TRIUMF

Progress and Goals of the TRIUMF nEDM Measurement

Dr. D. Fujimoto

2023-05-10

TUCAN
TRIUMF Ultra Cold
Advanced Neutron source

Discovery,
accelerated

What is “nEDM”?

neutron Electric Dipole Moment

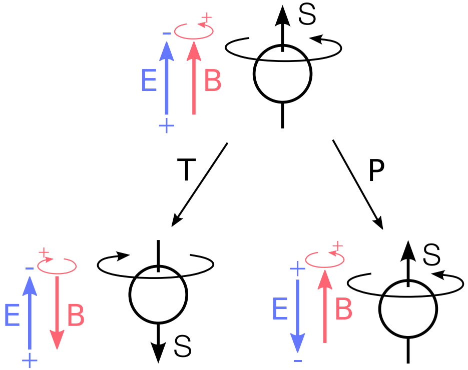
Why measure the nEDM?

Sakharov:

CP-symmetry violation is a necessary condition for baryogenesis

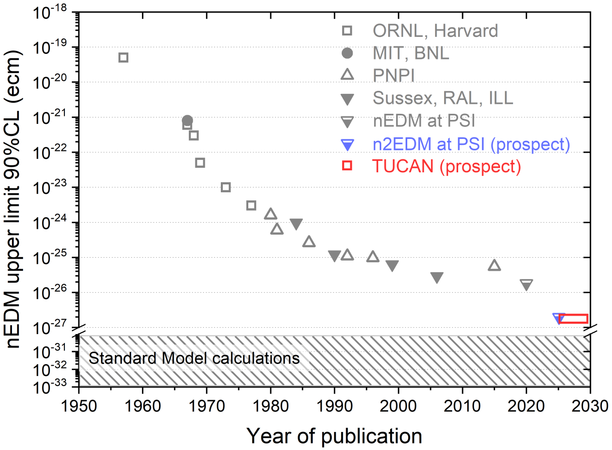
$$\mathcal{H} = -\left(\mu_n \boldsymbol{B} + d_n \boldsymbol{E}\right) \frac{\boldsymbol{S}}{|S|}$$

If $d_n \neq 0$ then $\mathcal{H}$ is asymmetric under time and parity inversion



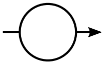
Who has measured the nEDM?

TUCAN Goal: $d_n \leq 10^{-27}$ ecm



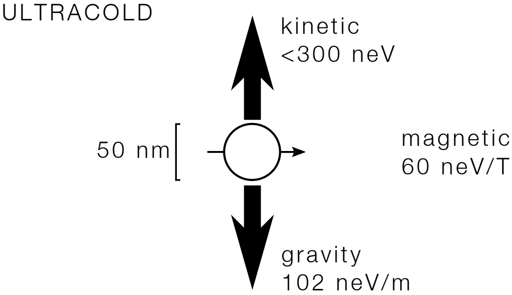
https://www.psi.ch/en/ltp-ucn-physics/n2edm

How to measure the nEDM?



(neutron)

How to measure the nEDM?



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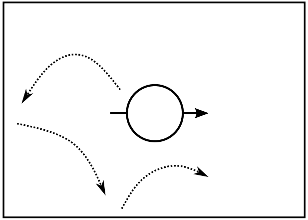

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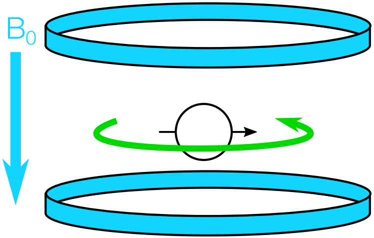
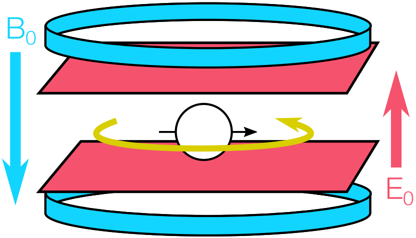


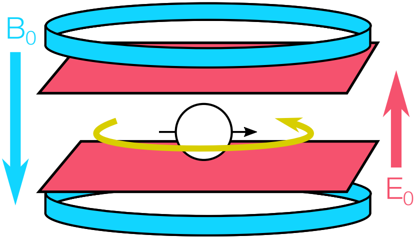
Larmor frequency : $\nu_\ell = \frac{1}{\pi\hbar}\left|\mu_{\mathrm{n}} B_0\right|$

How to measure the nEDM?



Larmor frequency : $\nu_\ell = \frac{1}{\pi\hbar} \left|\mu_{\rm n} B_0 - d_{\rm n} E_0\right|$

How to measure the nEDM?



Larmor frequency : $\nu_\ell = \frac{1}{\pi\hbar}\left|\mu_n B_0 - d_n E_0\right|$

nEDM : $d_n = \frac{\pi\hbar}{2E_0}({\nu_\ell}^{\uparrow\downarrow} - {\nu_\ell}^{\uparrow\uparrow})$

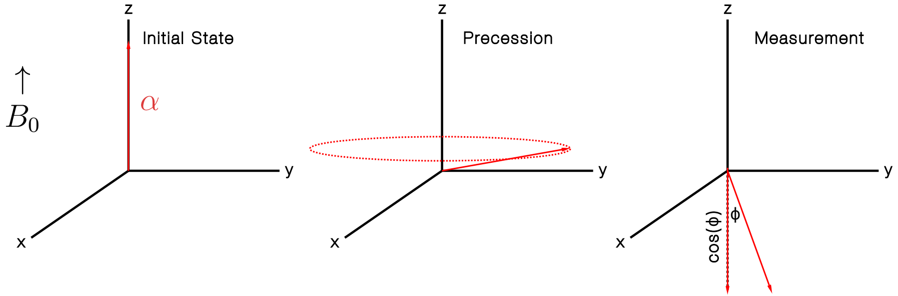
Spin polarization in the Ramsey cycle

Polarized neutrons in a static B_0:

$\rightarrow$ Apply B_1: "$\pi/2$" pulse over duration t_{flip}

$\rightarrow$ Free precession over duration t_{free}

$\rightarrow$ Apply B_1: "$\pi/2$" pulse over duration t_{flip}



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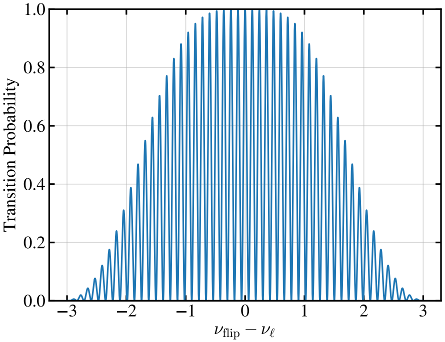
$$\nu_\ell = \frac{1}{\pi\hbar}\left|\mu_\text{n} B_0 - d_\text{n} E_0\right|$$

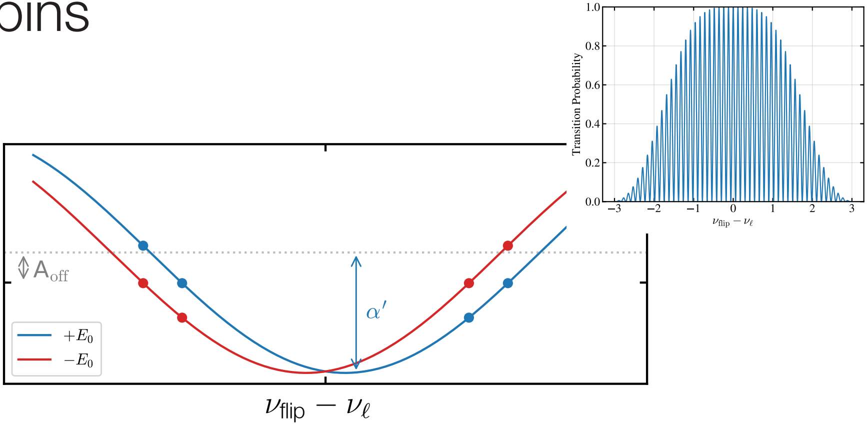
Look for a E_0-dependent phase shift



See Eq 12 of Ramsey, N. F. Phys. Rev. 78, 695–699 (1950)

Counting spins

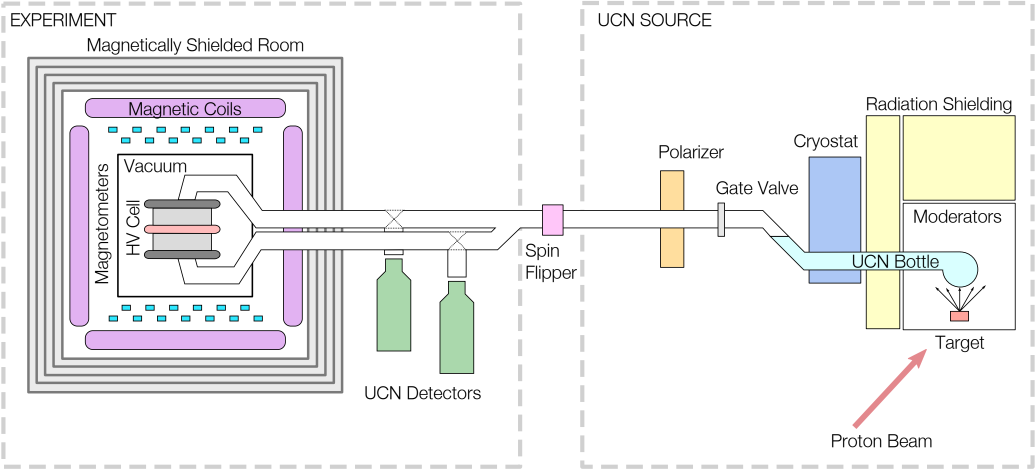
$$\mathcal{A} = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow}$$



Spin asymmetry at central fringe. Phase shift induced by E_0.

Fit with $\mathcal{A}(\nu_{\text{flip}}) = \mathcal{A}_{\text{off}} - \alpha' \cos\left(\frac{\pi}{\Delta\nu}(\nu_{\text{flip}} - \nu_\ell)\right)$

The TUCAN nEDM experiment



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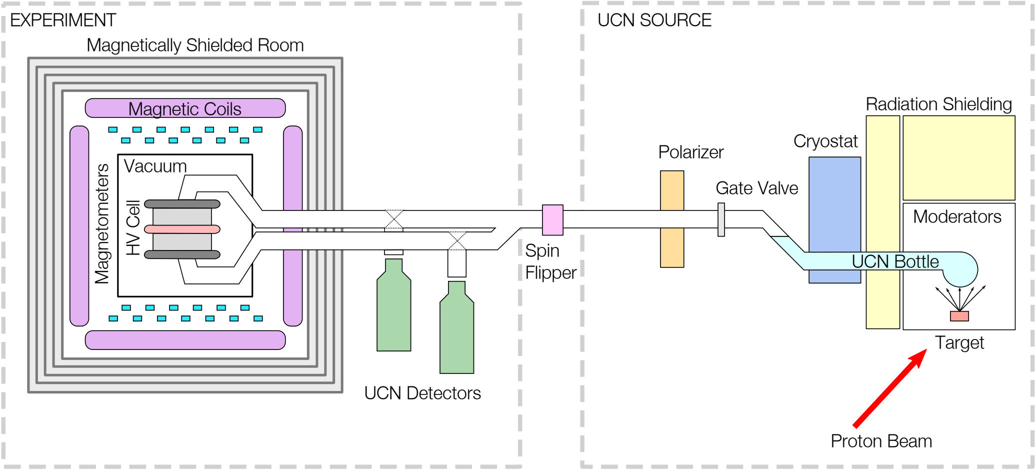
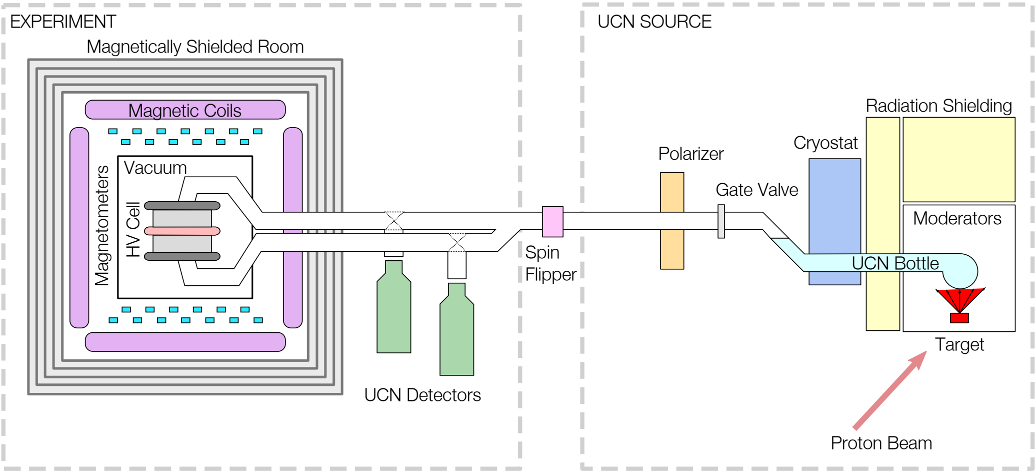


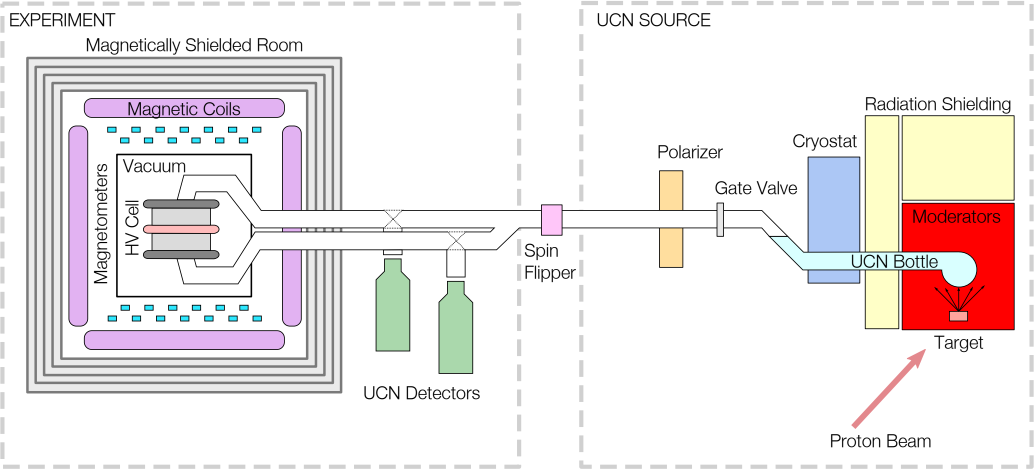
Proton beam current: $40\,\mu A$

The TUCAN nEDM experiment



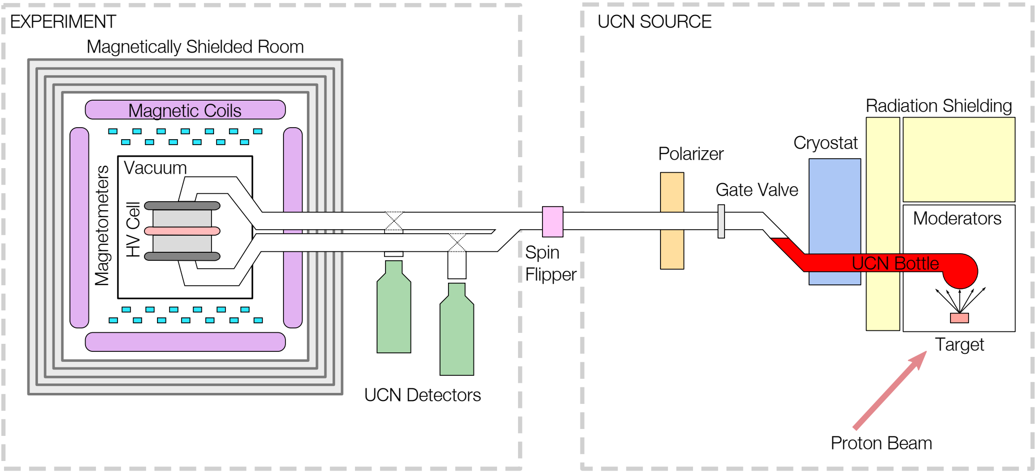
Spallation neutron production

The TUCAN nEDM experiment



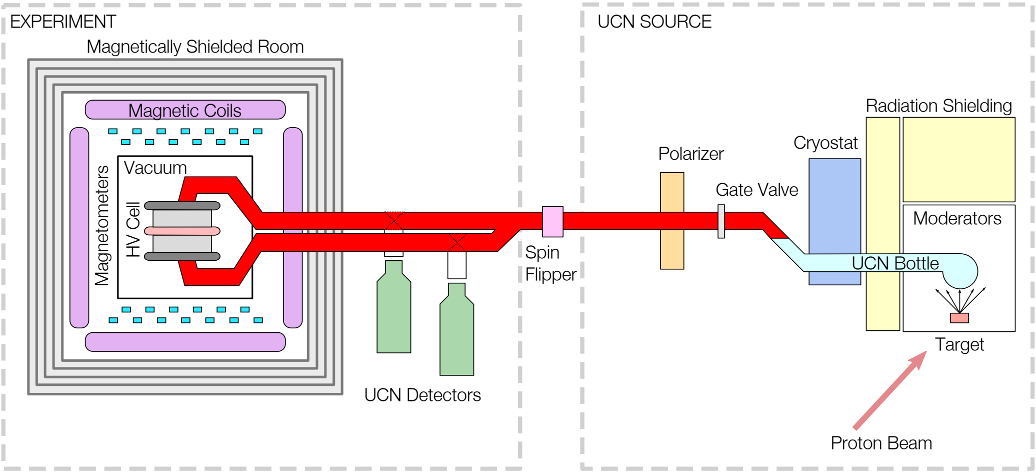
Moderators: D_2O and LD_2

The TUCAN nEDM experiment



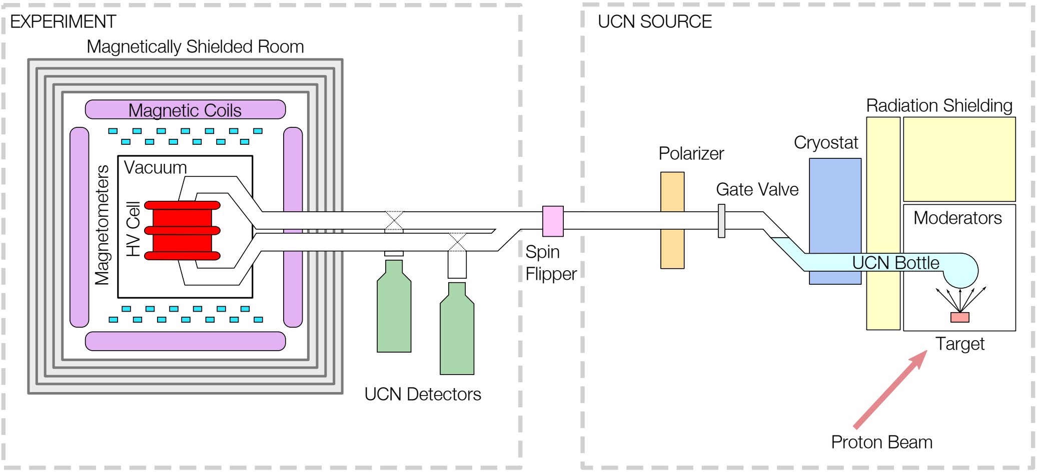
Expected storage lifetime in LHe-II bottle: $\sim 20\,\mathrm{s}$

The TUCAN nEDM experiment



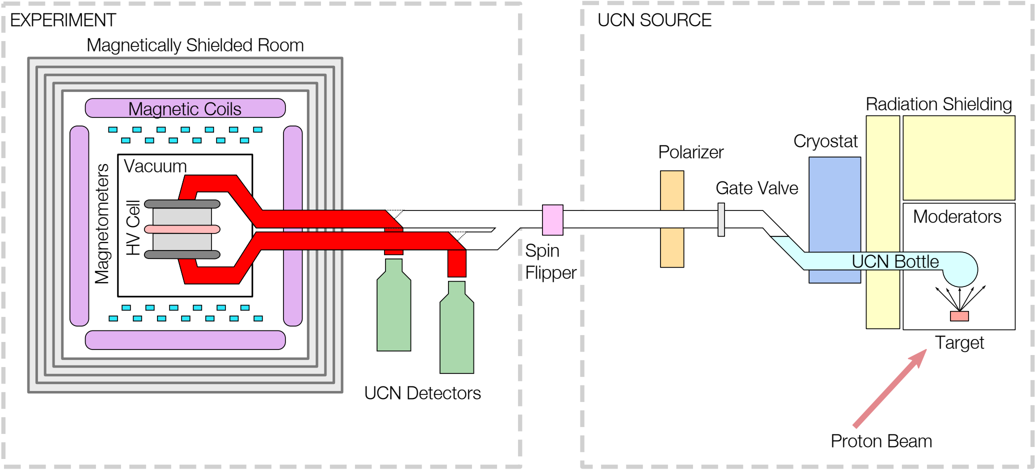
UCN diffuse down NiP-coated guides. About 1 % reach EDM cell

The TUCAN nEDM experiment



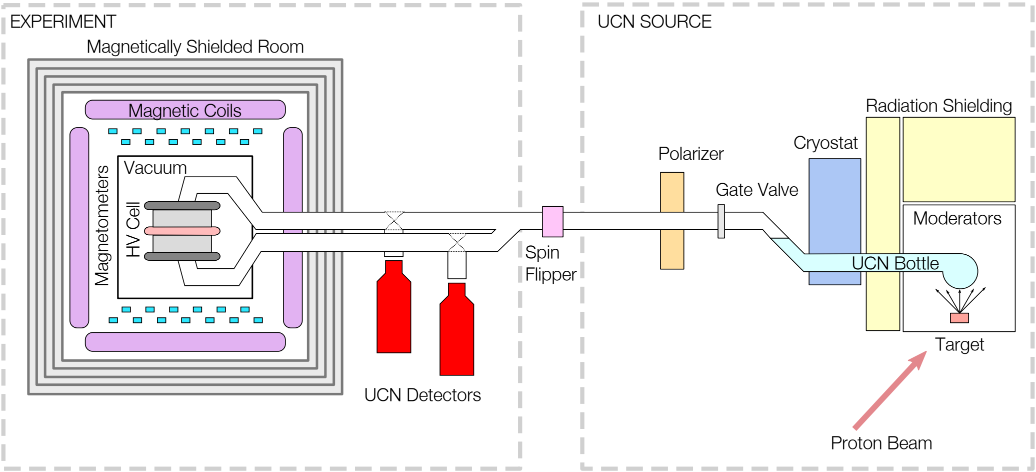
Applied fields: $B_0 = 1\,\mu\mathrm{T}$, $E_0 = 12.5\,\mathrm{kV/cm}$. UCN density: $\sim 200\,\mathrm{UCN/cm^3}$

The TUCAN nEDM experiment



About $10\,\%$ of UCN in cell reach detectors and are detected

The TUCAN nEDM experiment



Count $N_{\uparrow}$ and $N_{\downarrow}$ in each cell

Simulated UCN Statistics

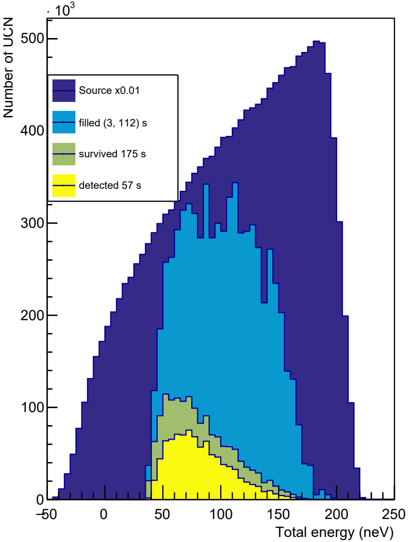
Simulated transport and storage efficiency:

Source → Detected: $\sim 0.1\,\%$

Statistical uncertainty:

$$\sigma(d_n) \propto \frac{1}{\sqrt{N}}$$

Expect ~ 300 days of measurement time



S. Sidhu, et al. EPJ Web of Conferences **282**, 01015 (2023)

TUCAN Experiment Features

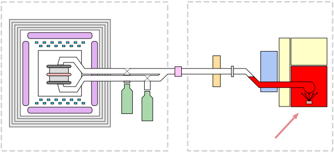
- → Intense neutron source
- → Guiding fields
- → Magnetically shielded room
- → Ambient field compensation
- → Self-shielded B_0 coil
- → Double precession cells
- → Hg comagnetometer
- → Cs magnetometer array

$$\sigma(d_n) \propto \frac{1}{\sqrt{N}}$$

$$\nu_\ell = \frac{1}{\pi\hbar}\left|\mu_\mathrm{n} B_0 - d_\mathrm{n} E_0\right|$$

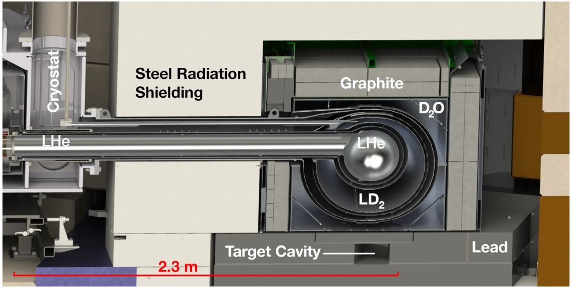
$$d_\mathrm{n} = \frac{\pi\hbar}{2E_0}\left(\nu_\ell^{\uparrow\downarrow} - \nu_\ell^{\uparrow\uparrow}\right)$$

The UCN Source



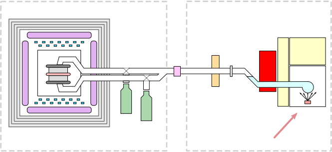
Components:

- → $40\,\mu$A proton beam
- → Tungsten target
- → Moderators: D_2O and LD_2
- → Graphite reflectors
- → Converter: Isopure He-II (1.15 K)



Result: neutrons at ~ 1 mK (~ 100 neV)

The UCN Source

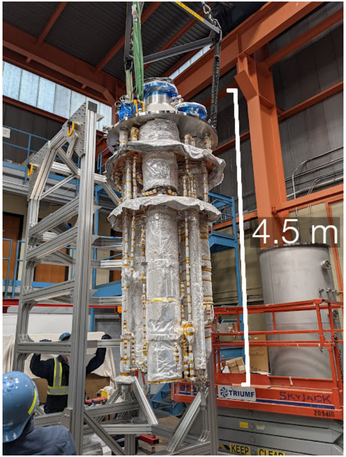


Timeline:

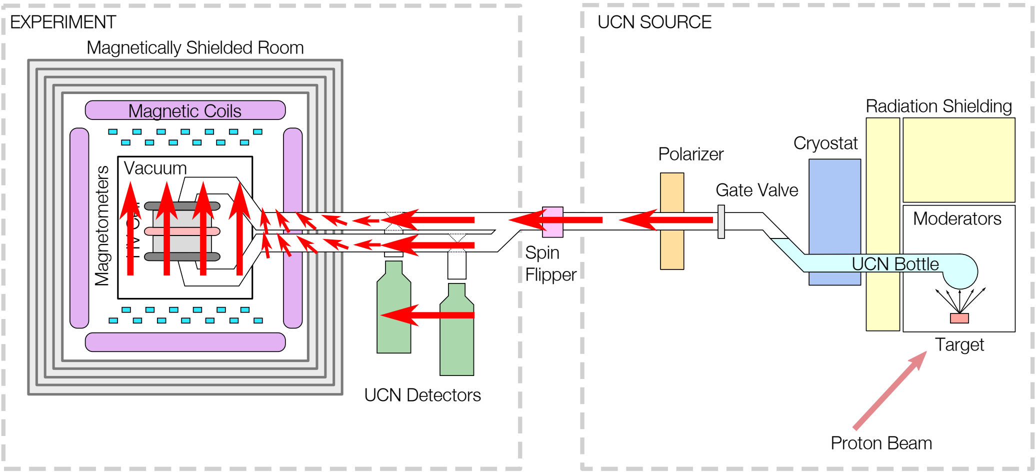
→ 2023: Cryostat installation

→ 2024: First UCN with this source

→ 2025: Production-levels of UCN



Guiding Fields



Guiding Fields

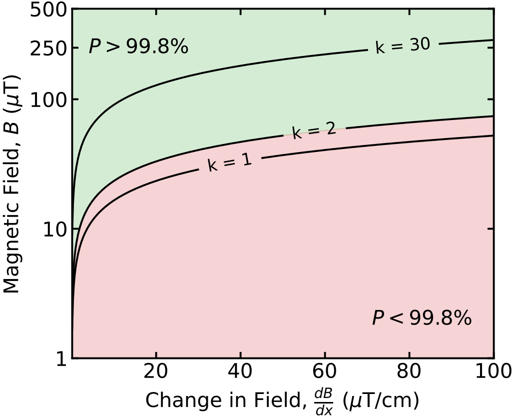
Polarization is preserved when transport is adiabatic

$$k = \gamma_n \frac{B^2}{\frac{dB}{dt}} \gg 1$$

Guiding Fields

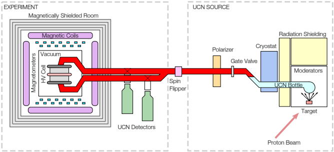
Field inhomogeneity along a linear path

$$k = \gamma_n \frac{B^2}{v_n \frac{dB}{dx}}$$

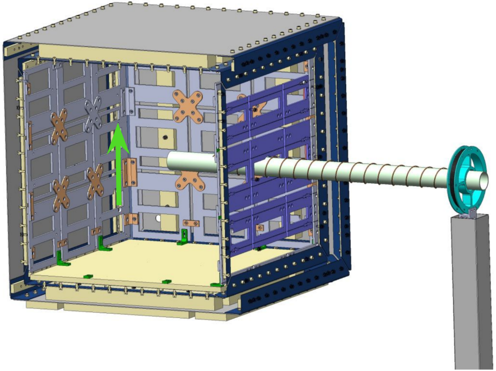


Credit: E. Klemets

Guiding Fields



- → Neutron polarization must be preserved during transport
- → Offline prototyping setup: mock polarizer, B_0 coil, guides, and MSR



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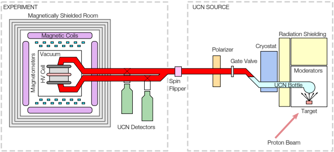

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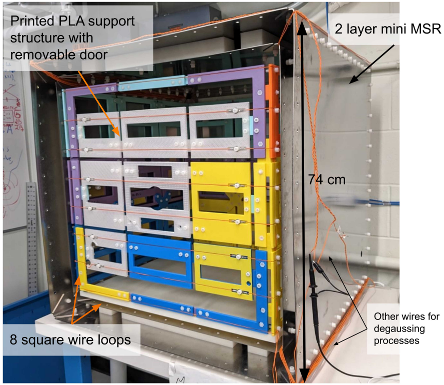

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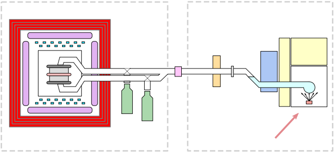
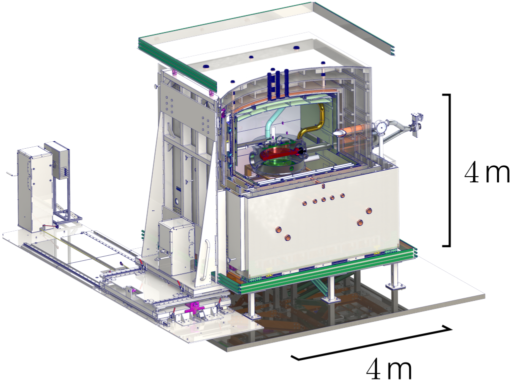
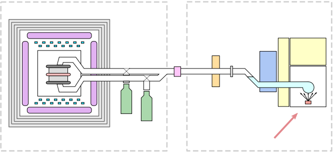
Magnetically Shielded Room



- $\rightarrow$ 4 layers mu-metal, 1 layer copper
- $\rightarrow$ Keep noise <1 pT over ~ 100 s
- $\rightarrow$ DC magnetic shielding factor: 10^5
- $\rightarrow$ Assembly complete end of 2023



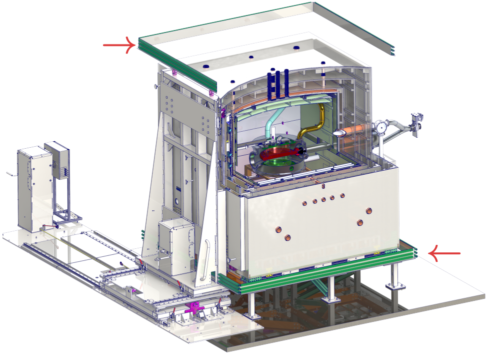
Ambient Magnetic Compensation



→ Split helmholtz coils counteract the cyclotron field

→ Includes platform for top access

→ Coils tested end of year



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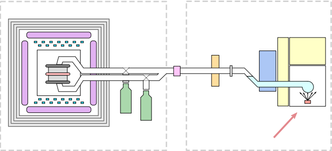

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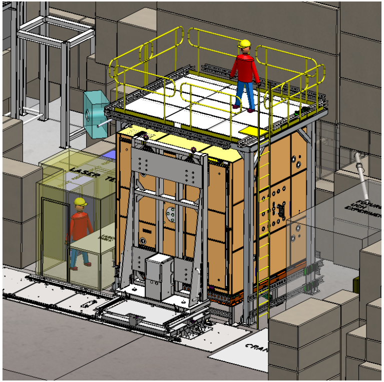
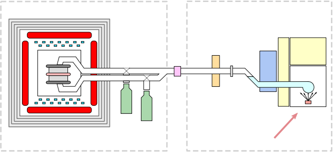
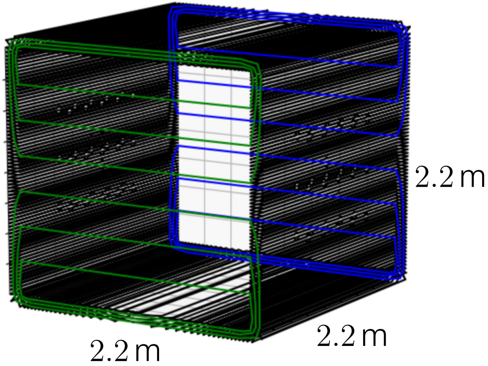


Self-shielded B_0 coil

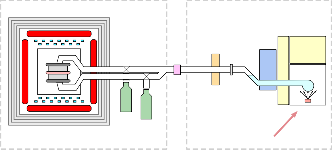


→ Produce a stable $1\,\mu$T magnetic field decoupled from mumetal

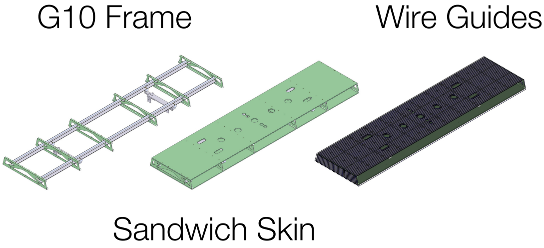


Credit: M. McCrea

Self-shielded B_0 coil



- → Produce a stable $1\,\mu$T magnetic field decoupled from mumetal
- → Lightweight and rigid support frame
- → 3D printed wire guides: <1 mm deviation over 2 m
- → Prototyping ongoing, commissioning in 2024



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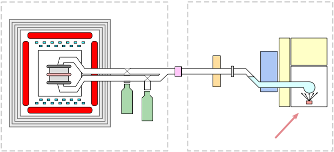

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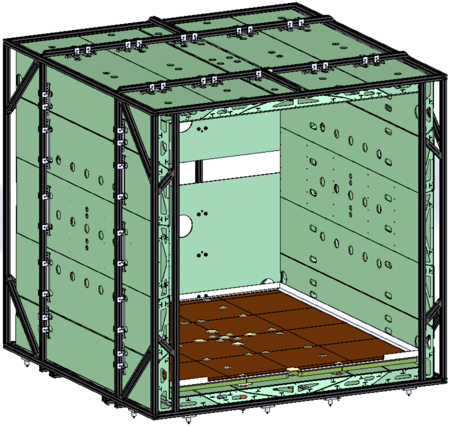

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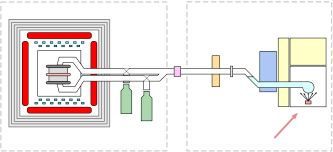

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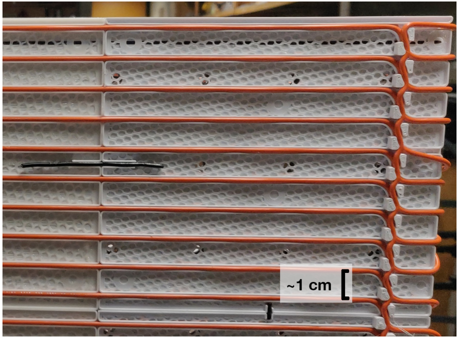
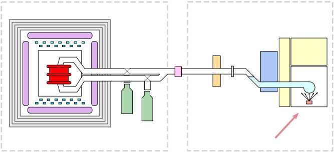


Wire guides

Credit: M. McCrea

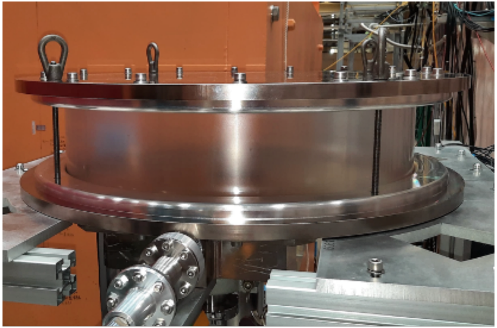
Double precession cells



→ Both orientations of electric field possible at once

→ Increases statistics due to larger volume

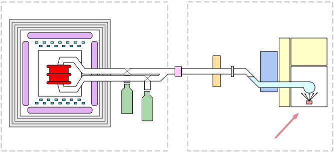
→ Reduces some systematic effects



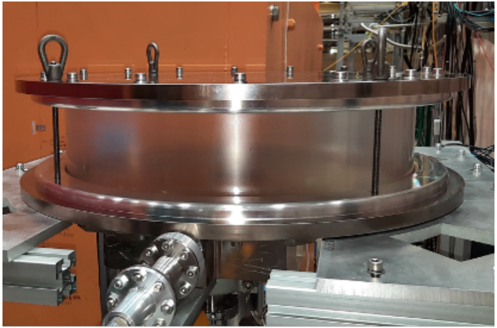
Storage and outgassing tests at JPARC

Credit: S. Vanbergen

Double precession cells



- → Both orientations of electric field possible at once
- → Increases statistics due to larger volume
- → Reduces some systematic effects
- → Temporarily de-scoped to single cell due to budget



Storage and outgassing tests at JPARC

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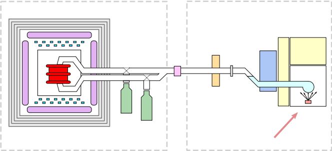
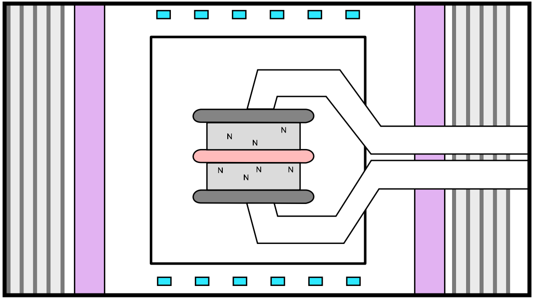
Hg Comagnetometer





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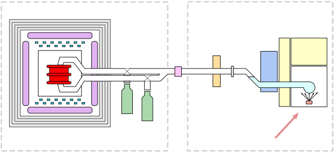
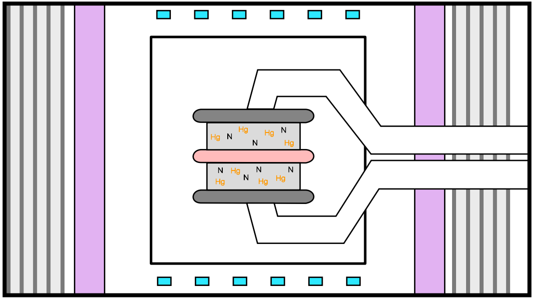


→ Fill space with Hg gas



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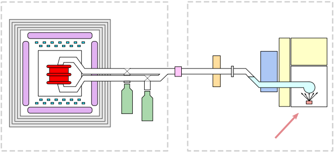
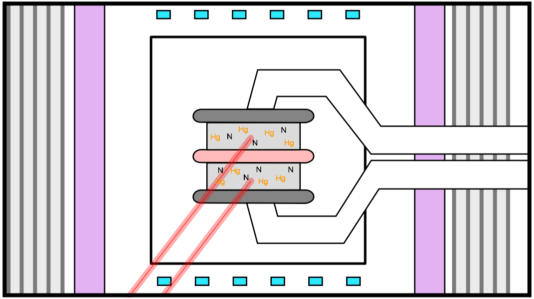


- $\rightarrow$ Fill space with Hg gas
- $\rightarrow$ Optically probe precession frequency
- $\rightarrow$ Result: in-situ measurement of $\langle B_0 \rangle$ on fT scale



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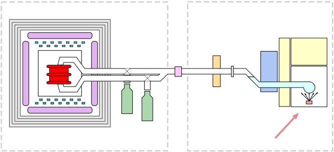
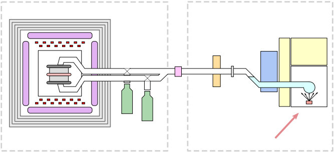


- → Fill space with Hg gas
- → Optically probe precession frequency
- → Result: in-situ measurement of $\langle B_0 \rangle$ on fT scale
- → Prototyped at UBC.
  Further development at TRIUMF in 2024

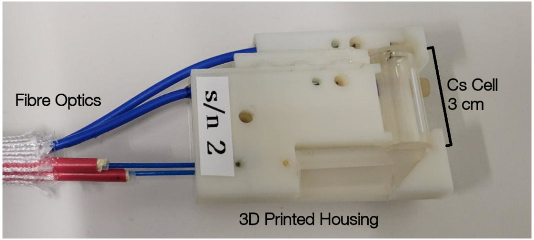
Cs Magnetometer Array



→ Array of 20 sensors outside of vacuum chamber

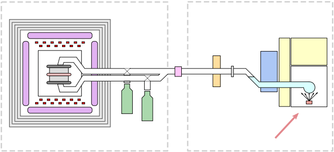
→ Measurement of field gradients

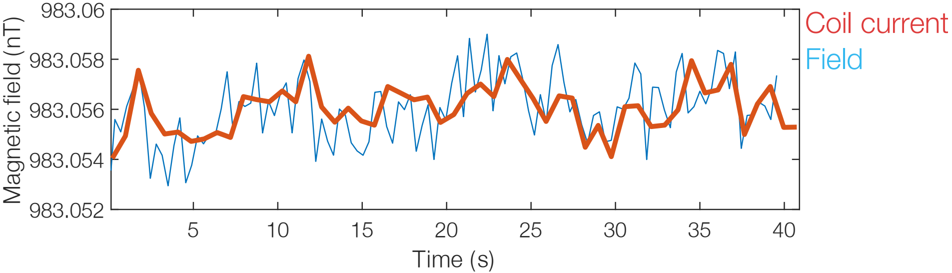
→ Development ongoing at TRIUMF. Moving into MSR 2024



Credit: W. Klassen

Cs Magnetometer Array





Applied field from small coil as measured by a single sensor ($\Delta B \approx 2\,$pT)

Credit: W. Klassen

TRIUMF

- → **Goal**: measure the nEDM to 10^{-27} ecm
- → UCN in 2024!
- → Magnetometry commissioning in 2024
- → Start neutron measurements in 2025

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(END)