TRIUMF UBC

Ultracold neutron storage lifetime measurements for a prototype cell for the TUCAN EDM experiment

TUCAN

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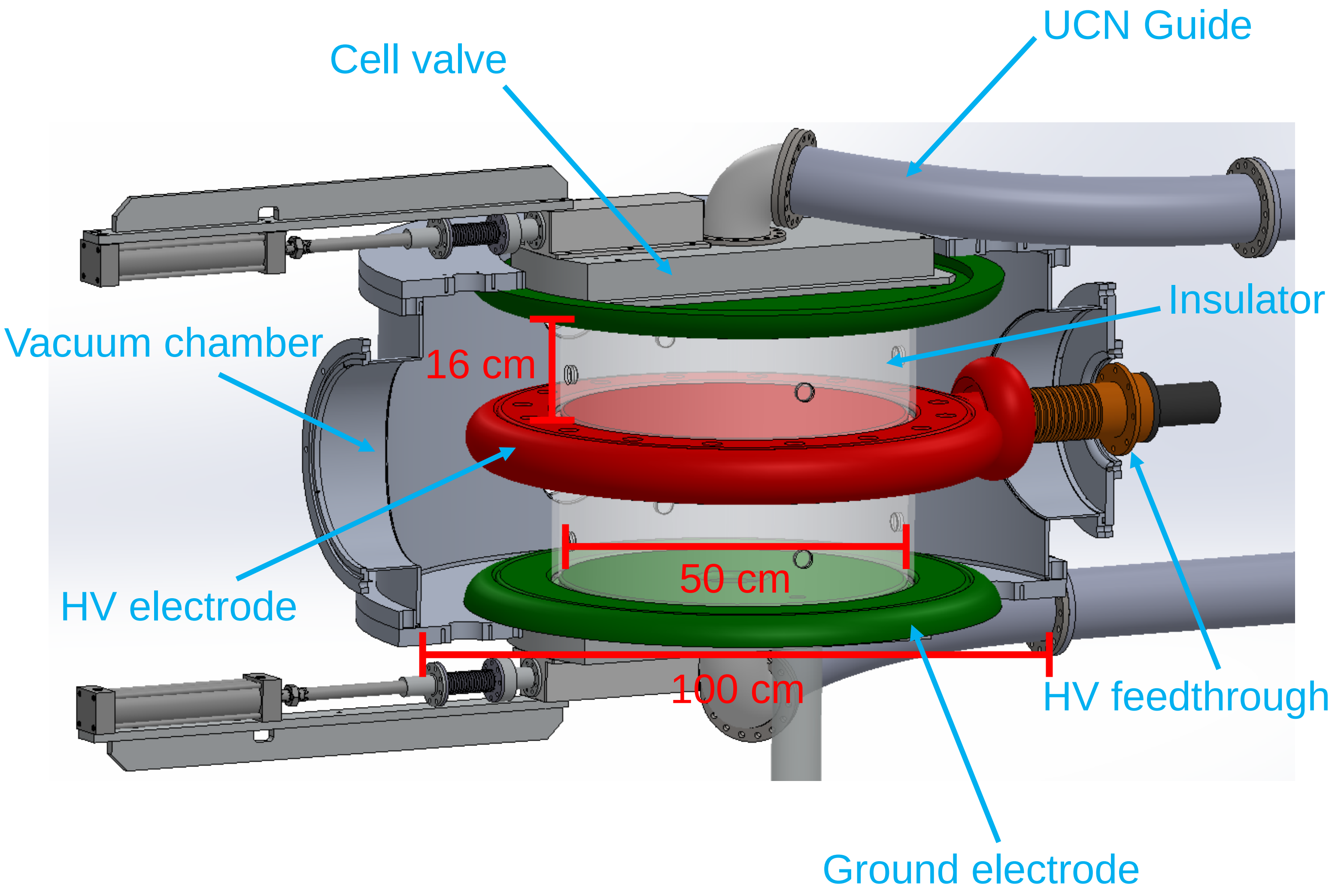
nEDM 2023

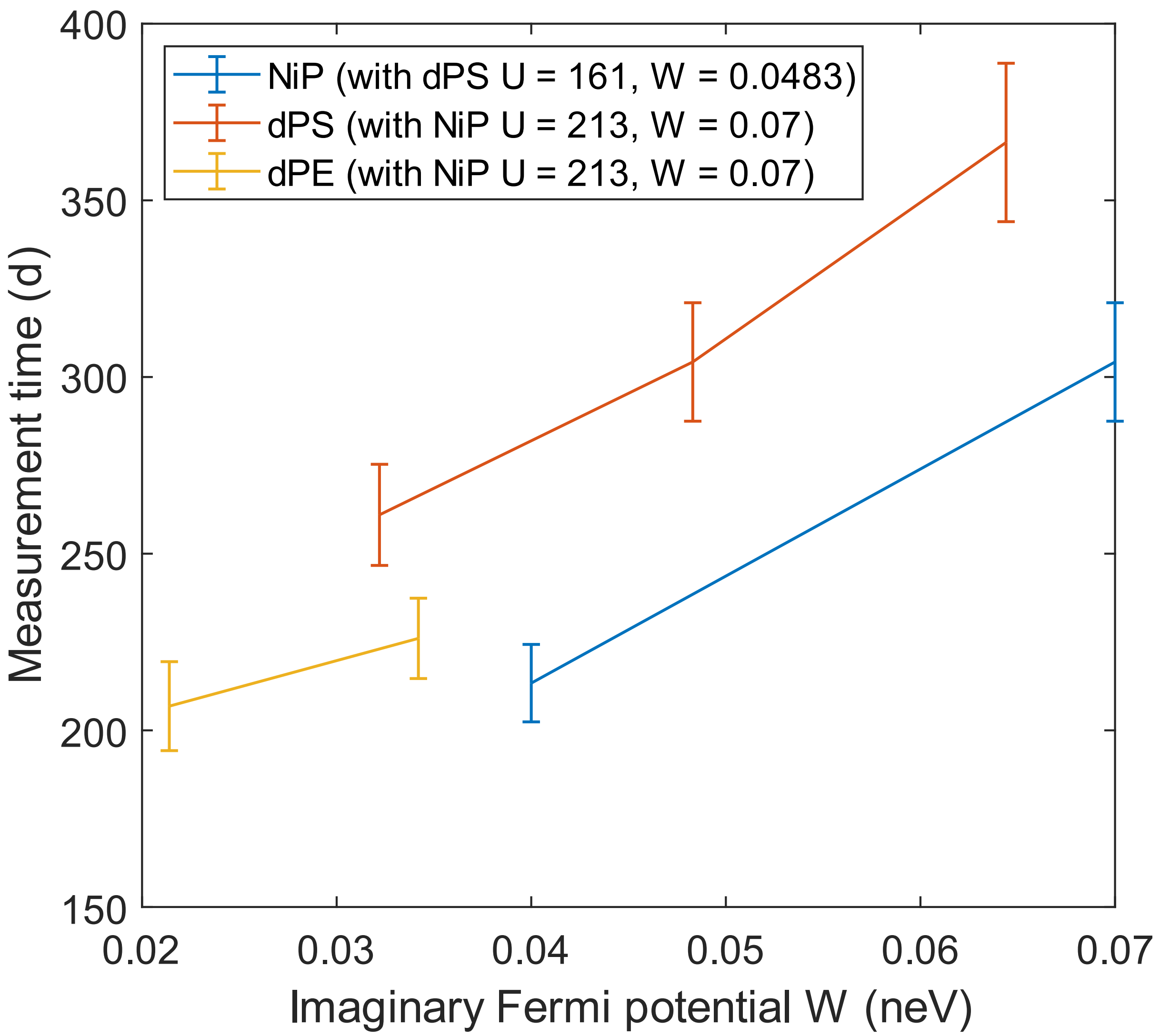
TUCAN EDM Cell Specifications

- Double cell (eventually)
- 50 cm inner diameter
- 13-16 cm electrode separation
- Compatible with 200 kV on central electrode
- 8.5 cm diameter guide entrances through ground electrodes
- Sufficiently non-magnetic parts to achieve systematic sensitivity
- Geometry and surface coatings compatible with achieving statistical sensitivity



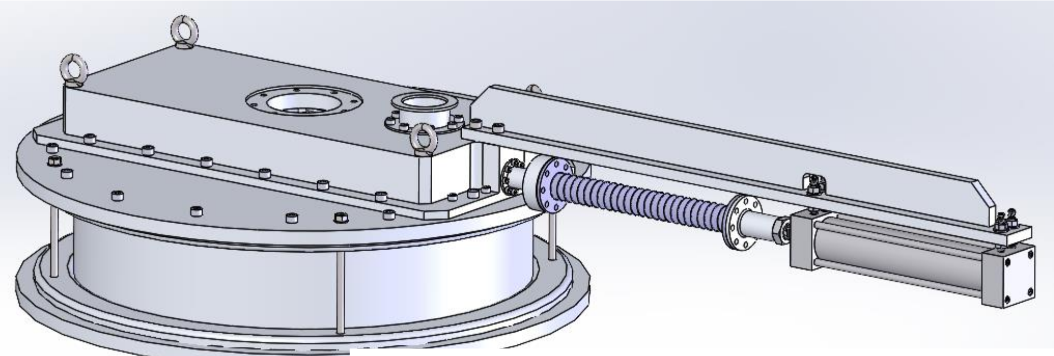
Surface Parameter Requirements

- Experiment optimization shows that coating quality impacts measurement time significantly
  - S. Sidhu's talk on statistical optimization
- Increase of W from 0.032 to 0.064 neV adds ~100 days to our measurement time
- No DLC electrode coatings yet, so we are testing with NiP
  - See A. Zahra's and R. Mammei's talks on DLC coatings

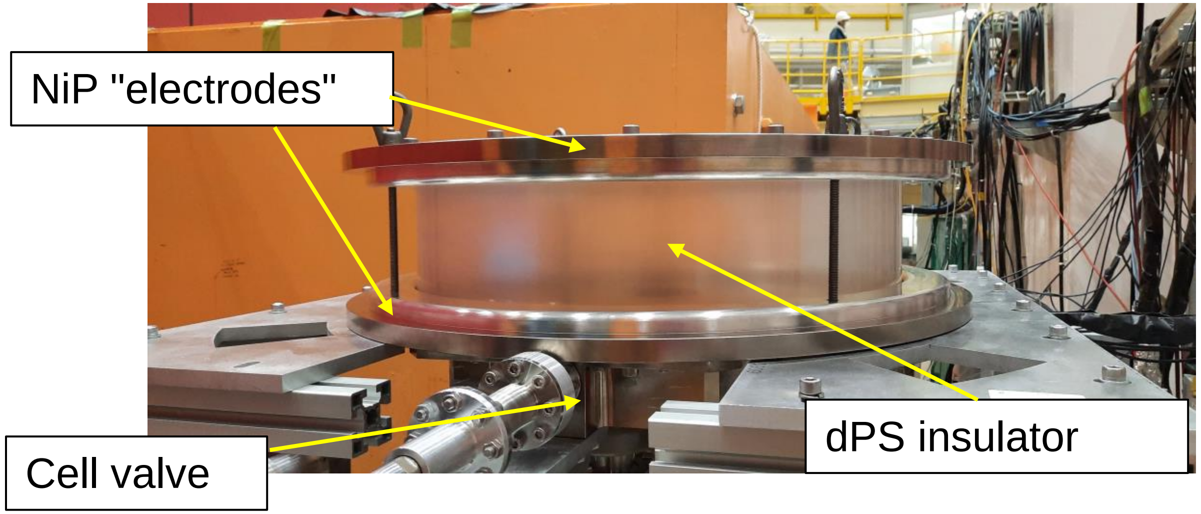


TUCAN EDM Cell Prototype

- Major UCN components only
  - Not HV compatible
  - No co-magnetometer windows or gas valve
  - No other interfaces to other systems
- 50 cm ID, 13 cm electrode separation
- NiP coatings on aluminium “electrode” plates
- NiP coating on UCN valve
- Deuterated-polystyrene coating on Rexolite (cross-linked polystyrene) insulators

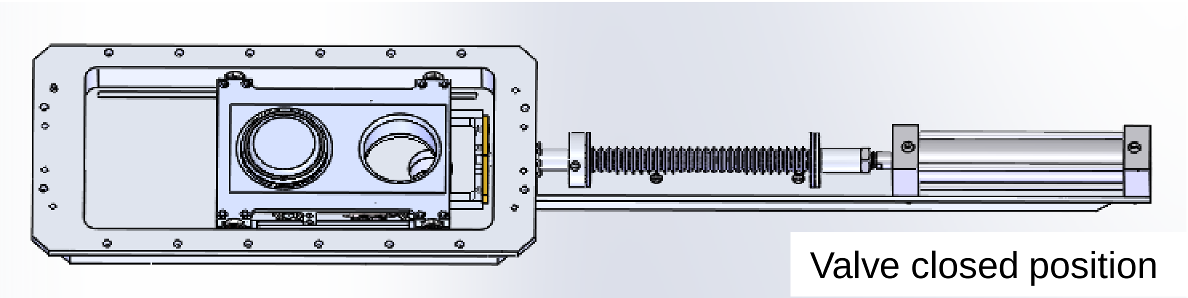


Valve & prototype cell CAD model

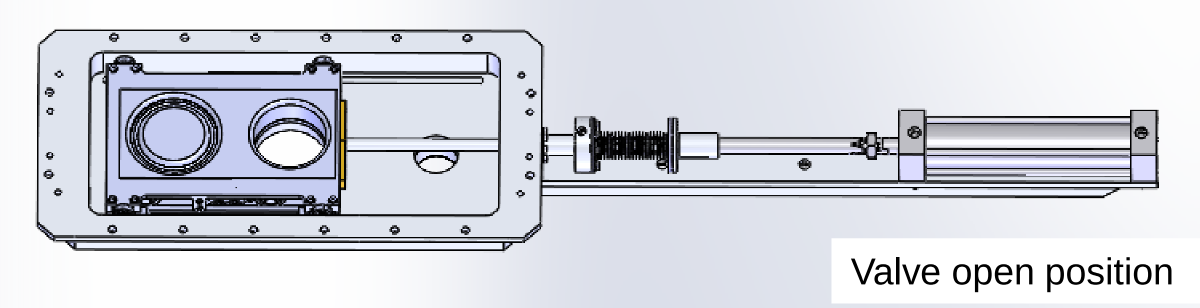


TUCAN EDM Cell Valve

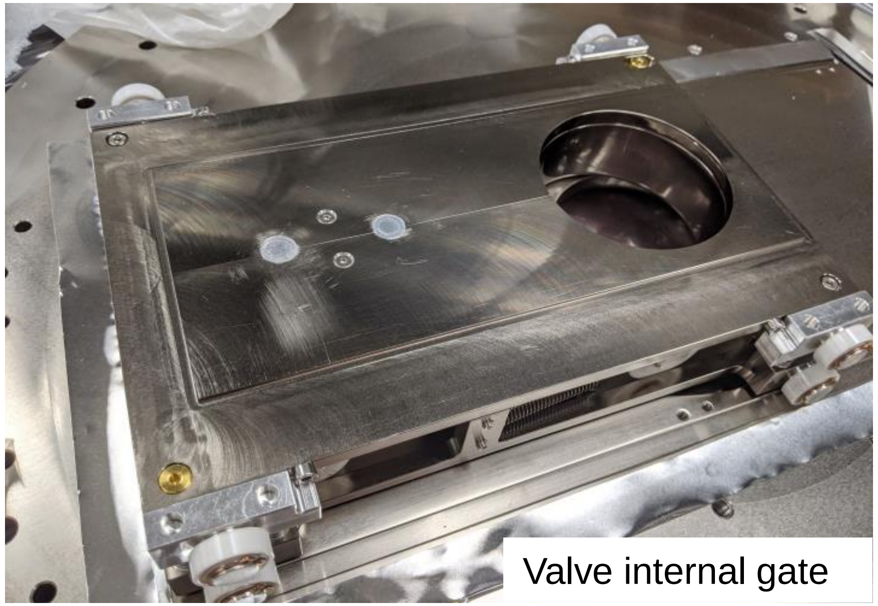
- Custom-built pneumatically-actuated UCN gate valve
- Integrated into the ground electrodes
- In open position: 2x 0.2mm slits
- Internal gate order of ~100 (mostly non-magnetic – some to be replaced) parts



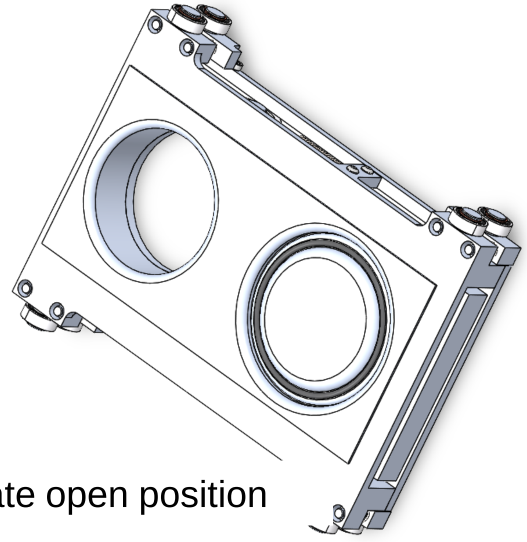
Valve closed position



Valve open position



Valve internal gate

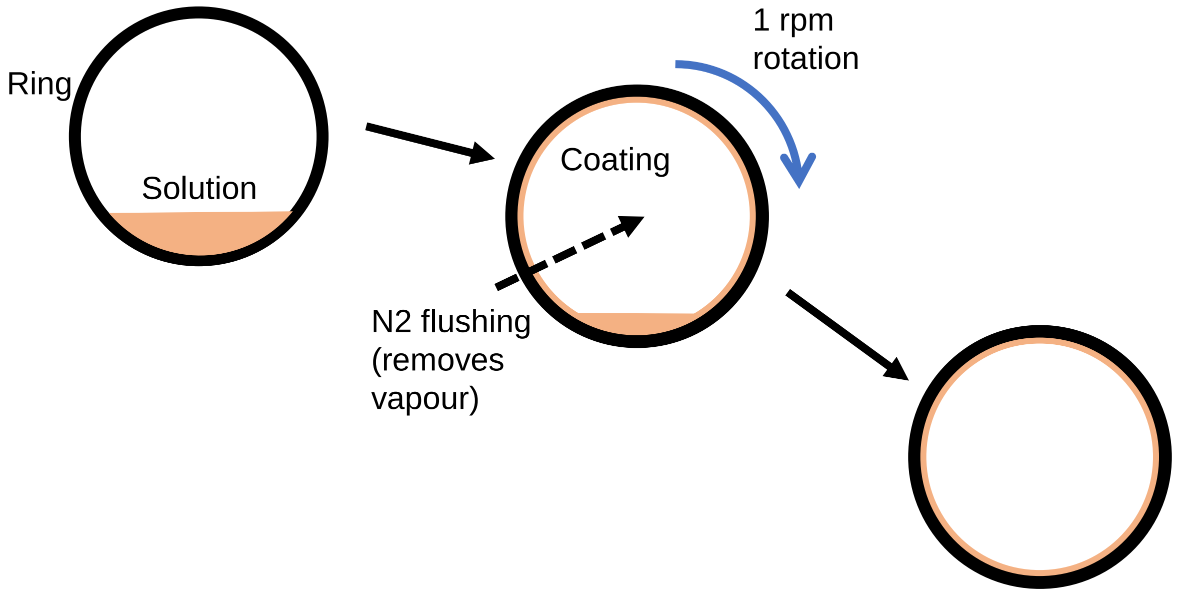


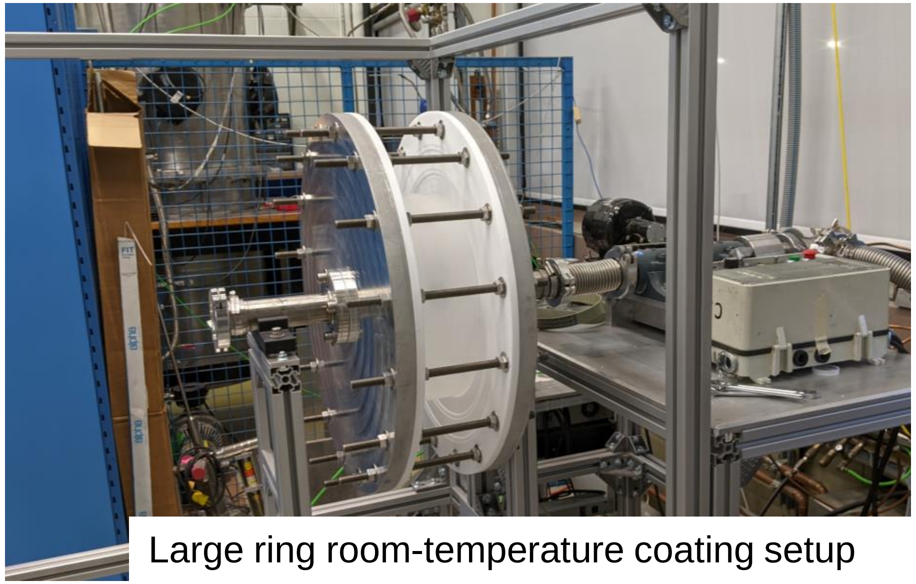
Gate open position

Gate closed position

Deuterated-Plastic Coating Facility

- “Rotational coating” of large insulator rings with deuterated plastic coatings (5-10 um)
- dPS coating on full-scale ring achieved early 2022
- dPE coatings have been successful at small-scale (10.16 cm ID) but not at full-scale





Large ring room-temperature coating setup

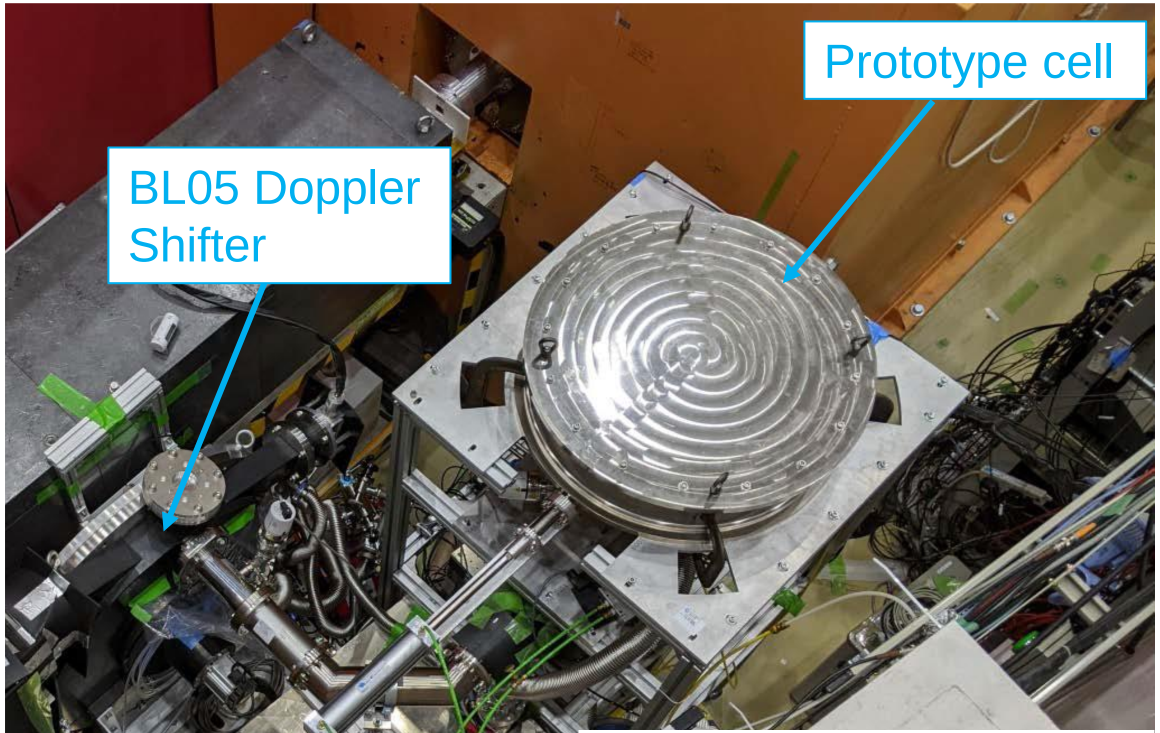
Small-ring high-temperature coating setup

Storage Lifetime Measurement at J-PARC MLF BL05

BL05: Neutron Optics and Fundamental Physics

Purpose

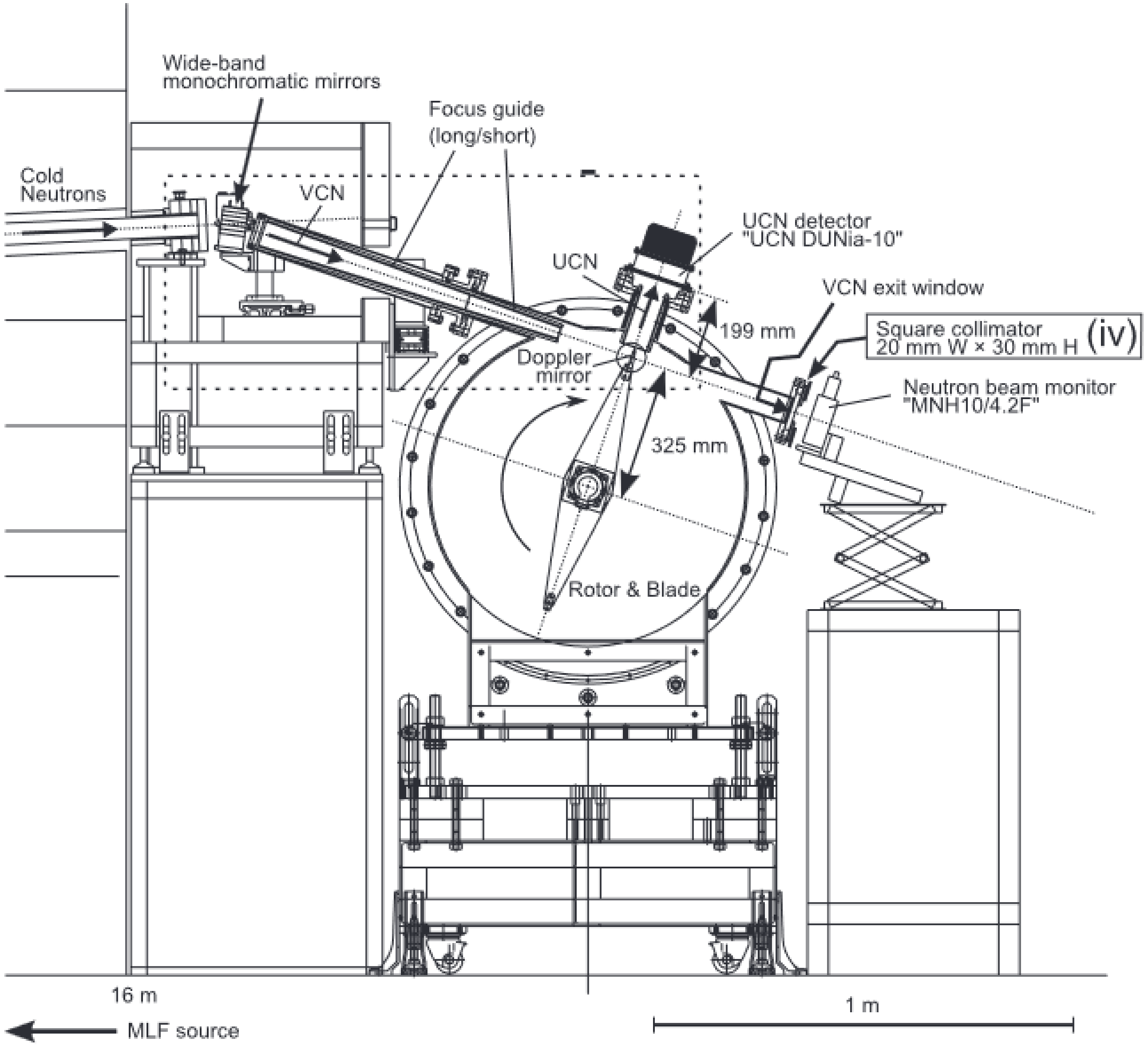
Characterize whether the cell prototype performs at the desired level for TUCAN EDM



Prototype cell installed in BL05

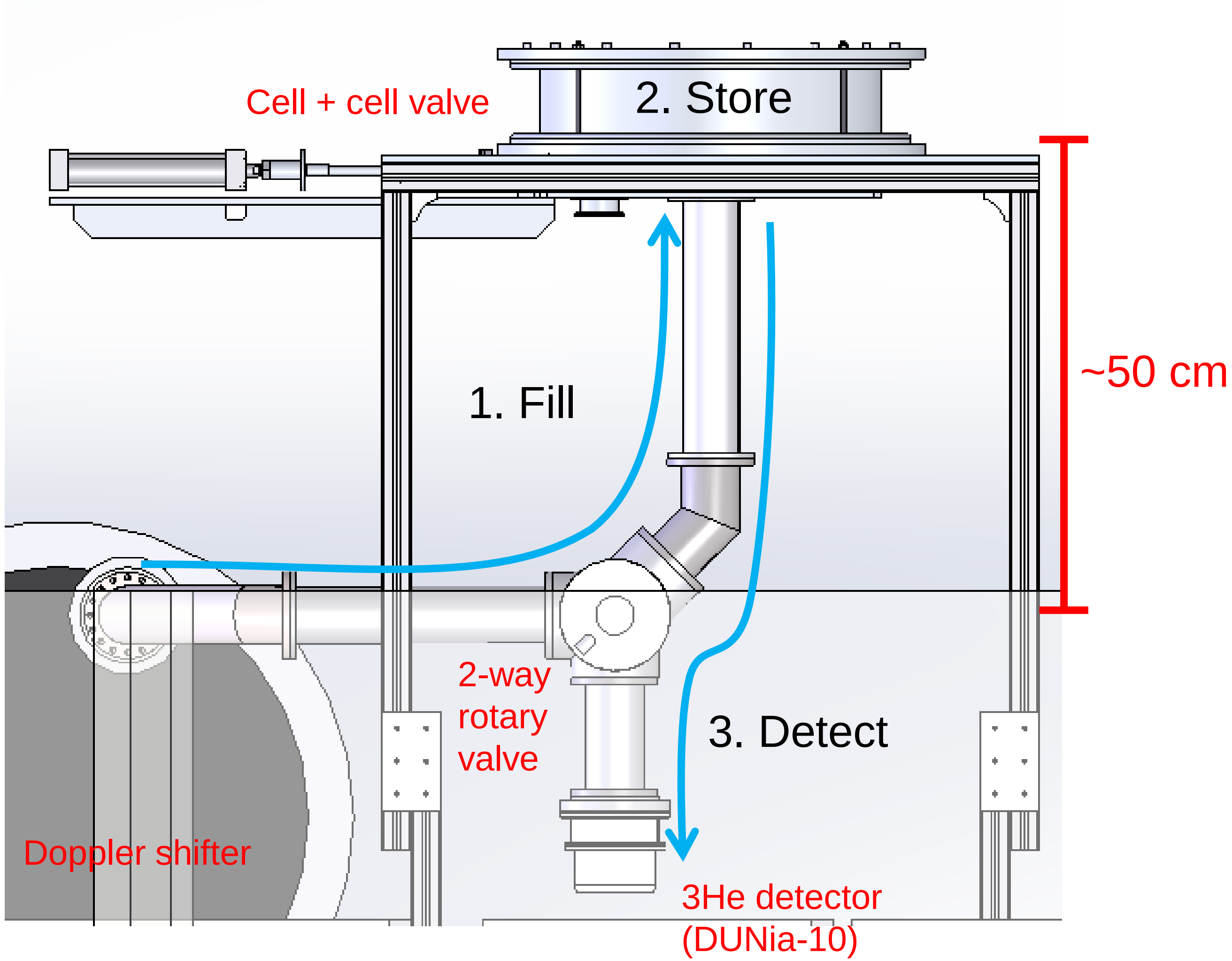
J-PARC MLF BL05 Facility

- J-PARC MLF: home to one of the two most powerful spallation sources in the world (together with Oakridge's SNS)
- BL05: cold neutron beamline equipped with Doppler-shifting turbine
- Top port and side port (out of page)
- Al protection foils
- ~90 VCN/UCN per second measured with a detector connected to side port



Experiment Layout

1. UCN are filled into storage volume from Doppler shifter
2. UCN are stored for a variable time *t*
3. UCN are emptied into the detector
4. Resulting *N* vs *t* data yields a lifetime τ when fit to a decay function



Analysis Method

- To understand these measurements in terms of our future EDM experiment, we are interested in the material parameters W & U, not the raw lifetime τ.
- Fit the data to an analytical formulation for storage lifetimes (previously used by W. Schreyer to analyze our NiP guides: 10.1016/j.nima.2023.168106)

Analysis Method

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- Number of UCN *N*(*t*) after time *t* is

$$N(t) = \int_{H_{min}}^{H_{max}} \frac{dN}{dH} \exp[-t\tau^{-1}(H)]\, dH$$

Energy $H = E + mgz$ relative to bottom of cell

Energy spectrum

Energy-dependent storage lifetime

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$$N(t) = \int_{H_{min}}^{H_{max}} \frac{dN}{dH} \exp[-t\tau^{-1}(H)]\, dH$$

- Lifetime depends on total energy *H* as

$$\tau^{-1}(H) = \frac{\sqrt{\frac{2H}{m}}}{4\gamma(H)} \int_a^b \frac{H - mgz}{H} \sum_i \frac{dA_i}{dz} \mu_i(H - mgz) dz + \tau_\beta^{-1}$$

$$\gamma(H) = \int_a^b \frac{dV}{dz} \sqrt{\frac{H - mgz}{H}}\, dz$$

Differential area

Beta-decay lifetime

Energy-dependent loss rate for surface *i*

Differential volume

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$$\gamma(H) = \int_a^b \frac{dV}{dz} \sqrt{\frac{H - mgz}{H}}\, dz$$

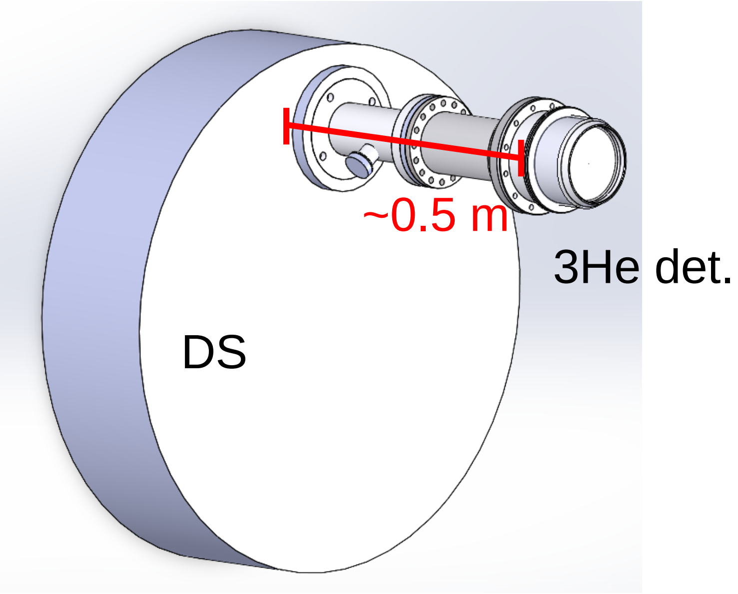
- μ_i is the energy-dependent loss probability

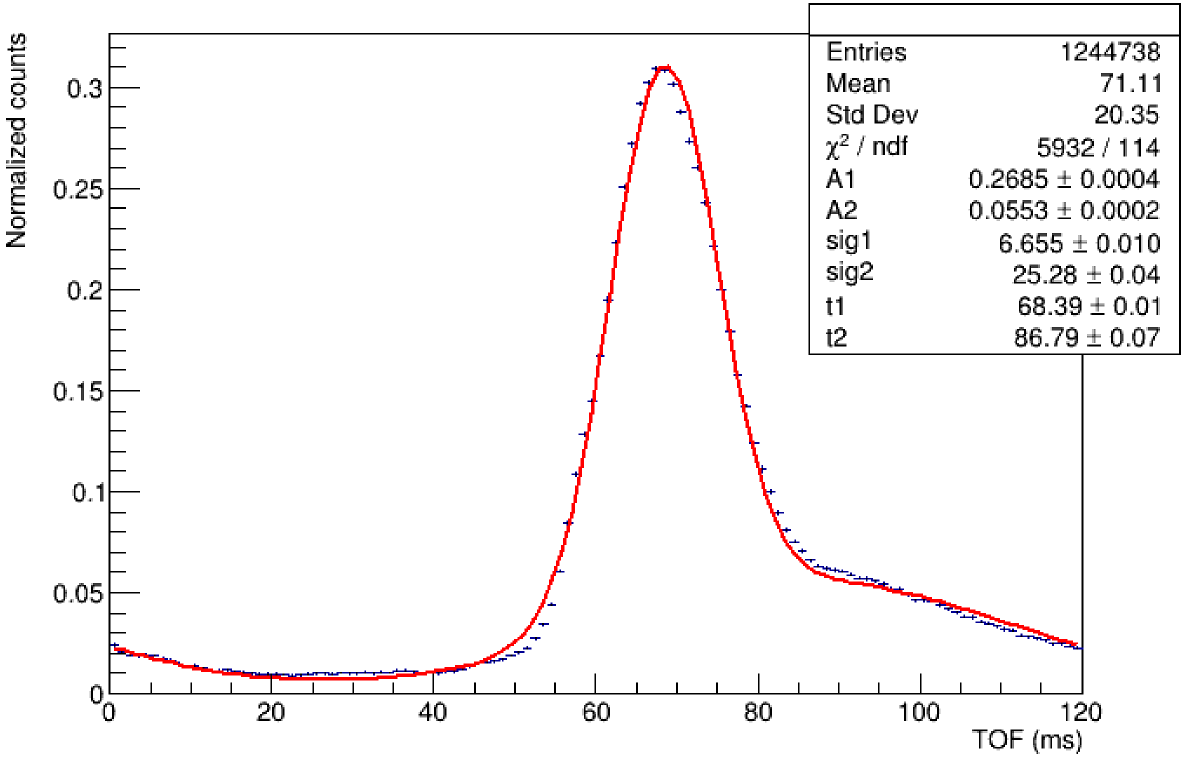
$$\mu_i(E) = 2\int_0^{\frac{\pi}{2}} \left(1 - \left|\frac{\sqrt{E\cos^2(\theta)} - \sqrt{E\cos^2(\theta) - U + iW}}{\sqrt{E\cos^2(\theta)} + \sqrt{E\cos^2(\theta) - U + iW}}\right|\right) \cos\theta \sin\theta\, d\theta$$

Surface material parameters

Doppler-Shifter Energy Spectrum

- Need to know $\frac{dN}{dH}$
- Doppler-shifter energy spectrum has only been measured from TOF

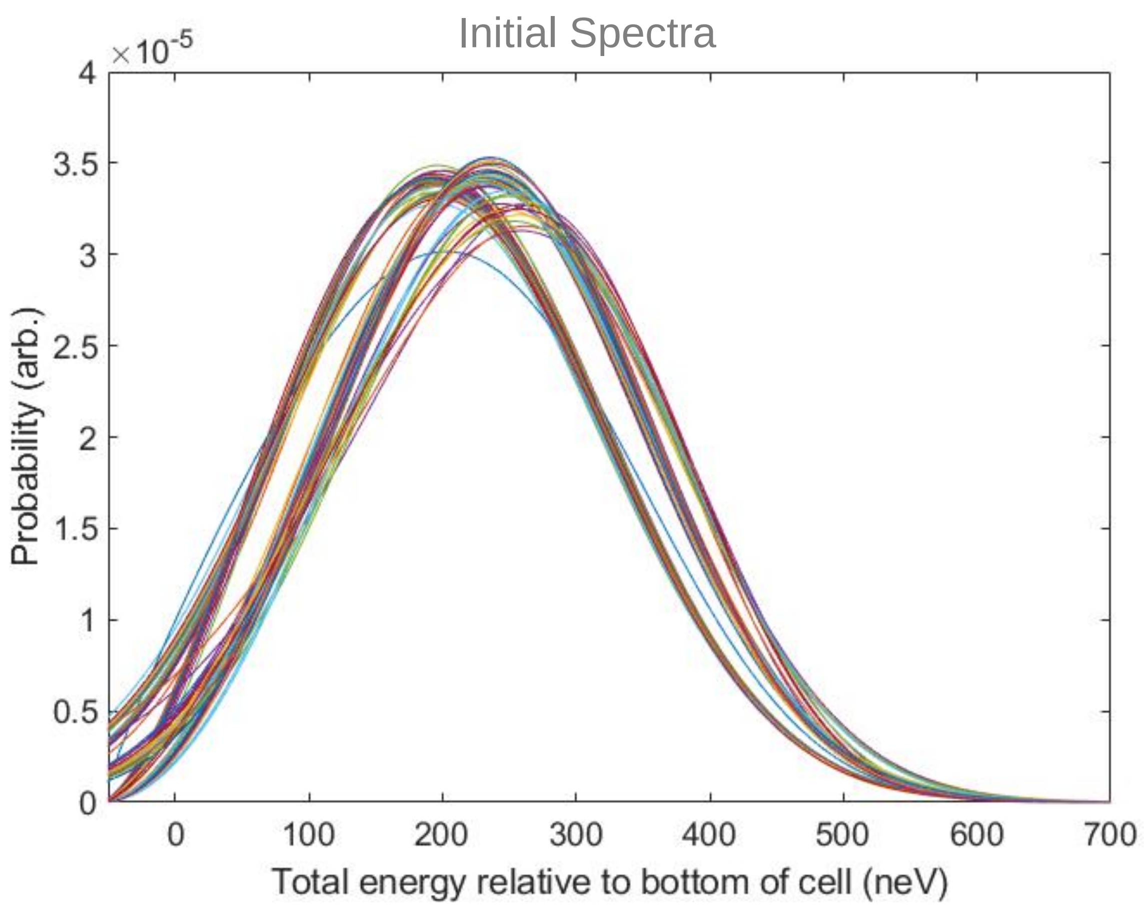




- Lack knowledge about the initial angular distribution

Doppler-Shifter Energy Spectrum

- Search for initial energy spectra that can reproduce the TOF
- Fit PENTrack simulations of TOF measurement to obtain initial energy spectra, for different:
  - Guide properties: imaginary Fermi potential, diffuse reflection probability
  - Foil properties: real Fermi potential
  - Angular distributions: collimated beam vs uniform distribution
  - Fitting functions: Gaussian, skewed gaussian, Weibull



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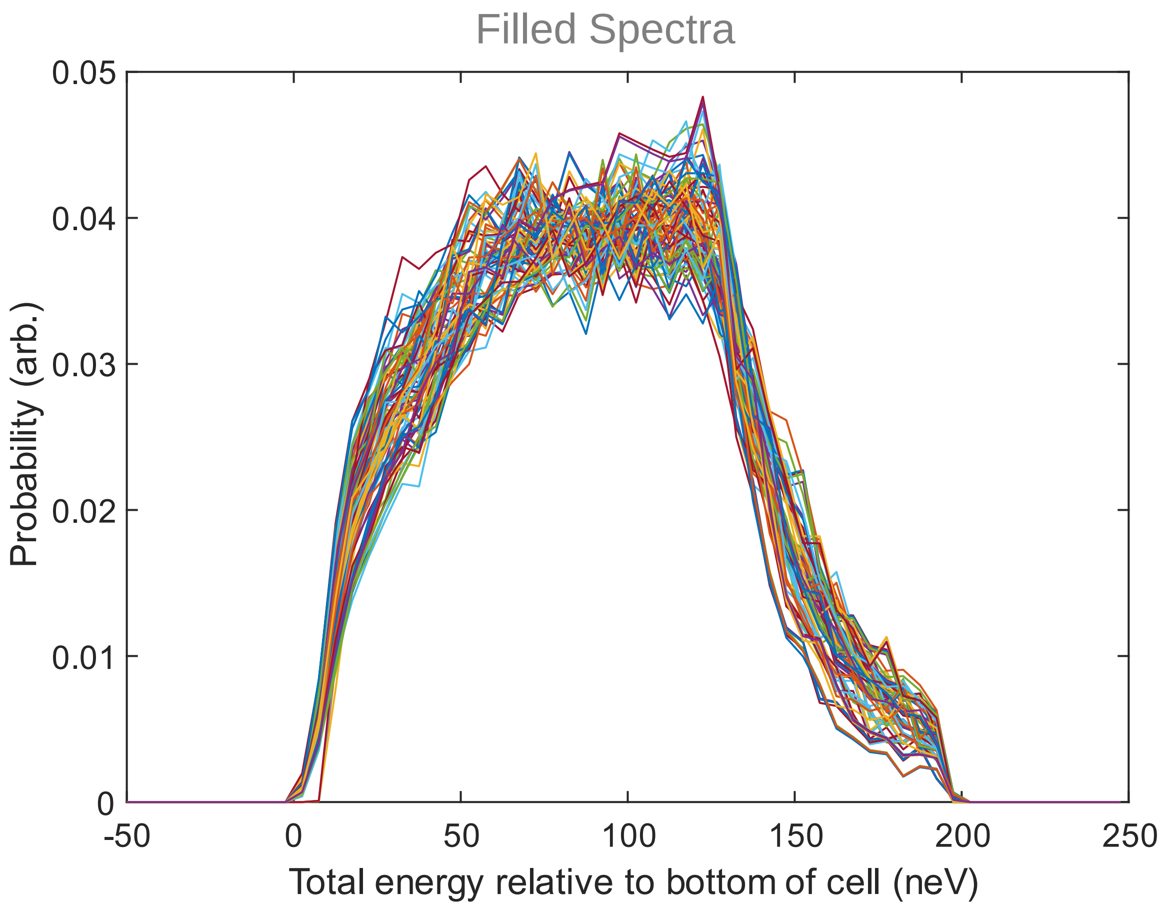
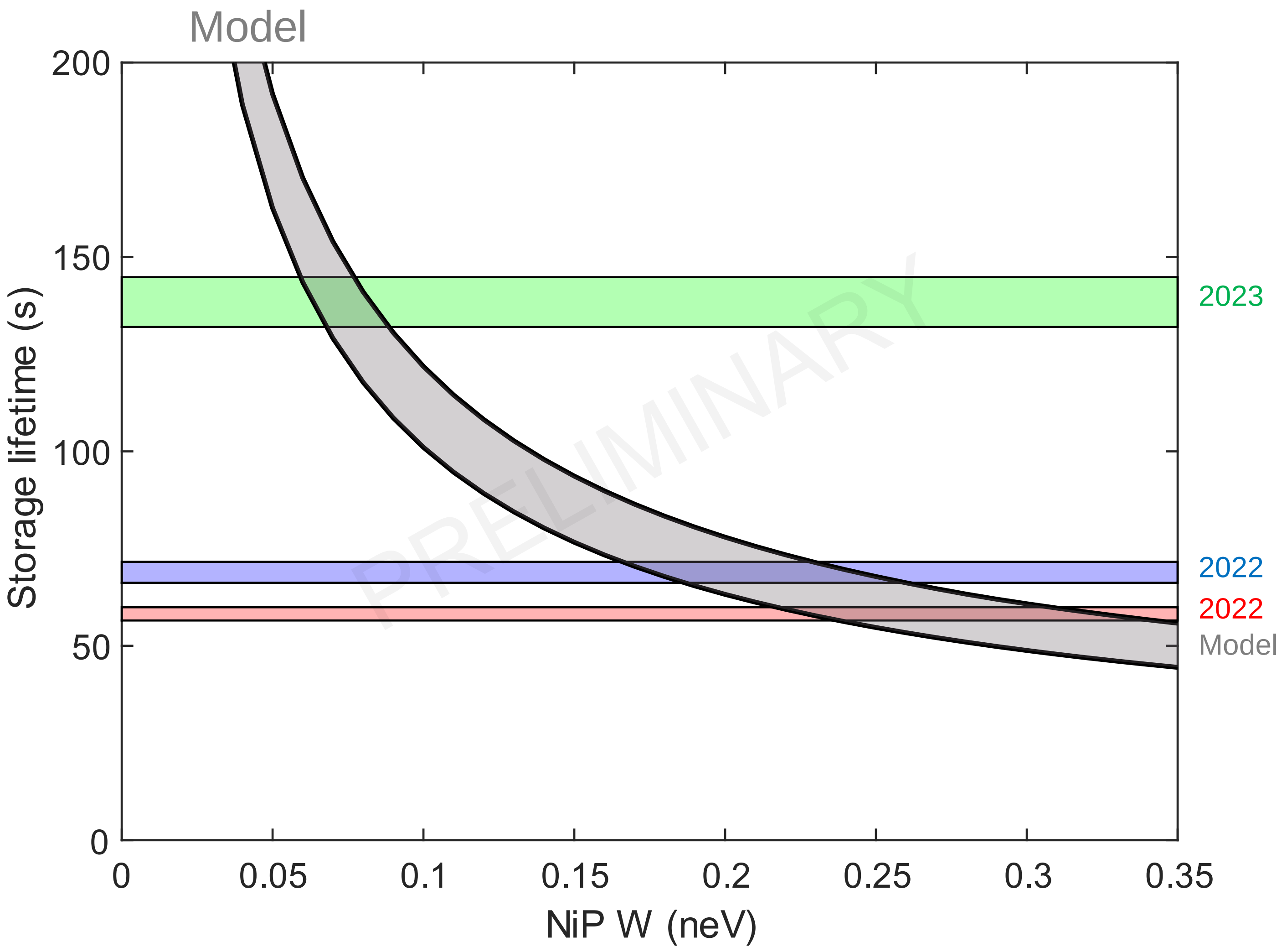
- Fit PENTrack simulations of TOF measurement to obtain initial energy spectra, for different:
  - Guide properties: imaginary Fermi potential, diffuse reflection probability
  - Foil properties: real Fermi potential
  - Angular distributions: collimated beam vs uniform distribution
  - Fitting functions: Gaussian, skewed gaussian, Weibull
- Propagate initial energy spectra to filled energy spectra using further simulations
- Use this range of possible filled energy spectra to analyze the lifetime data



Storage Lifetime Results: NiP/NiP Cell

- Baseline: cell with NiP-coated ring instead of plastic ring
- Assumed $U_{\mathrm{NiP}} = 213$ neV
- Three separate measurements
  1. 2022 Pre-baking
     $\tau = 68.9 \pm 2.7$ s
     W = (0.17, 0.26) neV
  2. 2022 Post-baking
     $\tau = 58.2 \pm 1.7$ s
     W = (0.22, 0.34) neV
  3. 2023 No baking
     $\tau = 138.4 \pm 6.4$ s,
     W = (0.059, 0.089) neV
- Final result is similar to our UCN production volume (but not as good as our best guides)



Contamination of the Cell in 2022

- Baking the cell caused some unidentified liquid to appear in the guides.
- Hypothesis: low lifetime in 2022 was due to a high level of surface contamination from some source.
- Between 2022 and 2023 we re-cleaned every part in the cell and valve and replaced Buna-N O-rings with baked Viton O-rings.
- We did not definitively identify the source of the contamination.

Storage Lifetime Results: NiP/dPS Cell

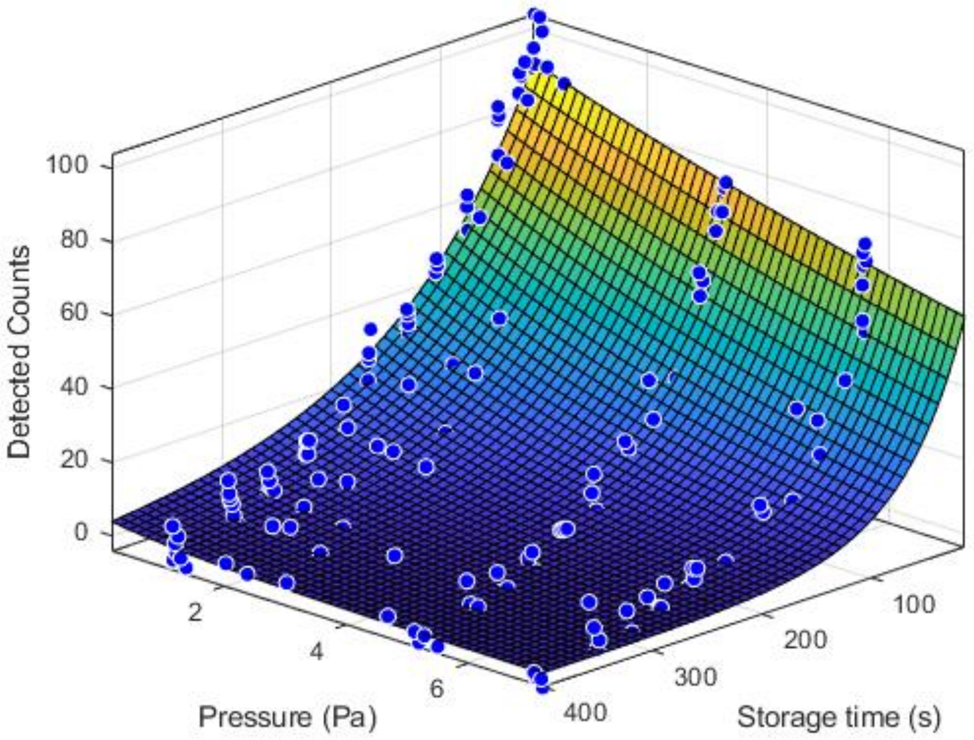
- dPS ring appears to outgas a lot
- Cell has no pumping connection when closed
- Effect can be removed:
  1. Intentionally vary pressure by reducing pumping power
  2. Determine pressure inside cell as a function of pressure outside cell
  3. Treat counts as a function of pressure and storage time

$$N(P_f, P, t) = R\left(\frac{1}{\tau_0} + \frac{1}{\tau_{\text{hole}}} + \alpha P_f\right)^{-1}\left(1 - e^{-60\left(\frac{1}{\tau_0}+\frac{1}{\tau_{\text{hole}}}+\alpha P_i\right)}\right) e^{-t\left(\frac{1}{\tau_0}+\alpha P\right)}$$

Correction for valve being open

Pressure during filling

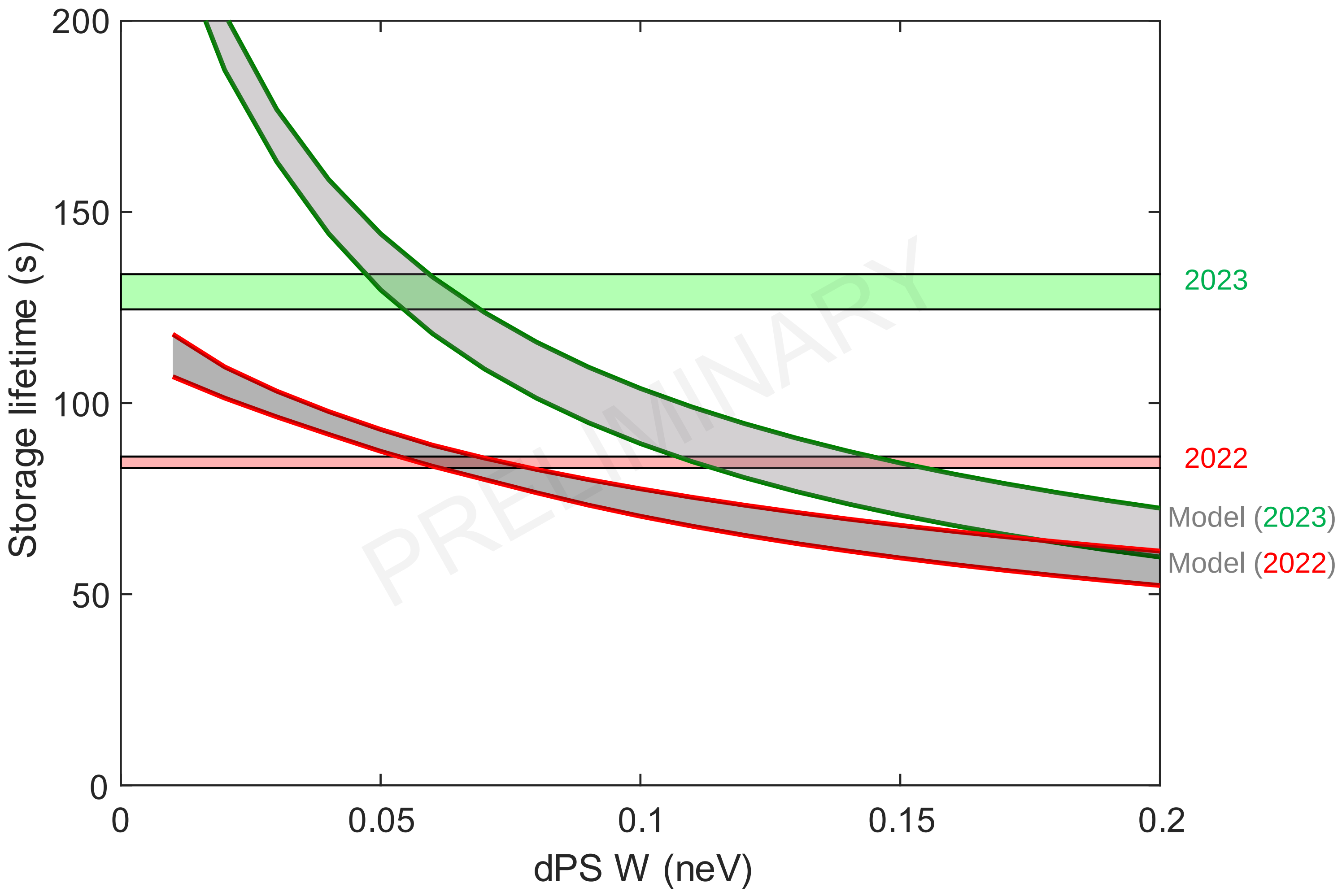
Average pressure during measurement



Without pressure compensation: 119.0 ± 3.8 s
True wall lifetime: 129.1 ± 4.6 s

Storage Lifetime Results: NiP/dPS Cell

- Gray-shaded regions: analysis of NiP/dPS cell assuming full range of NiP-lifetimes from baseline
  - Red outline: 2022
  - Green outline: 2023
- Assumed $U_{\mathrm{dPS}} = 161$ neV
- Two measurements
  1. 2022 (Post-NiP-baking)
     $\tau = 84.5 \pm 1.5$ s
     W = (0.050, 0.079) neV
  2. 2023 No baking
     $\tau = 129.1 \pm 4.6$ s,
     W = (0.045, 0.069) neV
- Results both agree, and are on the higher side of our simulated range (0.032, 0.064)

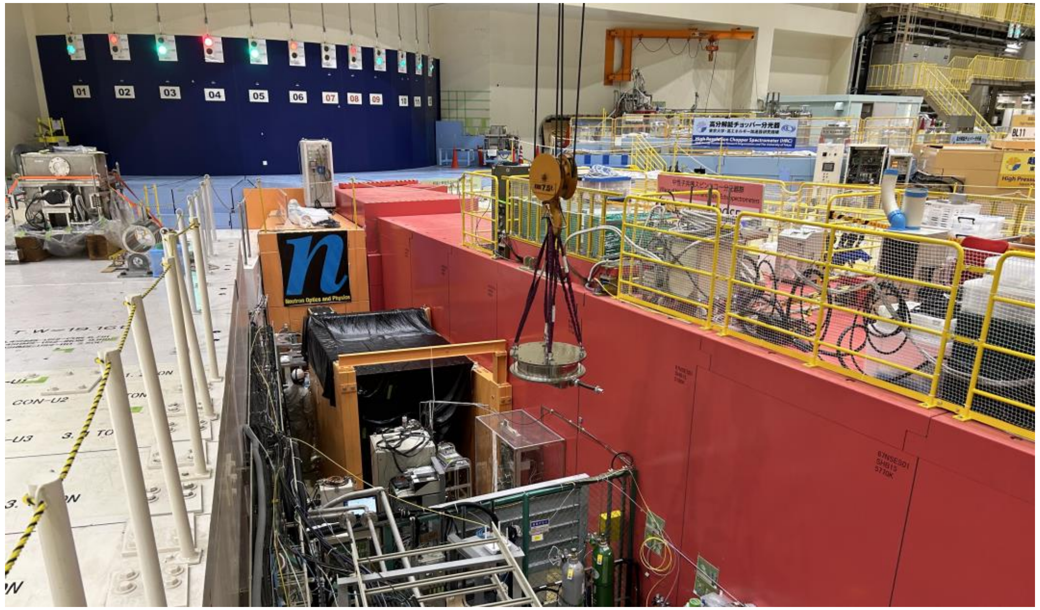


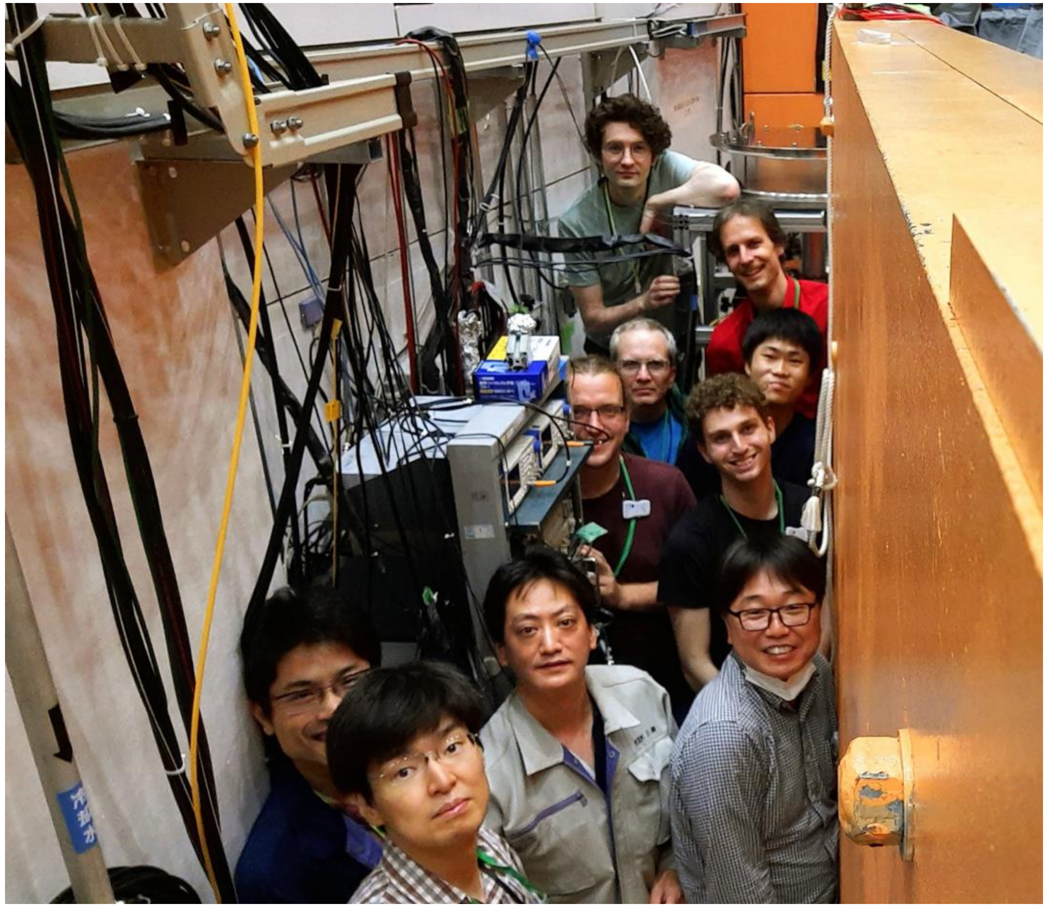
Summary

- Built a prototype EDM cell to test UCN valve and coatings for the TUCAN EDM experiment
- Had some challenges with cleanliness of the cell
- Results are not ideal, but suitable for achieving the TUCAN EDM target sensitivity according to optimization simulations

Thank you!

Beamtime Participants
H. Akatsuka, A. Brossard, T. Higuchi, I. Ide, S. Imajo, S. Kawasaki, J. W. Martin, K. Mishima, R. Picker, I. Press, S. Vanbergen





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