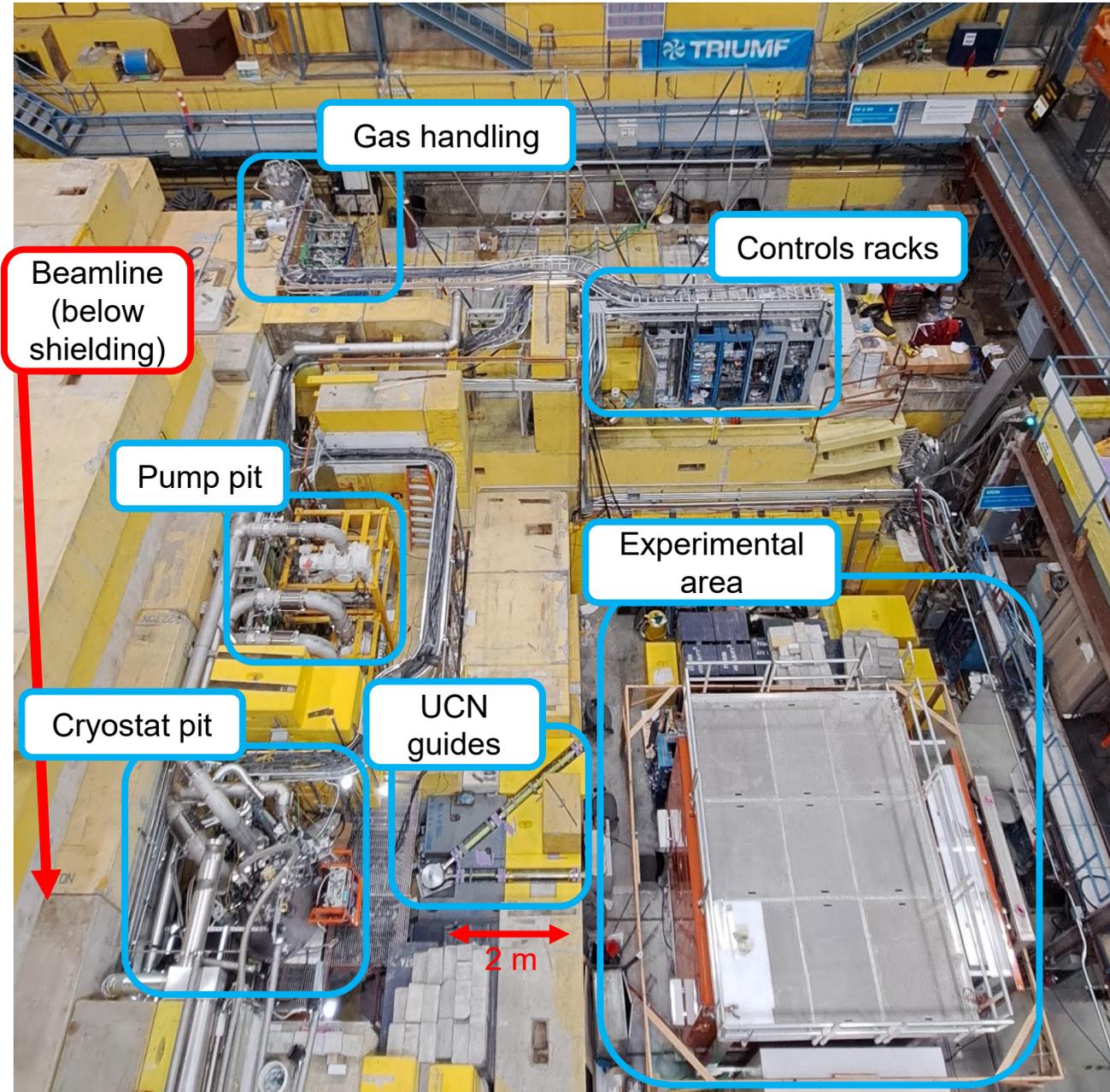
- 2011: Proton beamline design begins

- 2014-2016: Beamline construction

- 2017-2019: Installation and operation of prototype source (previous RCNP source) (https://doi.org/10.1103/PhysRevC.99.025503)

- 2018: Conceptual design of the TUCAN source

- 2021-2025: Build, installation, and cryogenic commissioning of the TUCAN source

- June 2025: First UCN production without LD2 (https://doi.org/10.48550/arXiv.2509.02916)

- December 2025: UCN production with LD2

- **January 2026: Filling of prototype storage cell**

Timeline of the TUCAN Source
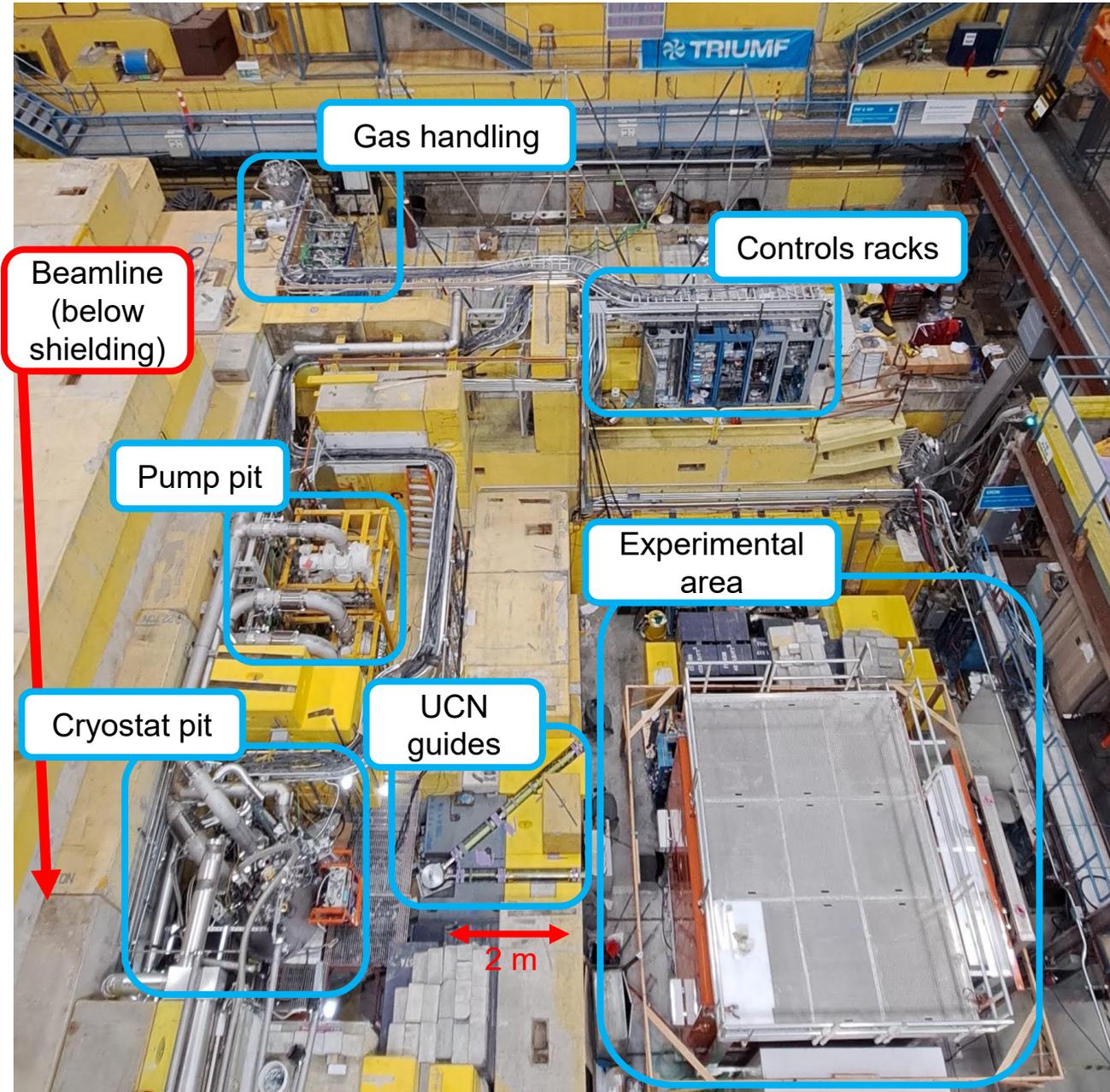

- 2011: Proton beamline design begins

- 2014-2016: Beamline construction

- 2017-2019: Installation and operation of prototype source (previous RCNP source) (https://doi.org/10.1103/PhysRevC.99.025503)

- 2018: Conceptual design of the TUCAN source

- 2021-2025: Build, installation, and cryogenic commissioning of the TUCAN source

- June 2025: First UCN production without LD2 (https://doi.org/10.48550/arXiv.2509.02916)

- December 2025: UCN production with LD2

- **January 2026: Filling of prototype storage cell**

First validation of TUCAN EDM experimental reach
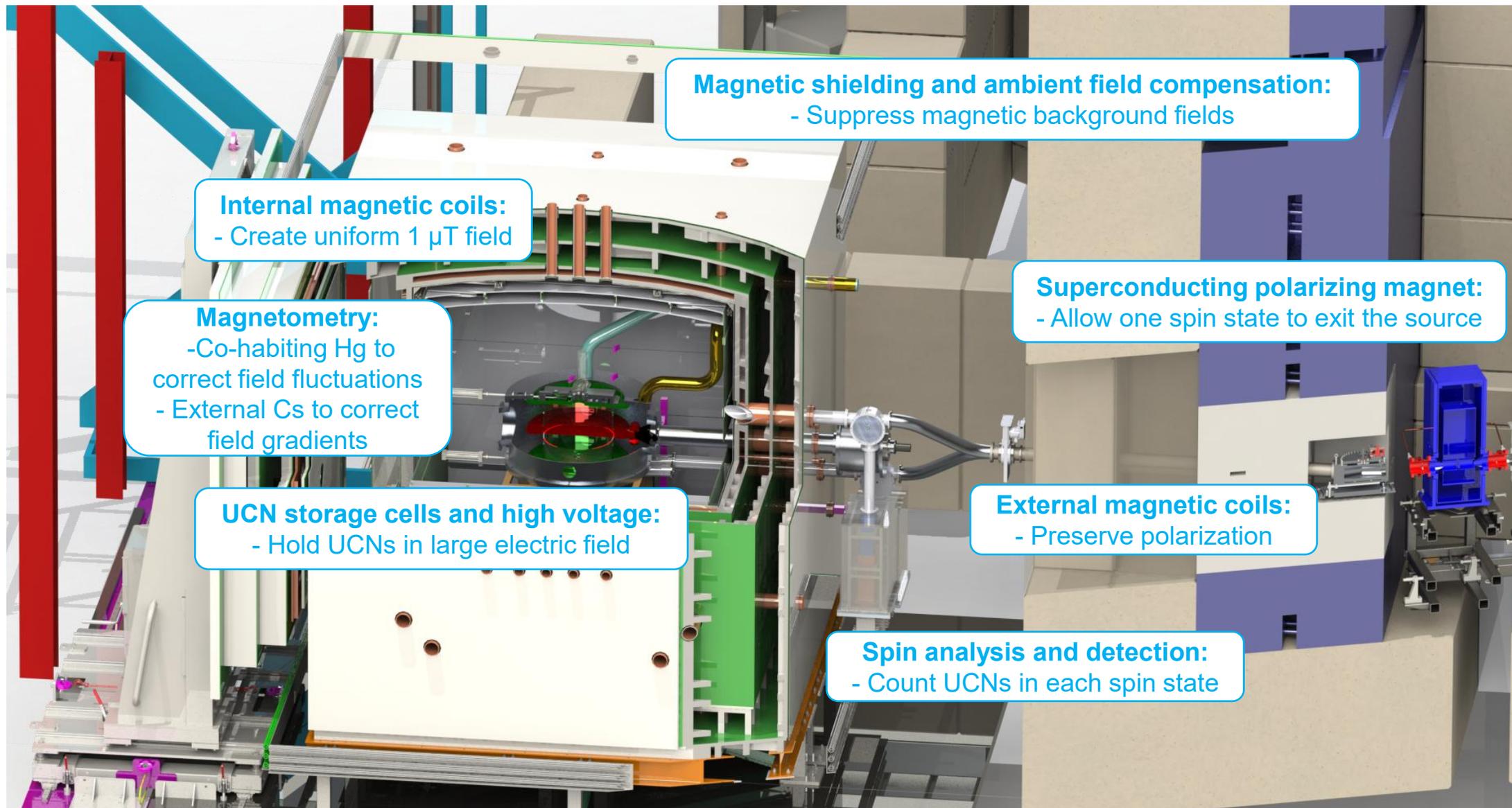
The TUCAN EDM Experiment

The TUCAN Source and EDM Experiment

nEDM spectrometer implementing Ramsey's method

Connecting UCN guides to two experimental ports

Polarizing superconducting magnet

UCN source using He-II with D2O/LD2 moderators and a spallation target

TUCAN EDM

Magnetic shielding and ambient field compensation:
- Suppress magnetic background fields

Internal magnetic coils:
- Create uniform 1 µT field

Magnetometry:
-Co-habiting Hg to correct field fluctuations
- External Cs to correct field gradients

Superconducting polarizing magnet:
- Allow one spin state to exit the source

UCN storage cells and high voltage:
- Hold UCNs in large electric field

External magnetic coils:
- Preserve polarization

Spin analysis and detection:
- Count UCNs in each spin state

A Phased Approach

Shifted resources from experiment development to source construction in 2023

	OC100 (One cell, 100 kV)	2C200 (two cells, 200 kV)
Principle	Development platform	Full experiment
Number of cells	One	Two
HV	100 kV	200 kV
UCN coatings	NiP, DLC, dPS	DLC, dPE
Magnetometry	Hg, 20x Cs	Hg, 50x Cs
Statistical reach	10^{-26} $e$cm in weeks/months	10^{-27} $e$cm in 2-3 years
Systematic effects	"Best effort"/$< 10^{-26}$ $e$cm	$< 10^{-27}$ $e$cm

A Phased Approach

Shifted resources from experiment development to source construction in 2023

Tried to secure more funding in recent Canadian/Japanese funding rounds $\Rightarrow$ not successful

	OC100 (One cell, 100 kV)	2C200 (two cells, 200 kV)
Principle	Development platform	Full experiment
Number of cells	One	Two
HV	100 kV	200 kV
UCN coatings	NiP, DLC, dPS	DLC, dPE
Magnetometry	Hg, 20x Cs	Hg, 50x Cs
Statistical reach	10^{-26} $e$cm in weeks/months	10^{-27} $e$cm in 2-3 years
Systematic effects	"Best effort"/$< 10^{-26}$ $e$cm	$< 10^{-27}$ $e$cm

Prototype Storage Cell

- From 2019, we designed and built a prototype storage cell

- Same internal geometry as expected for real cells

- Cannot be used with HV

- Worse "electrode" coatings: electroless nickel-phosphour (NiP) instead of diamond-like carbon (DLC)

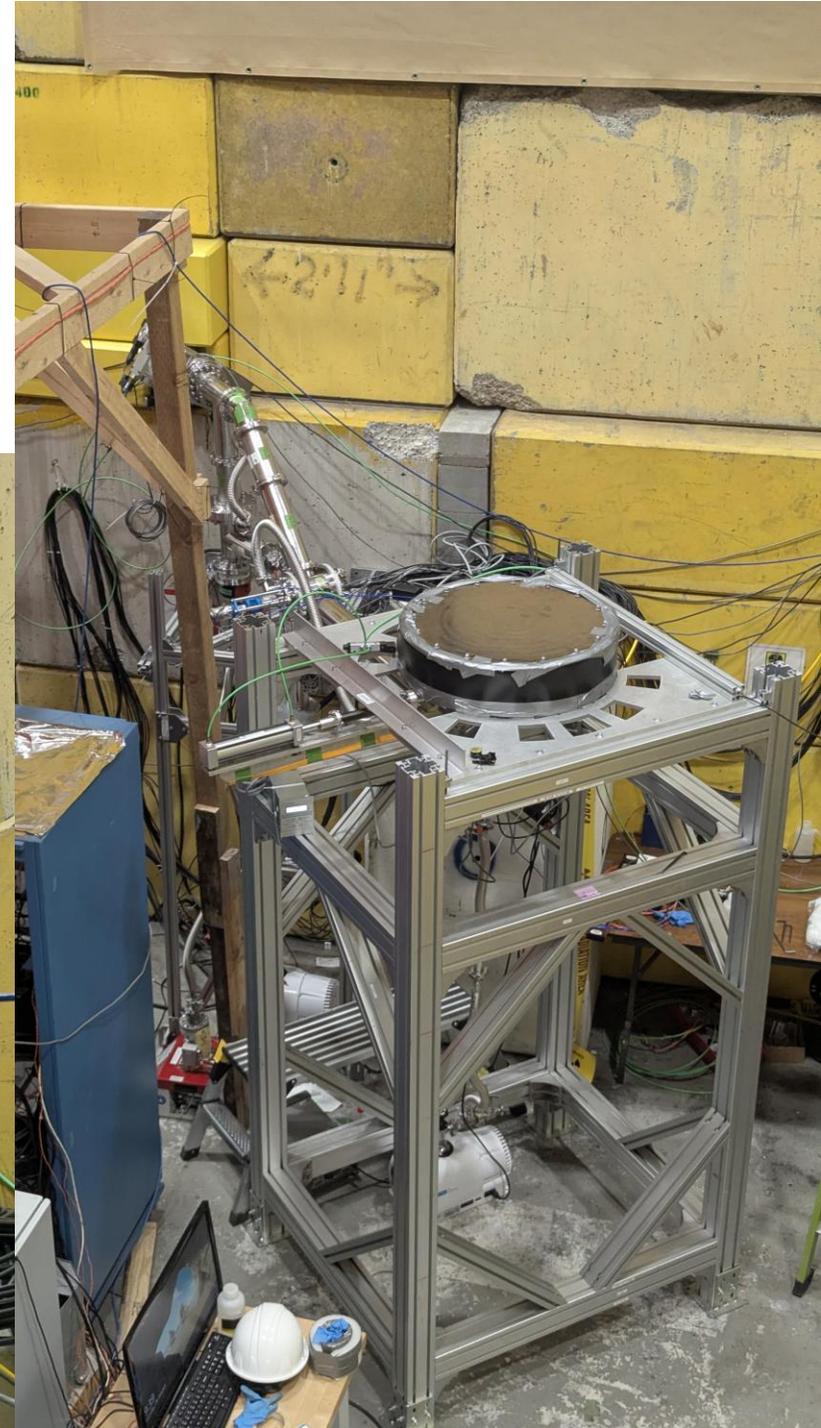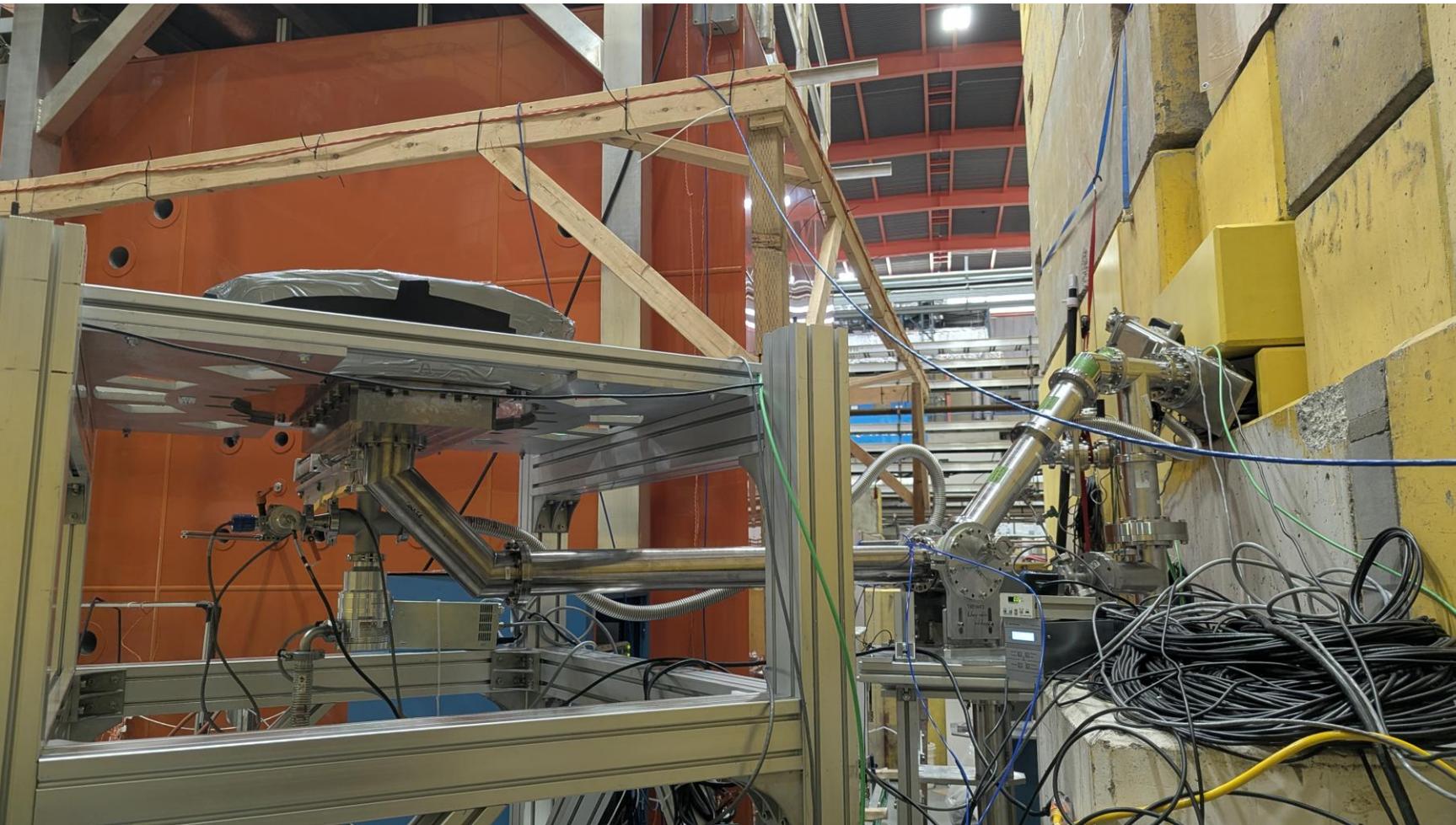- Correct "insulator" coating: deuterated polystyrene (dPS)
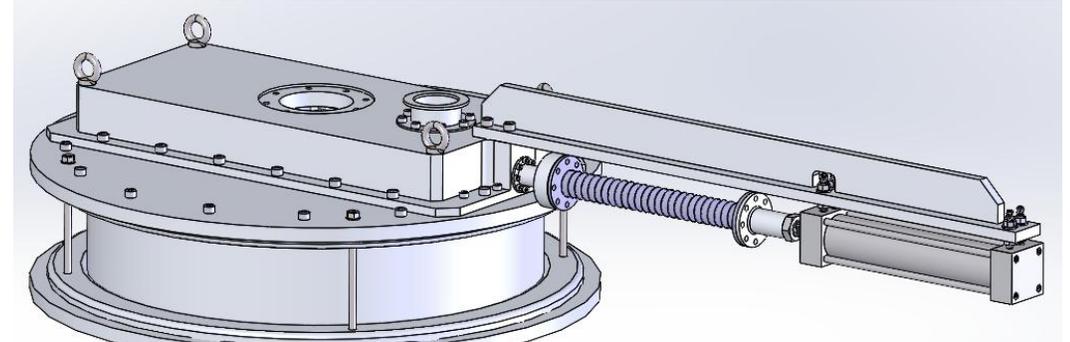
Valve & prototype cell CAD model

NiP "electrodes"
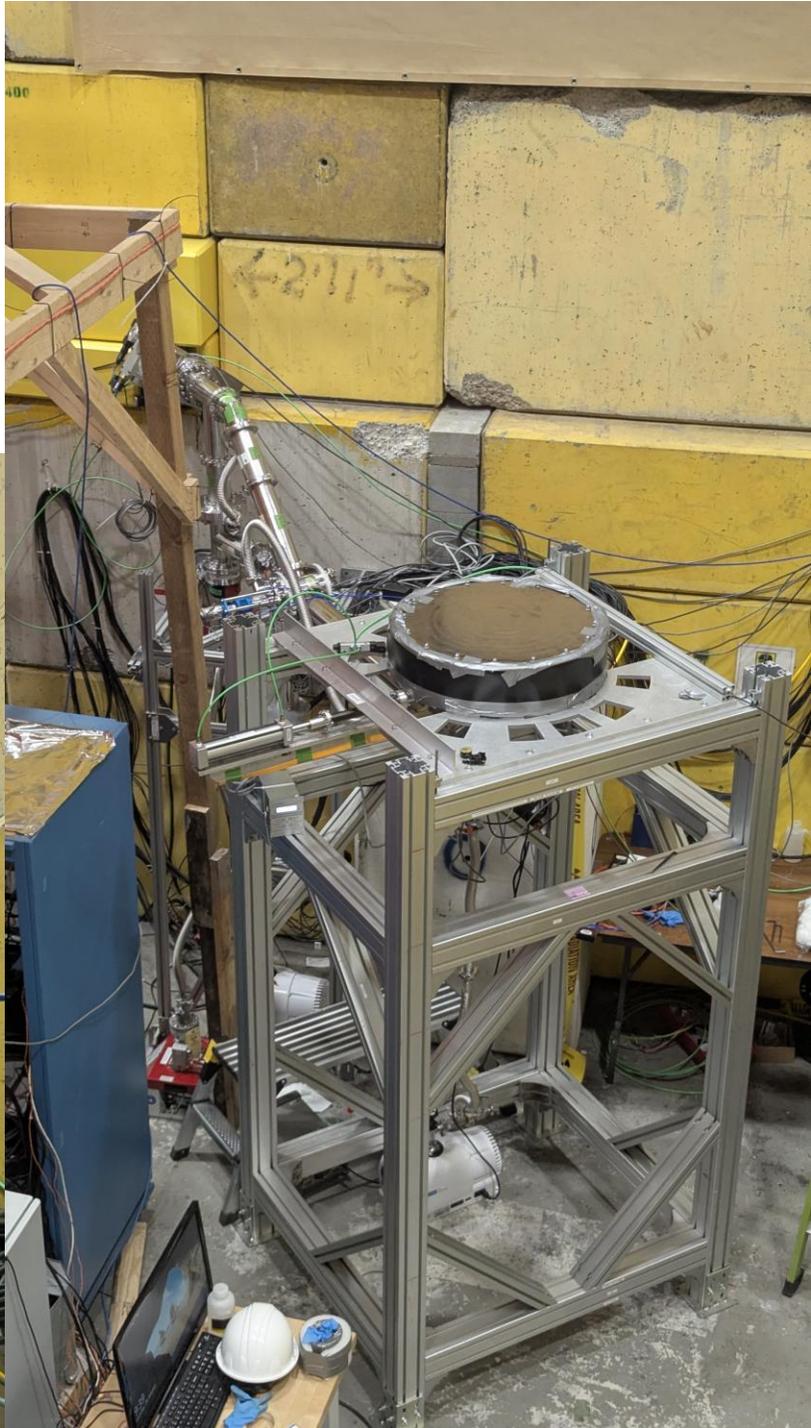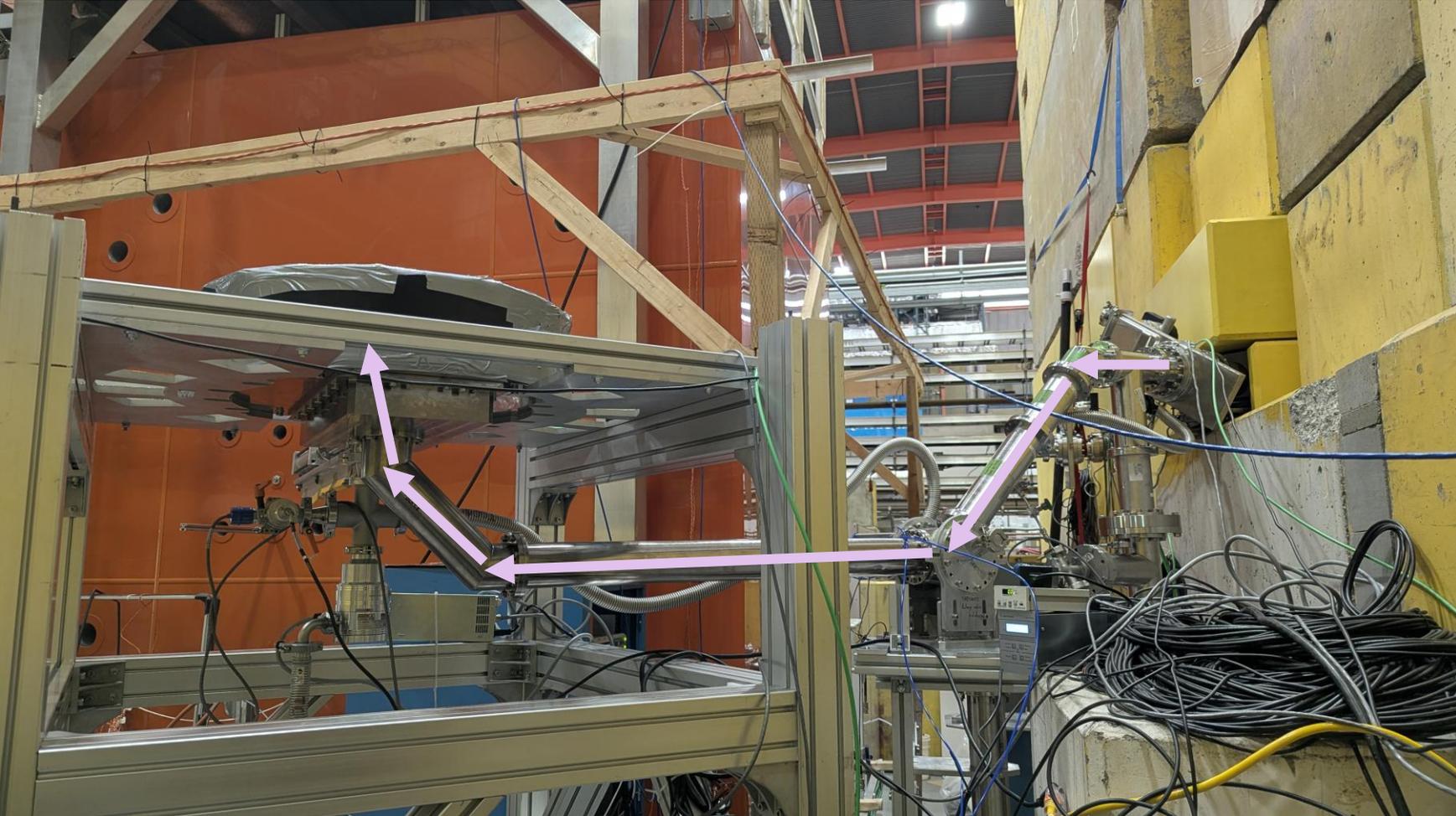
dPS insulator

Cell valve
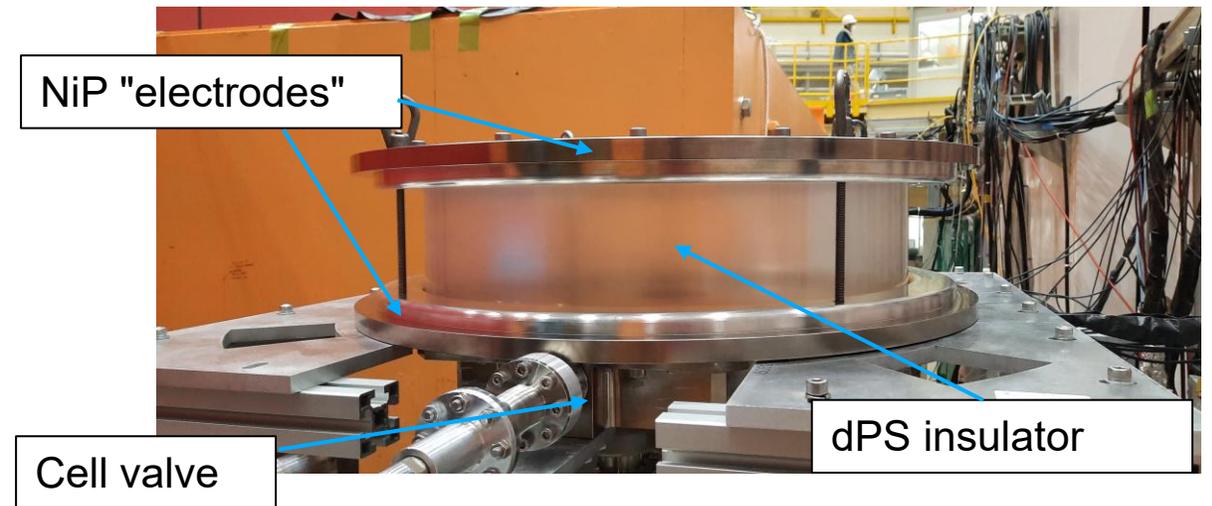
TRIUMF Measurements of Cell Loading/Storage

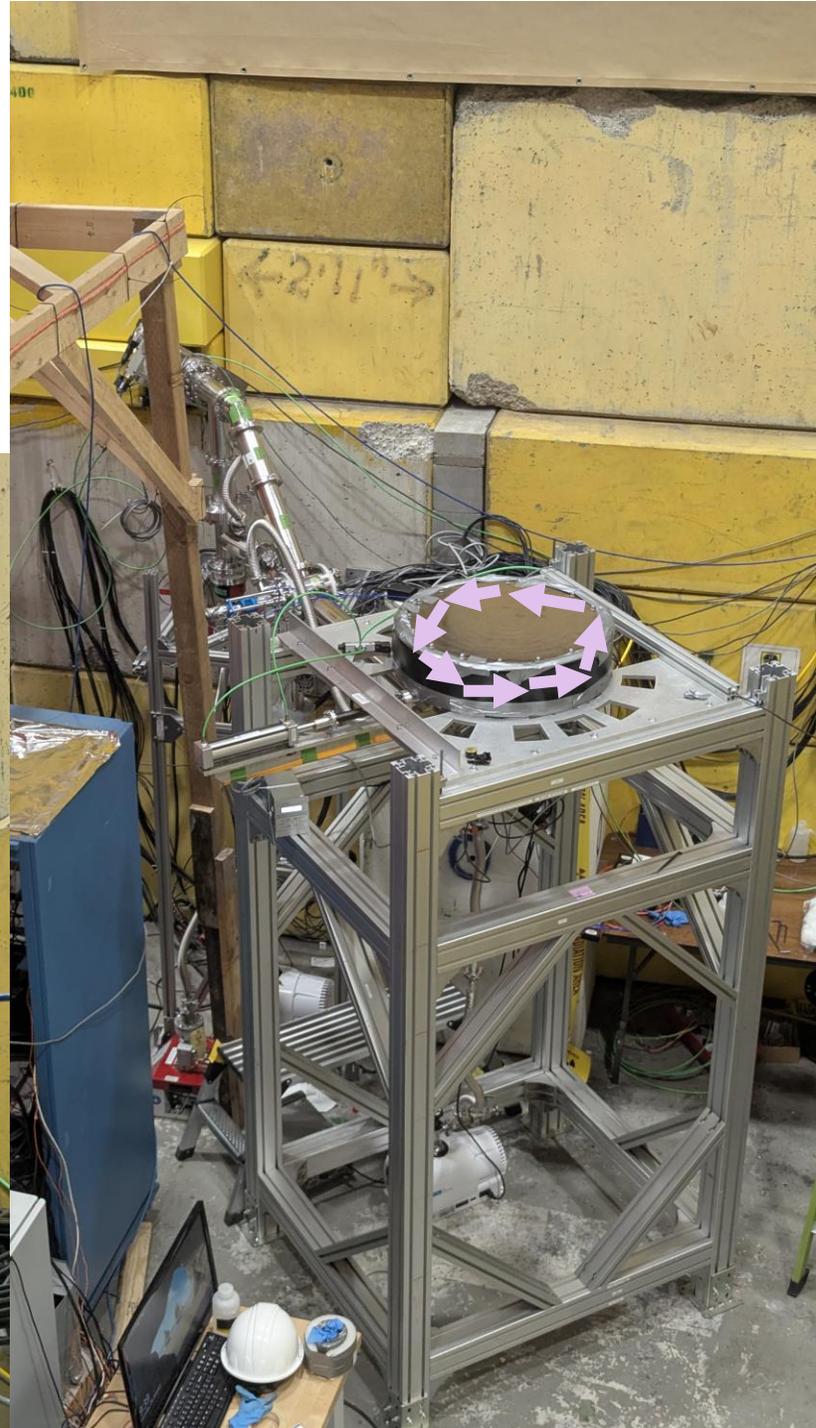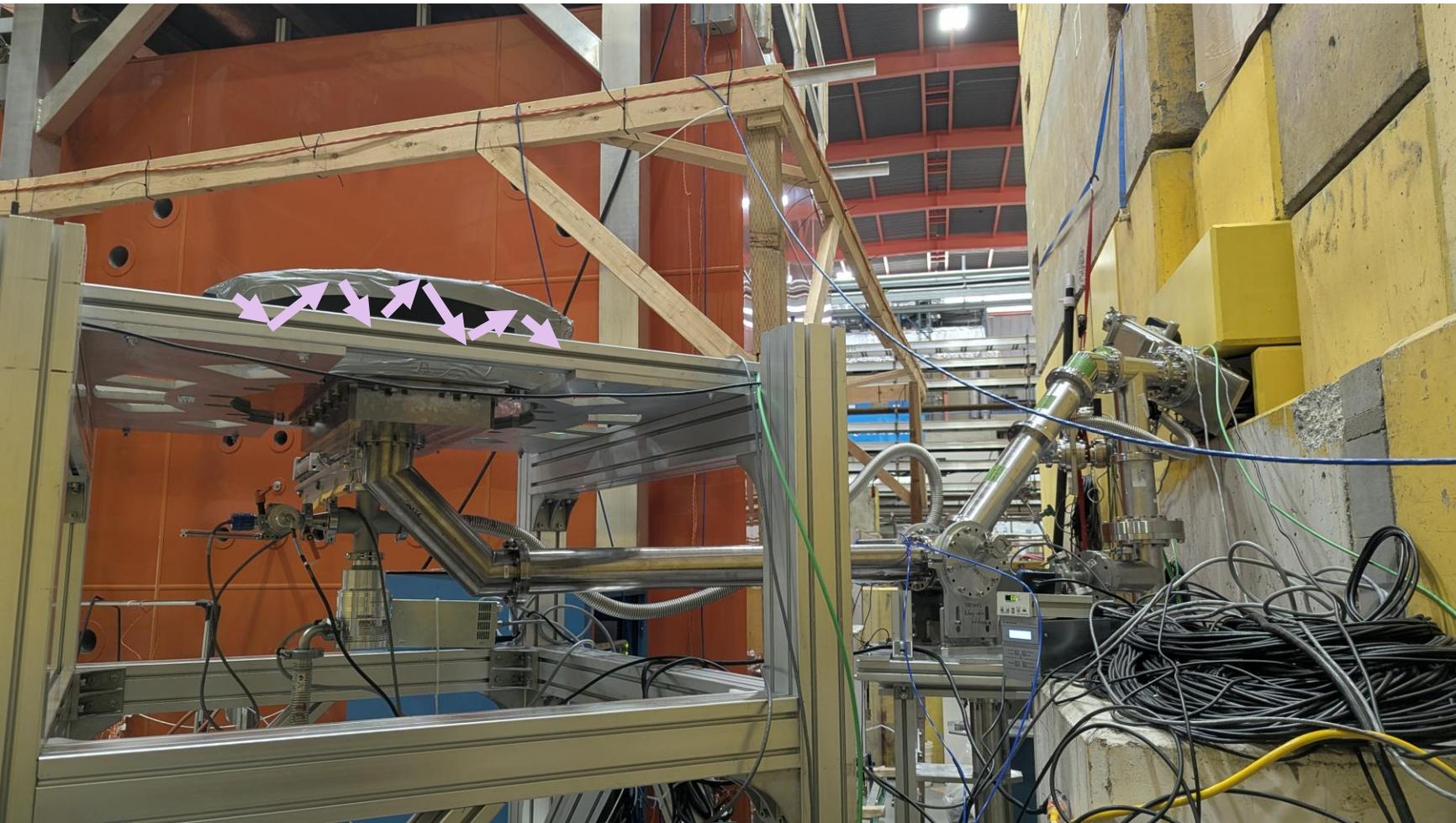In January 2026, we performed experiments with this cell connected to the TUCAN source

TRIUMF Measurements of Cell Loading/Storage

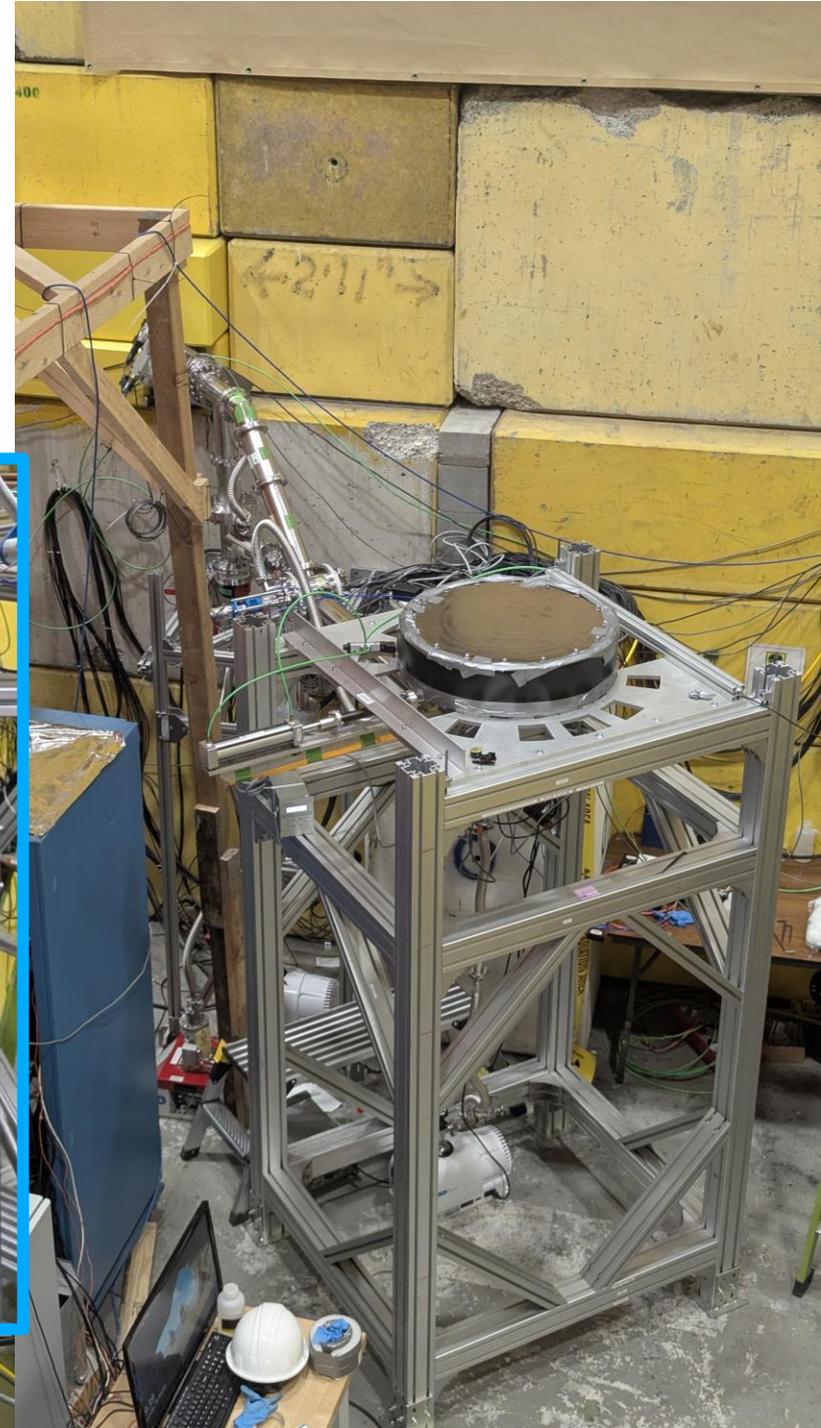1. Fill UCNs from the source into the cell

2. Close the cell valve and store the UCNs for some time
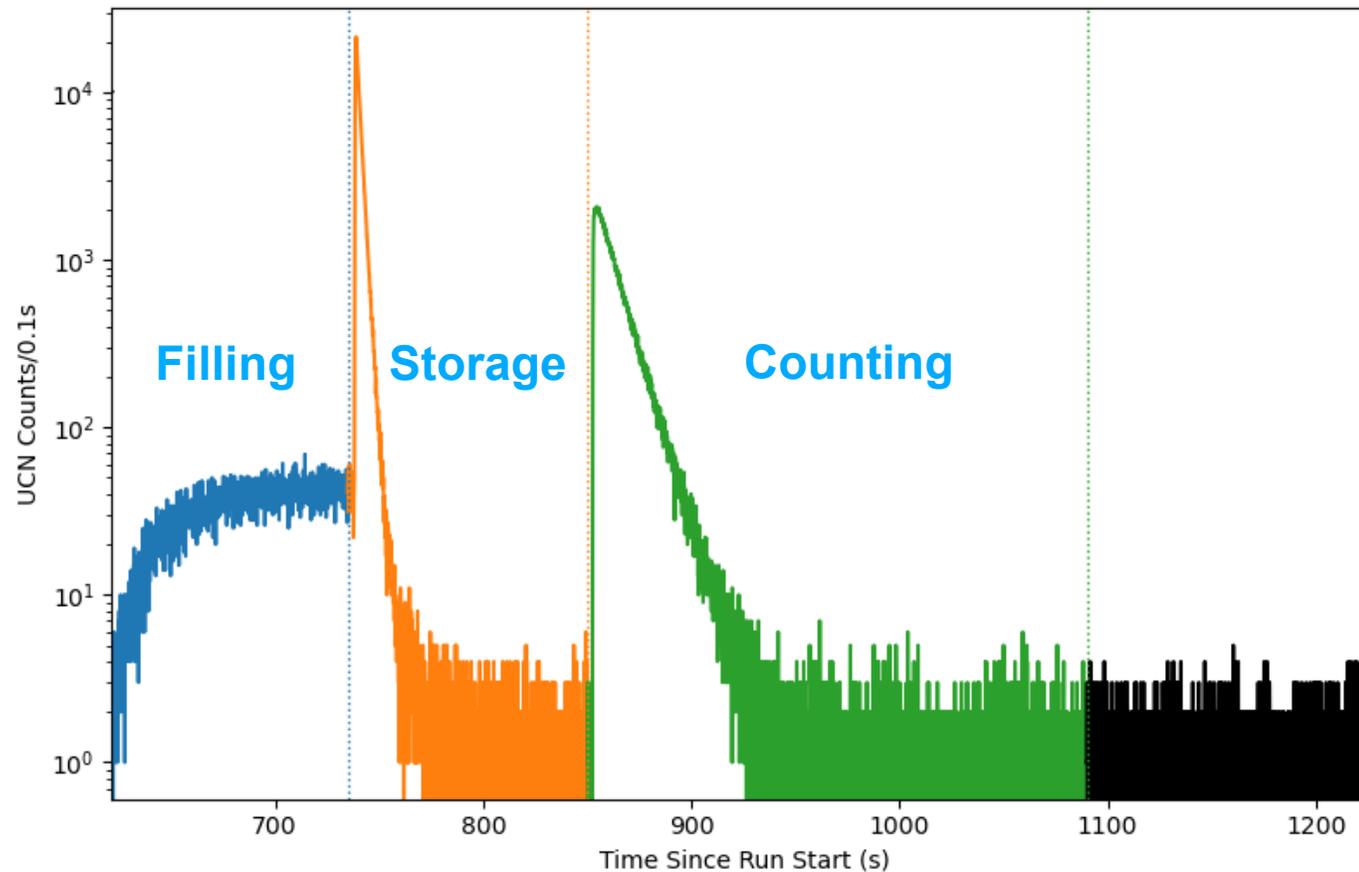
3. Empty UCNs from the cell into the 6Li detector
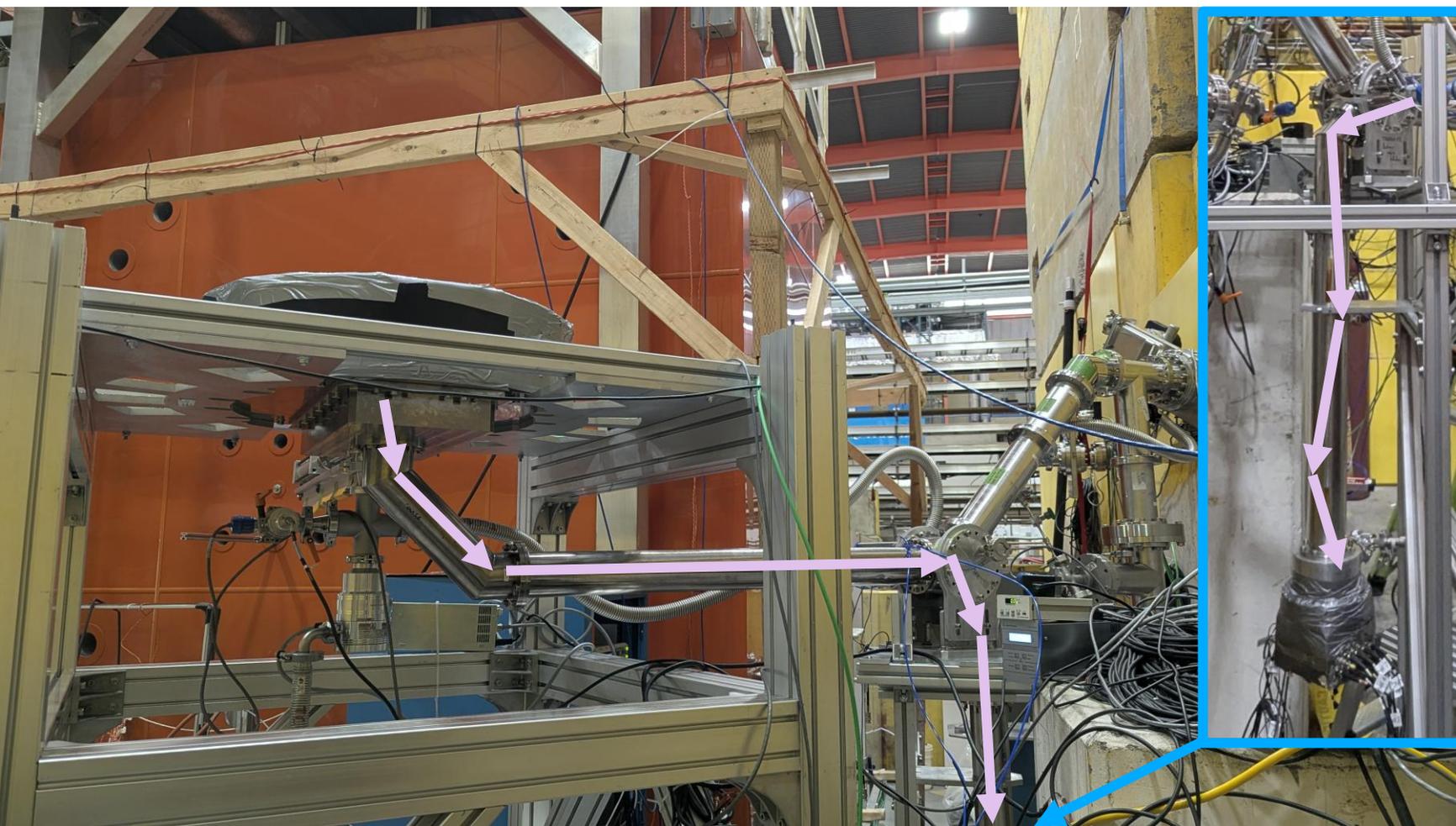
Experiment Sequence

Find optimum filling time, storage time, and counting time that would minimize per-fill uncertainty in an nEDM measurement
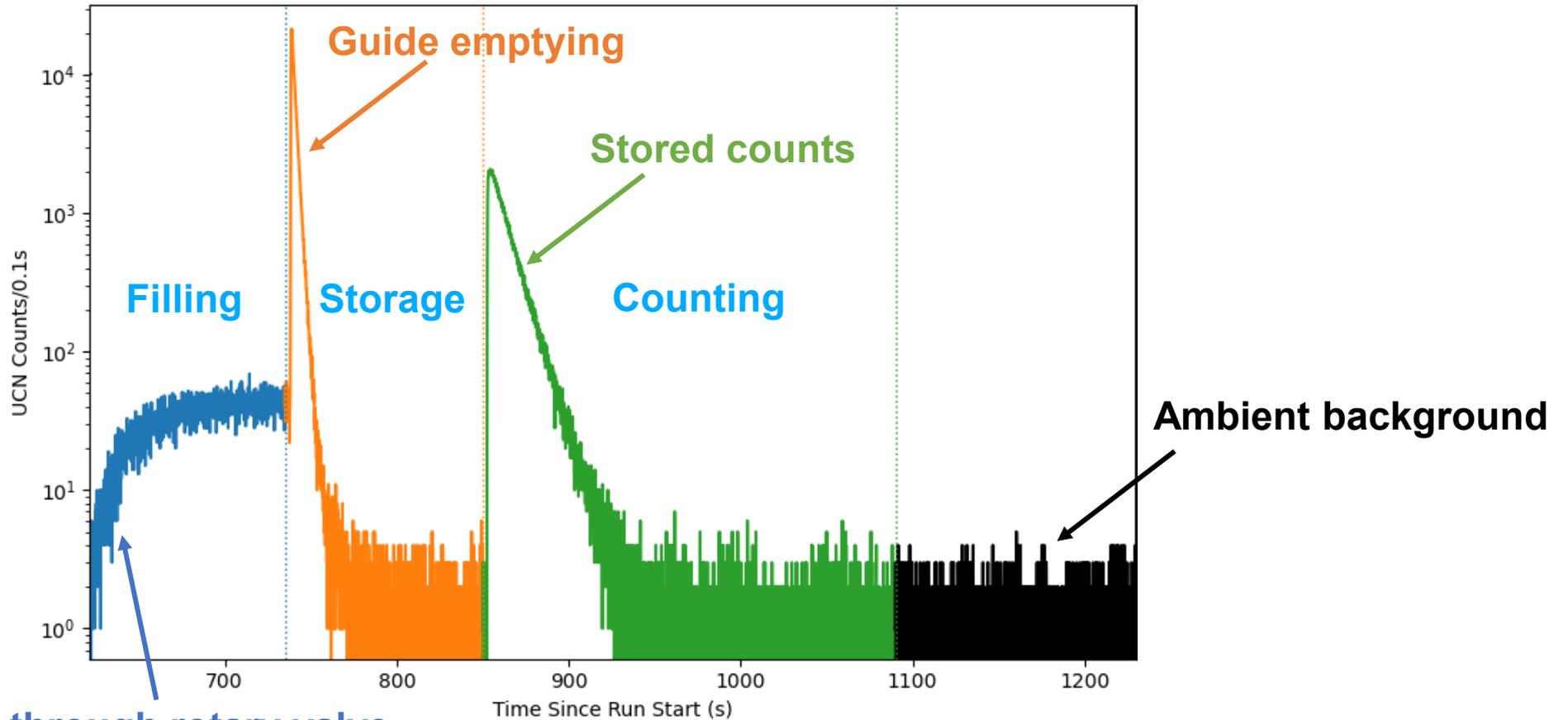
Detector rate during an example cycle

Repeated such cycles for different filling and storage times in a 2D scan.

Counting time optimization is done post-analysis by cutting.

Experiment Sequence

Find optimum filling time, storage time, and counting time that would minimize per-fill uncertainty in an nEDM measurement

Caveats

Unpolarized UCNs with titanium protection foil in source instead of polarized UCNs with superconducting magnet and aluminium protection foil in source

$\Rightarrow$ Ti foil measured to have 25% transmission $\Rightarrow$ similar to expected from SCM + Al foil

Source did not have full D2O volume or He-II volume

$\Rightarrow$ Increase of x1.3 expected from MCNP simulations

Beamline could only be operated at 26.67 uA instead of 40 uA

$\Rightarrow$ Increase of x1.5

Experiment had to be built with old, non-optimal guides

$\Rightarrow$ Gains not completely predictable, but some "obvious" fixes x1.25

$\Rightarrow$ Expected to increase counts by x2.4

Detection of unpolarized UCNs with simple detector instead of spin analyzer

$\Rightarrow$ Uncertain decrease in counts

Statistical Reach

- Optimum timings:
  - Filling: 110s
  - Storage: 160s
  - Counting: 40s

- Detected counts: 155K

- Assuming:
  - 100 kV
  - 1 cell
  - α = 0.6

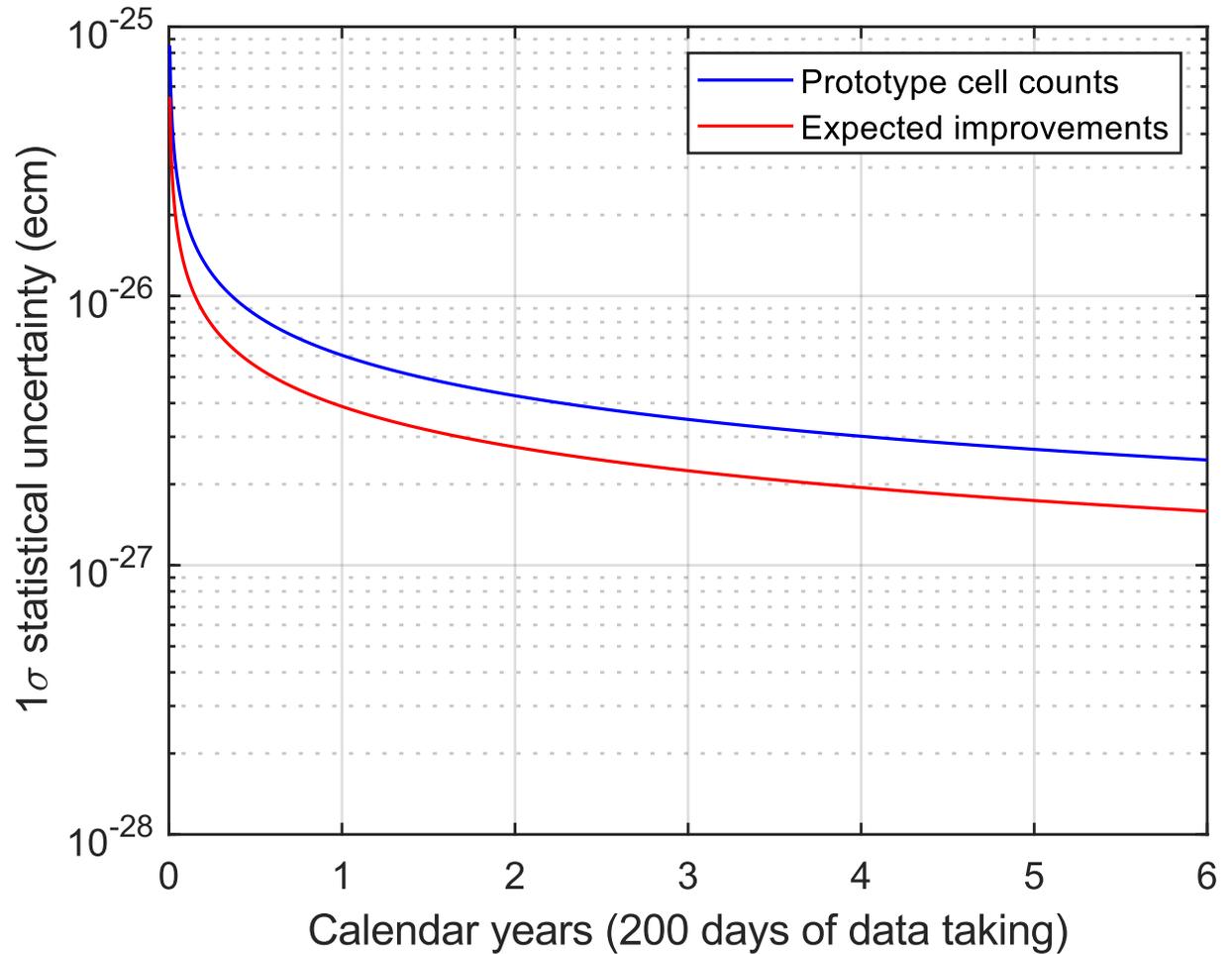- Expect to reach 10^{-26} ecm in 70 days
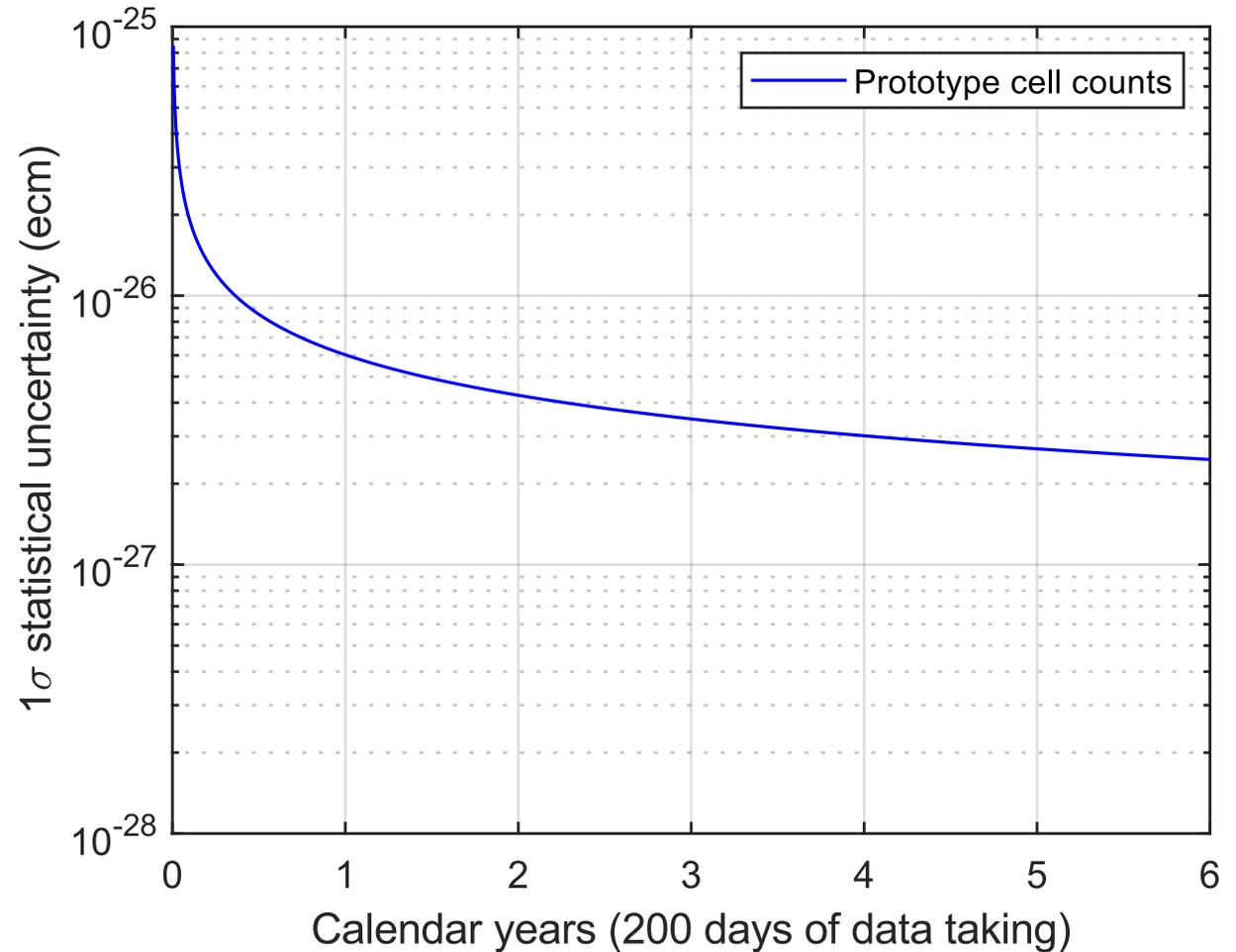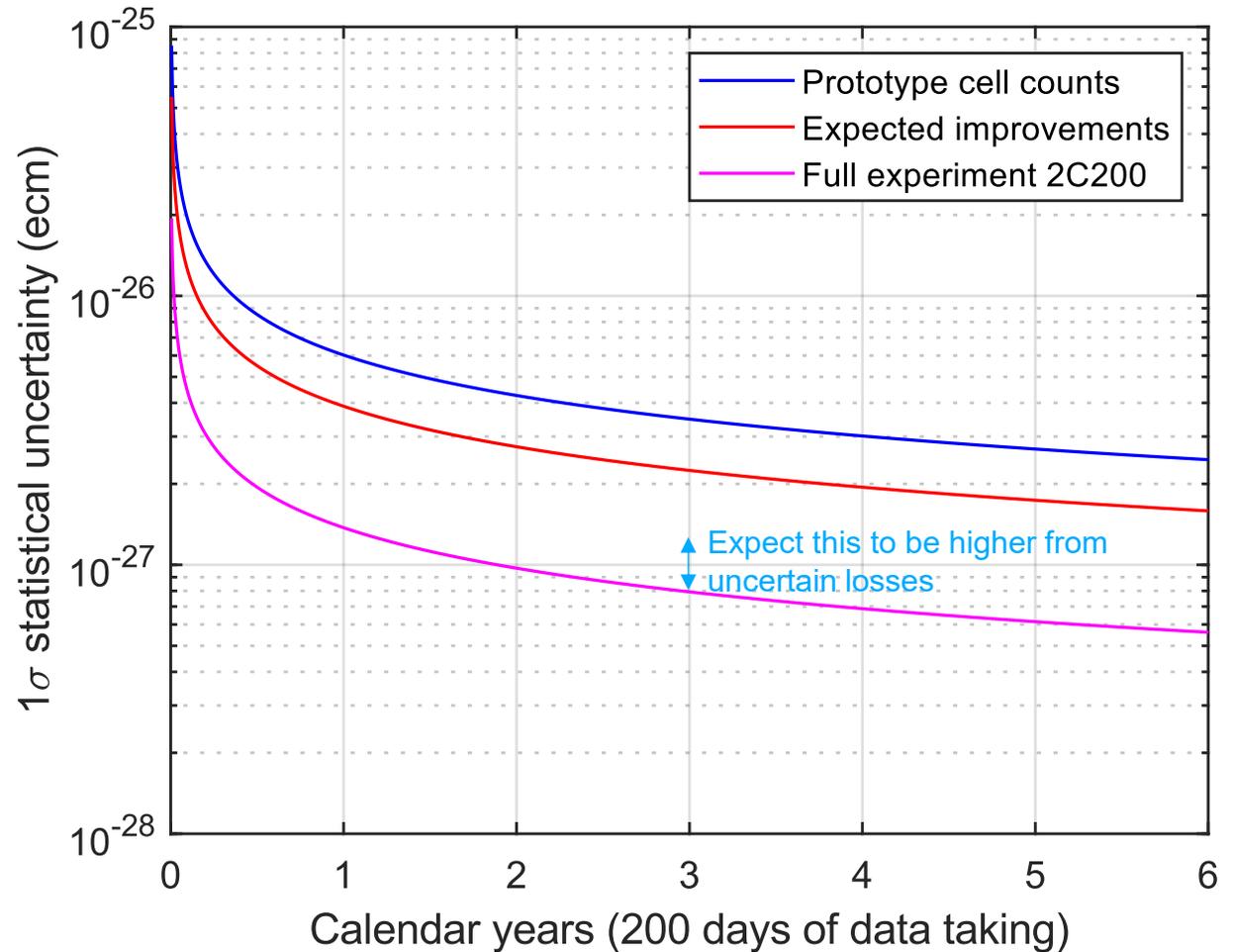
Statistical Reach

- Optimum timings:
  - Filling: 110s
  - Storage: 160s
  - Counting: 40s

- Detected counts: 2.4x155K

- Assuming:
  - 100 kV
  - 1 cell
  - α = 0.6

- Expect to reach 10^{-26} ecm in 1 month with improvements
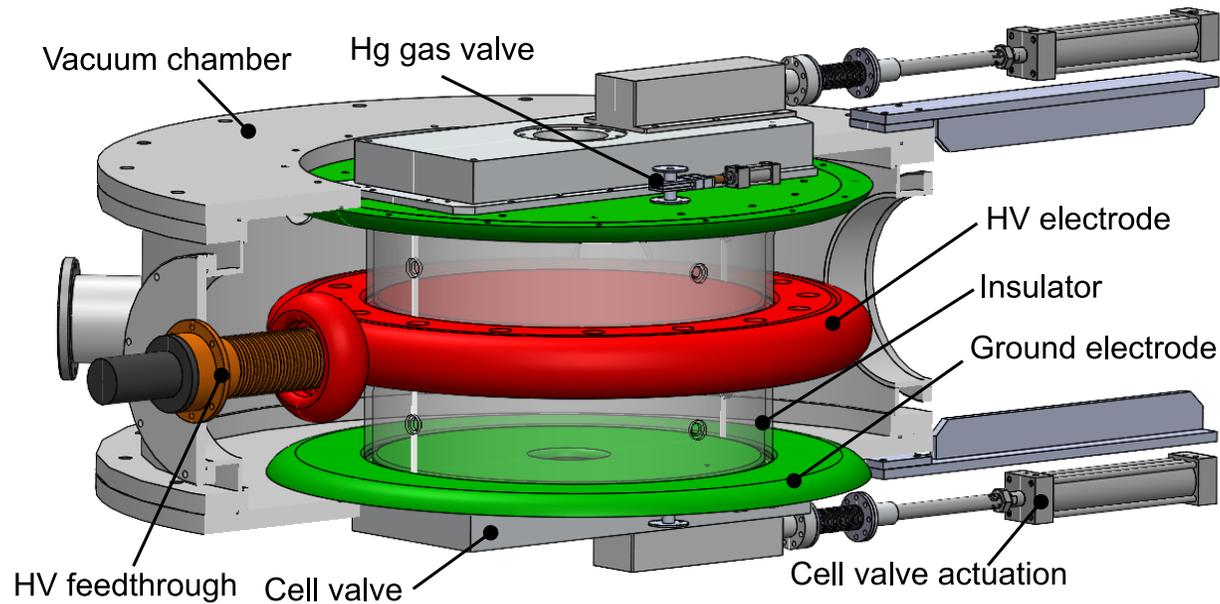
Statistical Reach

- Assuming:
  - 200 kV
  - 2 cell
  - α = 0.6

- Expect to reach 10^{-27} ecm in 2-3 years

- Other improvements are possible from
  - better UCN guides,
  - better cell coatings,
  - higher visibility

Progress Towards Building the TUCAN EDM Experiment

- TRIUMF long shutdown from Feb 2026 to Summer 2027

- Working on completing installation and commissioning of OC100 subsystems

- To start measurements on polarized UCNs in 2027
  - Polarized UCN filling, storage, detection
  - Ramsey cycles

- Trying again to secure funding for full experiment

Storage cells and HV

Vacuum chamber
Hg gas valve
HV electrode
Insulator
Ground electrode
HV feedthrough
Cell valve
Cell valve actuation

- Completing detailed design and beginning manufacturing

- Only building one cell to start

- Lots of small-scale testing at 100 kV

- Initially to be used with existing 100 kV supplies

Magnetic Shielding

Six layer magnetically-shielded room built by Magnetic Shields Ltd.

- 5 layers of MuMetal + 1 copper layer
- Shielding factor 37500 at 0.01 Hz, 2 uT
- Residual field 1-1.5 nT
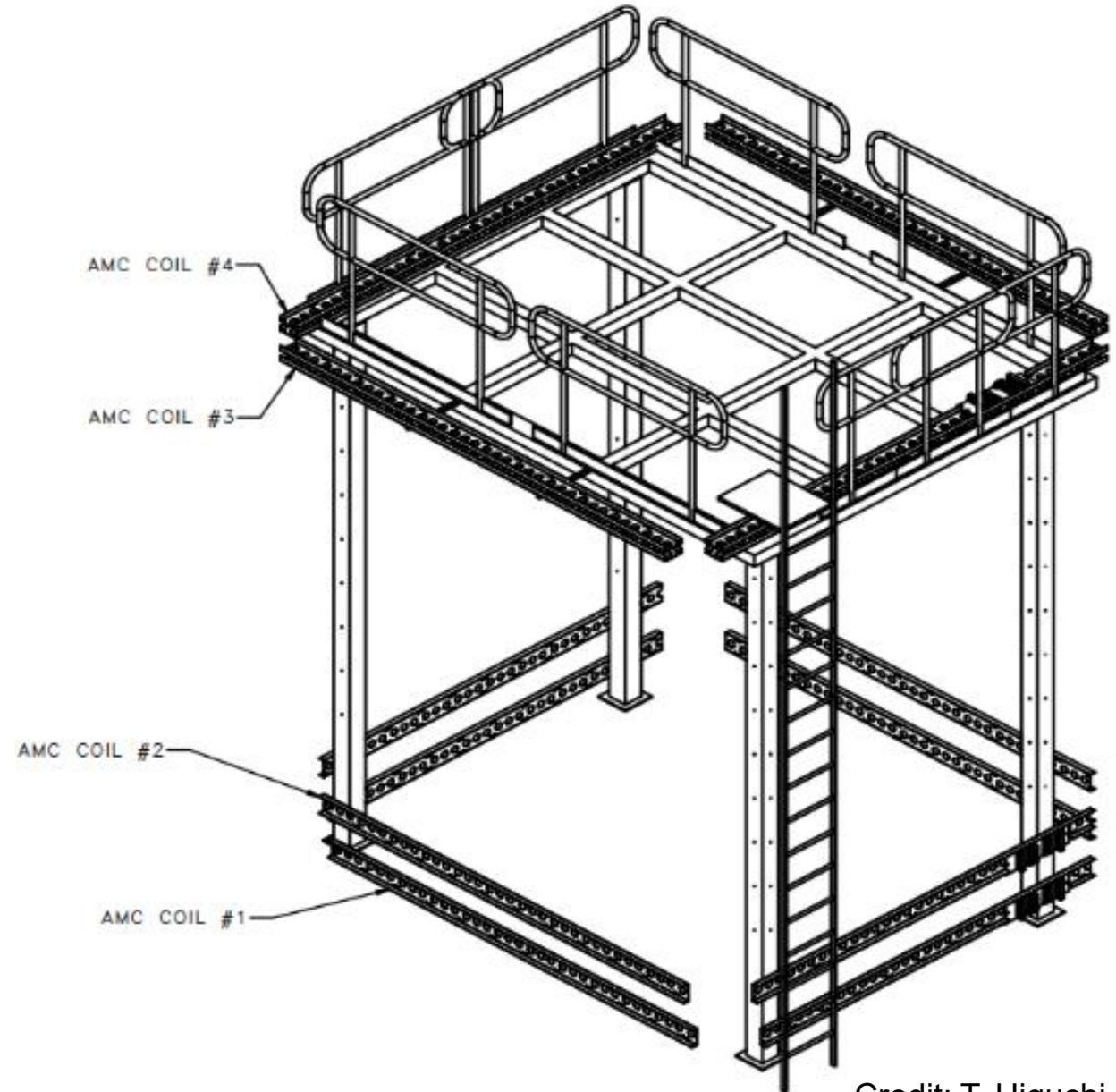- Working on degaussing improvements
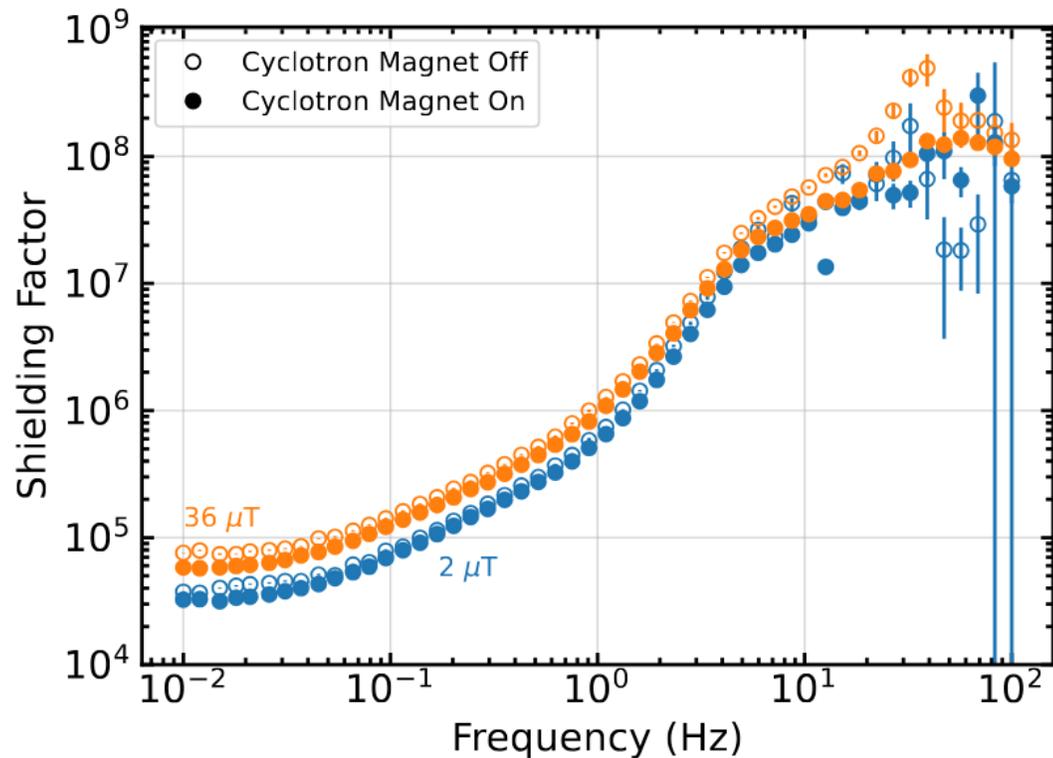
Credit: D. Fujimoto

Ambient Magnetic Compensation

- Single-purpose coils to counter specific field sources

- Biggest problem is the TRIUMF cyclotron fringe field: 400 µT
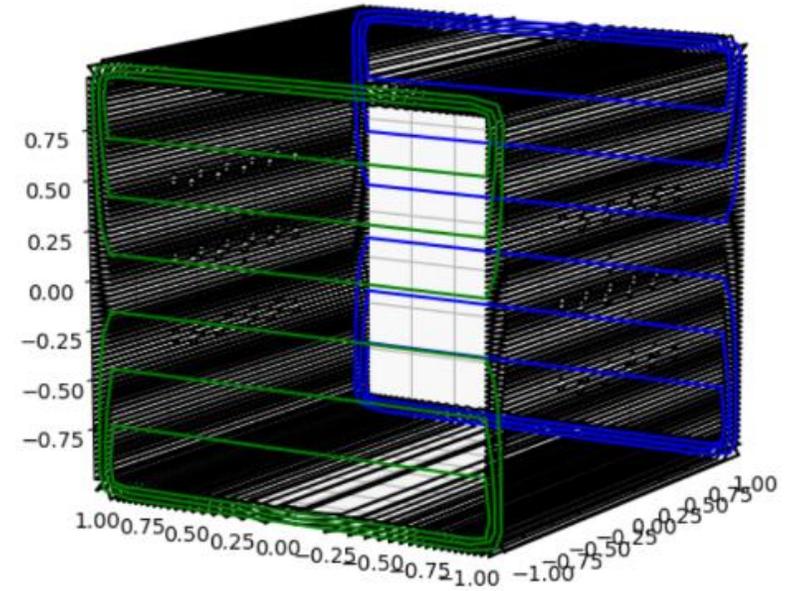
- Installation currently ongoing.

Credit: T. Higuchi

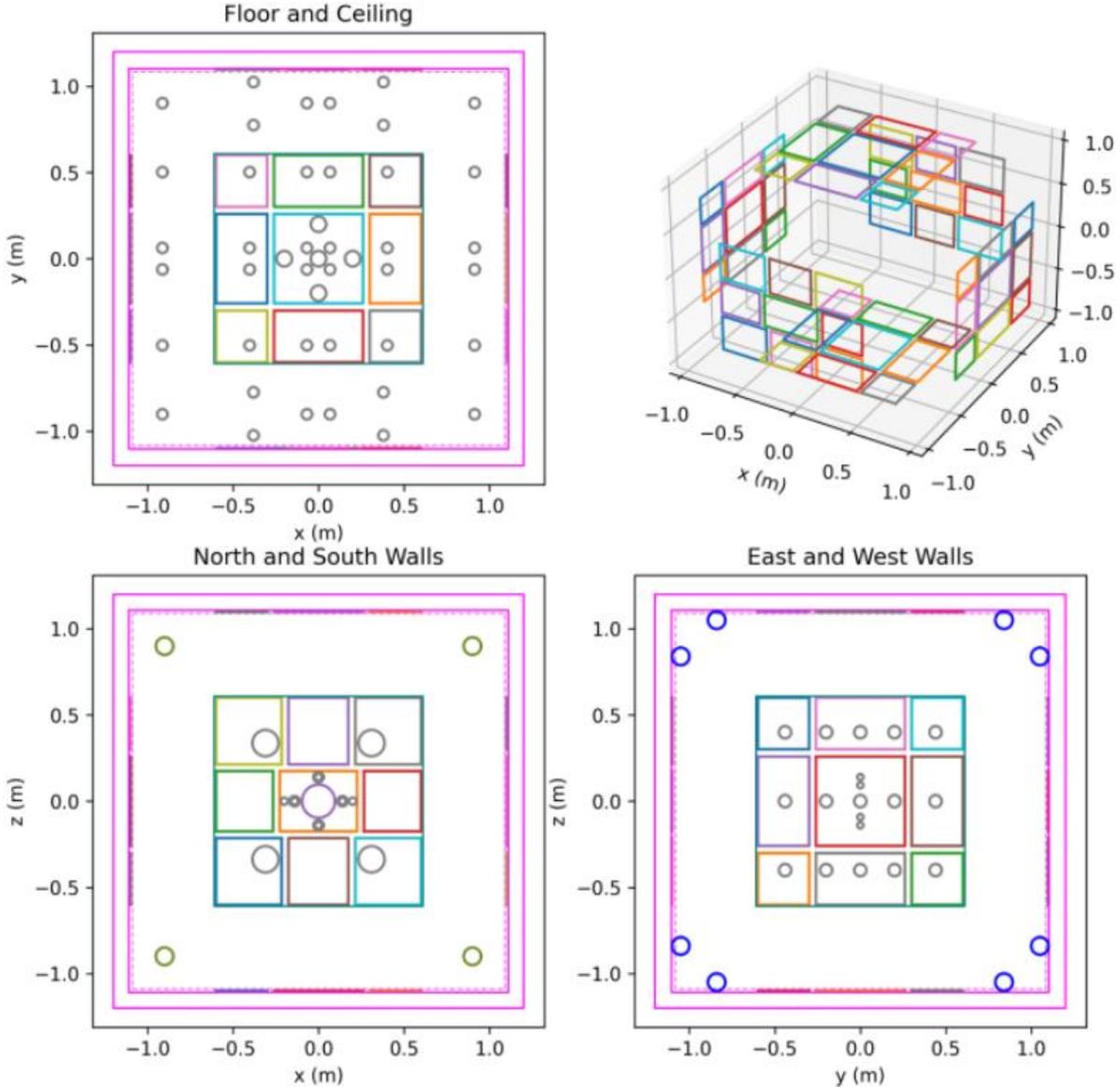# Internal Magnetic Coils: Main Field Coil

Credit: M. McCrea

- Self-shielded square cosine-theta coil

- 3D-printed wire guides glued onto G10+aluminium panels, attached to aluminium frame

- Assembly of panels ongoing

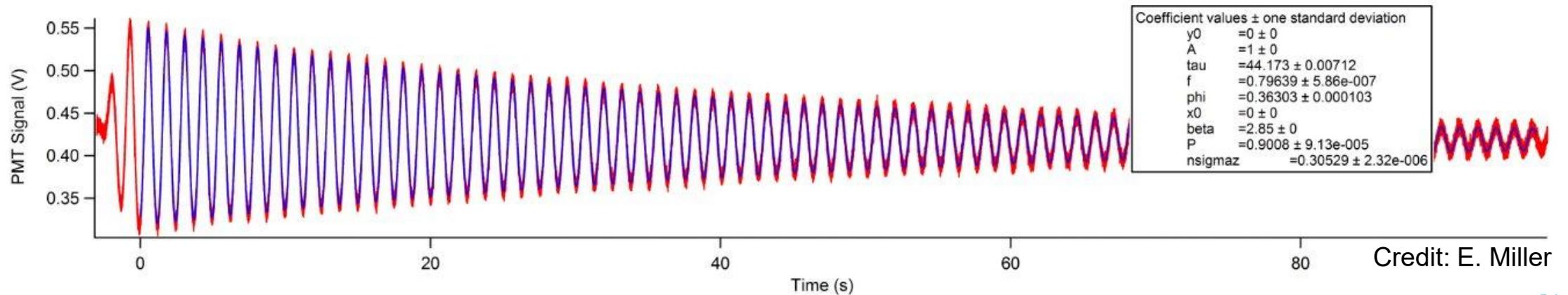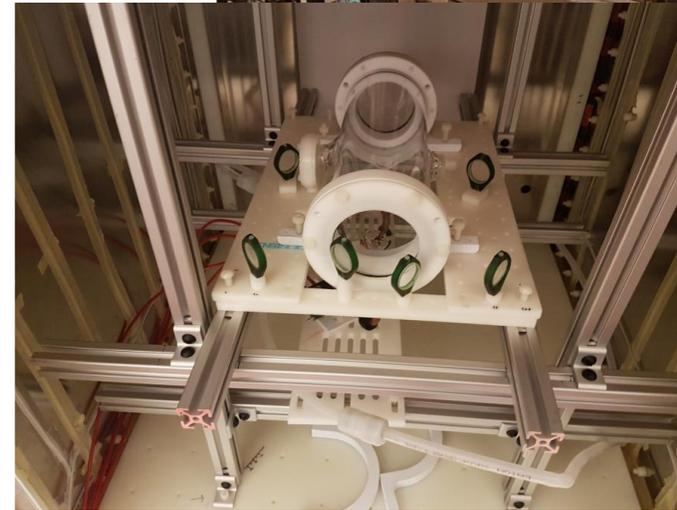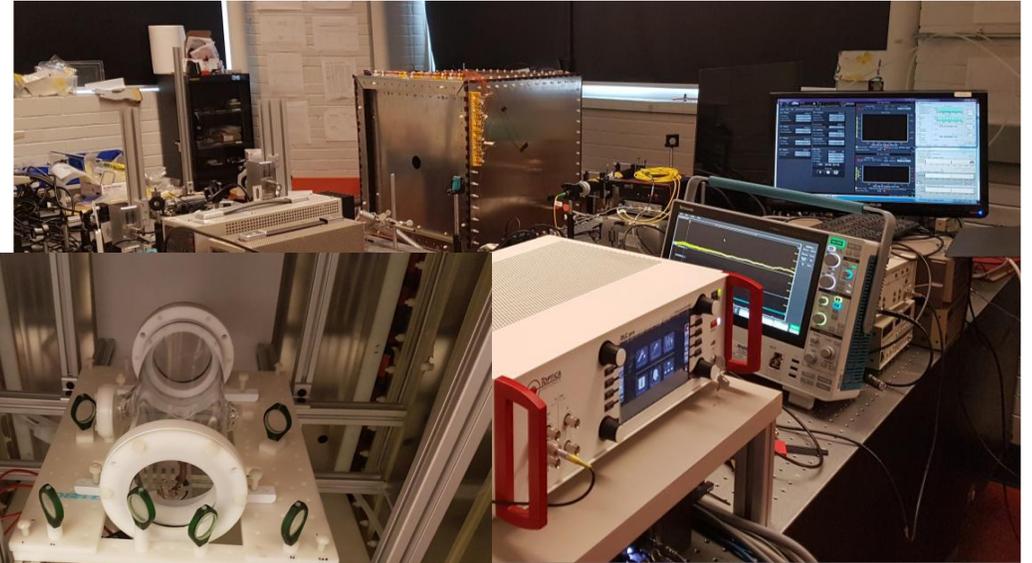# Internal Magnetic Coils: Shim Coils

- Square/rectangular coils attached directly to inner walls of MSR

- Prototype installed and tested

Credit: T. Mohammadi

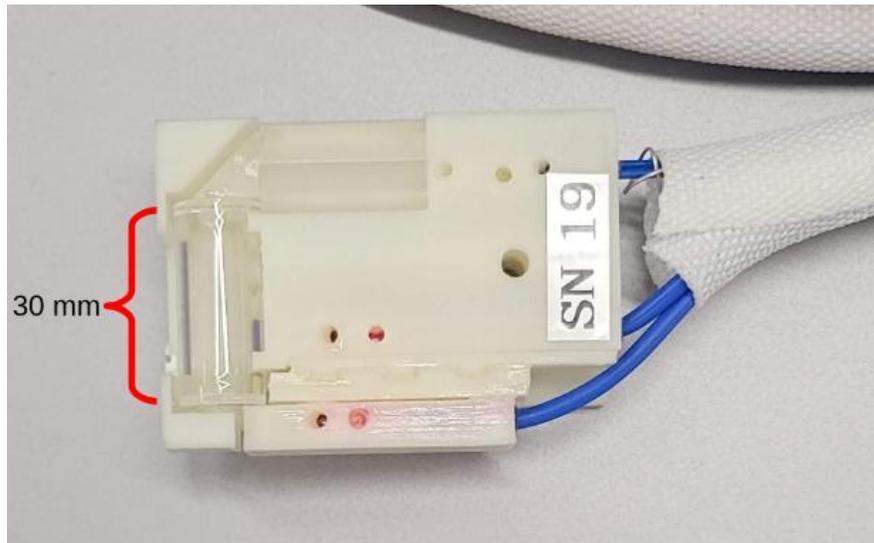# Magnetometry: Mercury

- Being tested inside small magnetically-shielded box

- To be installed in MSR after magnetic coils in 2026

Credit: E. Miller

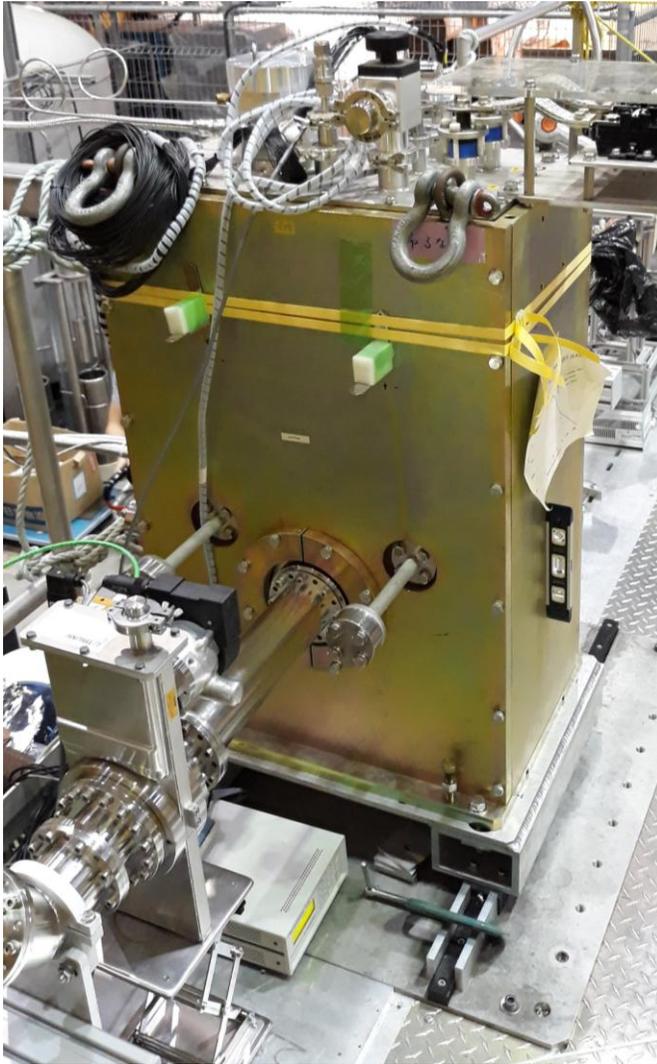# Magnetometry: Cesium

- Achieved sensitivity of 3.5 pT/$\sqrt{\text{Hz}}$ at 1 Hz and a stability of 90 fT over 150 s of measurement

- 20 magnetometers in MSR

- Undergoing characterization of light shifts

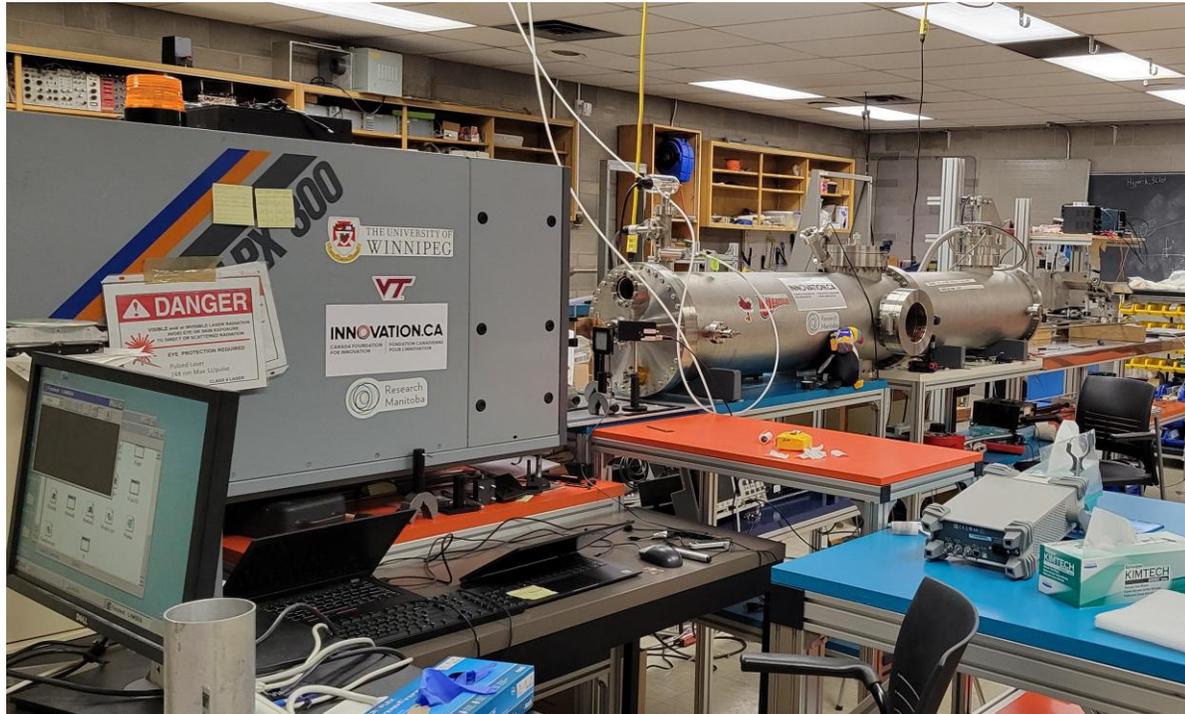

Credit: W. Klassen

Polarized UCN Handling

- Superconducting magnet installation being prepared

- Guide coils being optimized and prototyped

Credit: R. Stutters

Guide Coating Facility

- For diamond-like carbon coatings (https://doi.org/10.48550/arXiv.2510.06289)

- Tested two guides in January ⟹ one coating not diamond-like enough, the other not thick enough

Credit: R. Mammei

Spin Sensitive Detection

- Thin iron films and spin flipping magnets being done in Japan using UCNs and cold neutrons (https://doi.org/10.7566/JPSJ.93.091009)

- New detector ($CF_4 + {}^3He$) being developed to replace ${}^6Li$ detectors which are no longer manufacturable
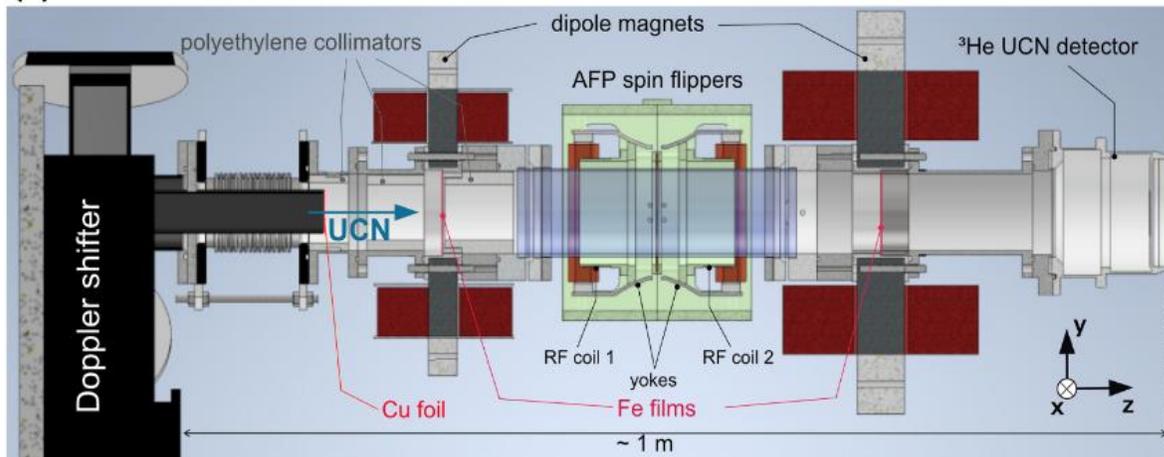
Credit: T. Higuchi

Credit: Tushar

The 10^{-28} ecm Horizon

Higher Statistics from the TUCAN Source

- TUCAN Source already appears capable of driving measurements down to the high 10^{-28} $e$cm level

- Improvements to the nEDM spectrometer will make this more feasible
  - better UCN guides,
  - better cell coatings,
  - higher visibility

- Improvements to the source also possible, but longer to develop/build

Table 5: Possible improvements of the moderator geometry ranked by their potential performance increase.

Improvement	Increase in UCN density
Beryllium converter vessel	90 %
AlBeMet or AZ80 converter vessel	30 % to 50 %
Thinner converter vessel	25 % per mm
Increased LD_2 volume	5 % per 15 L
Thinner vacuum separator/LD_2 vessel	5 % per mm
Thinner thermal shield/D_2O vessel	2.5 % per mm
Reduced spacing around converter	0.5 % per mm
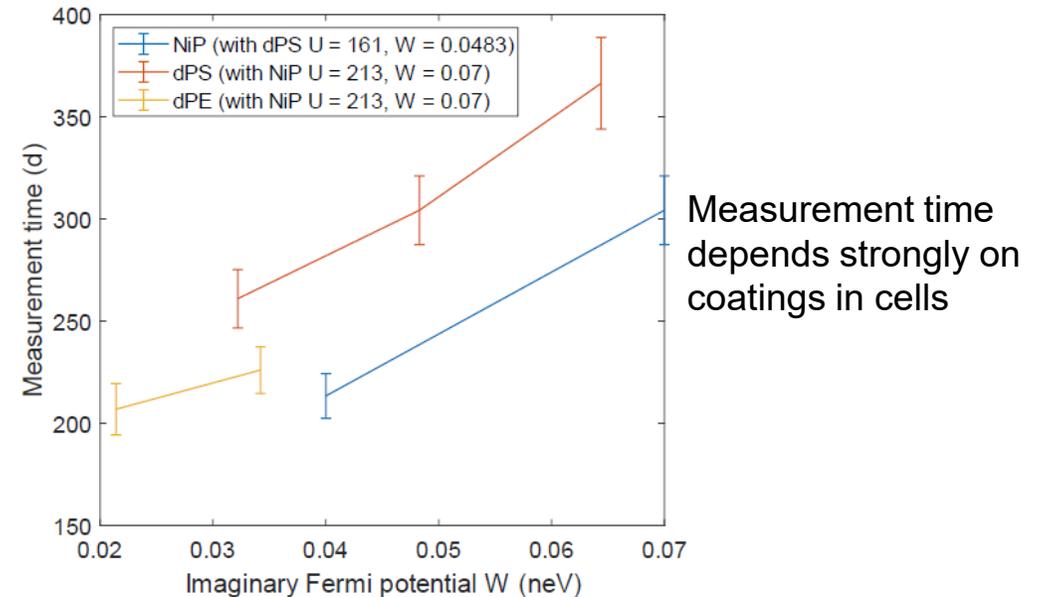
Measurement time depends strongly on coatings in cells

Reducing Systematic Effects with Dual Comagnetometry

- 10^{-28} $e$cm nEDM measurements need new techniques for systematics

- Hg comagnetometers introduce large systematics from gradients

$$\delta\omega_{BE} \approx -\frac{\gamma^2 E}{c^2}\left\langle B_x x + B_y y\right\rangle$$

- Gradients from
  - Background/coil non-uniformity
  - Magnetic contamination

Practically all materials have magnetic contamination
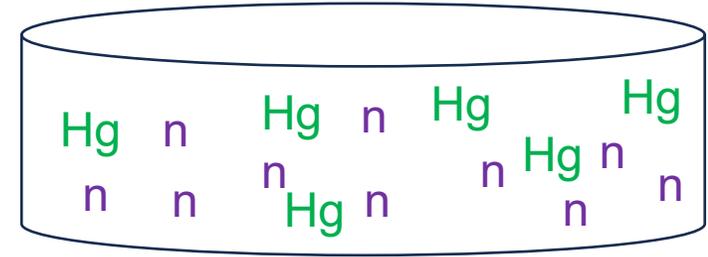Starts to look like a systematic noise floor

Reducing Systematic Effects with Dual Comagnetometry

- 10^{-28} $e$cm nEDM measurements need new techniques for systematics

- Hg comagnetometers introduce large systematics from gradients

$$\delta\omega_{BE} \approx -\frac{\gamma^2 E}{c^2}\langle B_x x + B_y y\rangle$$

- Gradients from
  - Background/coil non-uniformity
  - Magnetic contamination

- Second co-magnetometer: frequency shifts differ by γ^2 $\Rightarrow$ can be used to cancel total frequency shift from gradients

- Needs two species with EDMs measured more precisely than the nEDM target
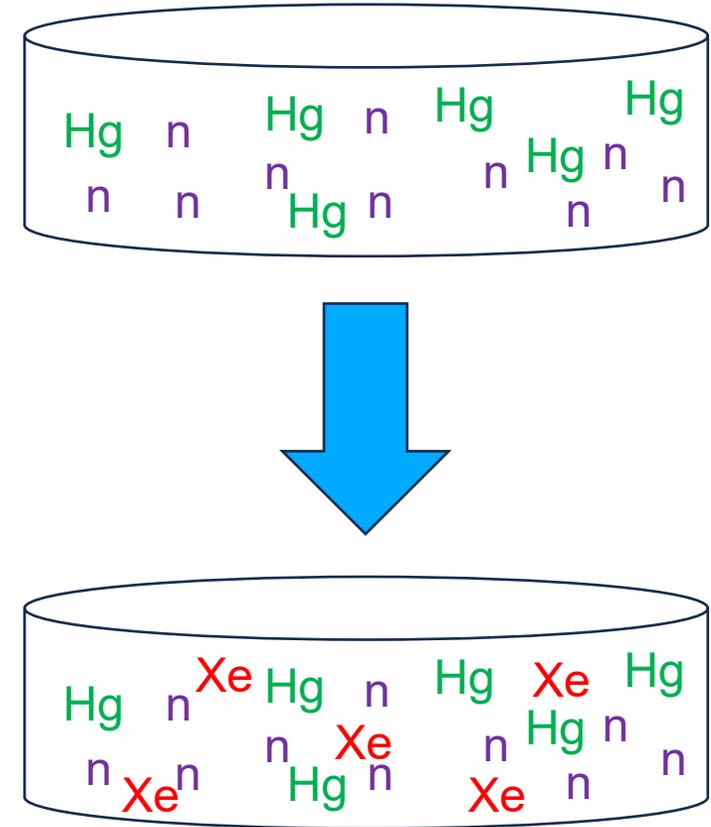
Conclusion

- TUCAN Source has demonstrated sufficient output for 10^{-27} $e$cm goal with 2-3 years of measurement time

- Progressing towards first EDM-like measurements in 2027 with reduced experiment

- Trying to secure funding for full experiment

- Dreaming of 10^{-28} $e$cm

Thank you for your attention!