TRIUMF

SFU SIMON FRASER UNIVERSITY
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TUCAN
TRIUMF Ultra Cold Advanced Neutron source

Steve Sidhu

Estimated performance of TUCAN source and EDM apparatus

Overview

In this talk, I will briefly describe

- How we simulate the TUCAN source and EDM experiment,
- How we compare different configurations,
- The estimated performance for our full experiment.

This work is summarized in my PhD thesis, `https://summit.sfu.ca/item/36485`.

Statistical sensitivity for Ramsey's method

For Ramsey's method, the statistical sensitivity is given by:

$$\sigma(d_n) \approx \frac{\hbar}{2\alpha_{\mathrm{det}} T_{\mathrm{Ramsey}} E \sqrt{N_{\mathrm{det}}}}$$

- To improve the precision of the experiment is we must either increase:
  the detected visibility (α_{det}),
  the time they interact with the E field (T_{Ramsey}),
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  the detected visibility ($\alpha_{\rm det}$),
  the time they interact with the E field ($T_{\rm Ramsey}$),
  the strength of the electric field (E),
  or the number of neutrons detected ($N_{\rm det}$).
- We have set our experimental requirements to reach a statistical sensitivity of $1 \times 10^{-27} e$·cm (1σ) in 400 measurement days. (Less than three calendar years.)
- Systematic studies will add additional days/years to obtain a final result.

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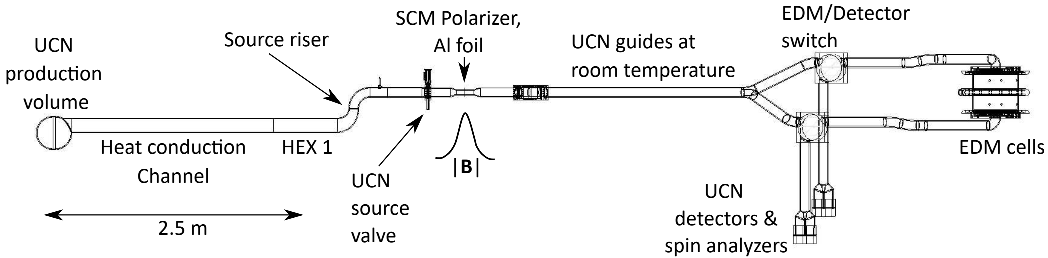

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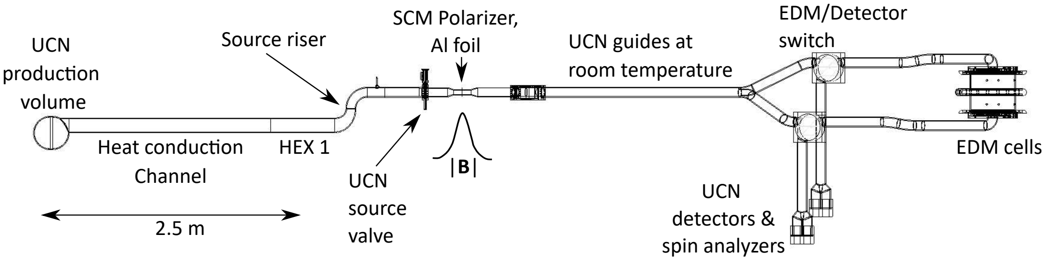

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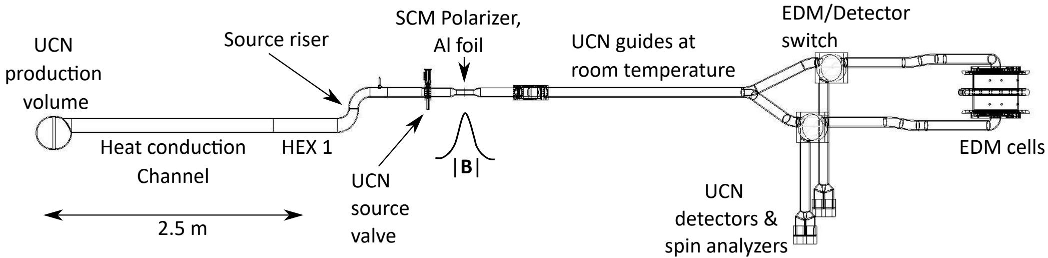

- Input values for Fermi potential, spin-flip probability, non-specular reflection probability must be added (must be measured).
- A new model was created for every configuration change (geometry, material, temperature), simulated, and analyzed.

Metric of comparison

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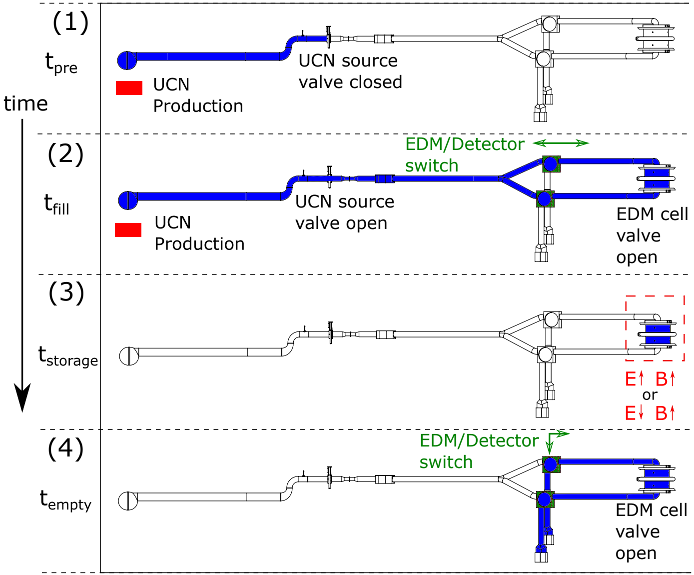
$$T_{\mathrm{meas}} = \frac{N_{\mathrm{cycles}}}{N_{\mathrm{cycles}}/\mathrm{day}}.$$

5. The configuration which yields the shortest T_{meas} is preferred.

Operation of the TUCAN EDM experiment

- The experiment will have 4 different periods.



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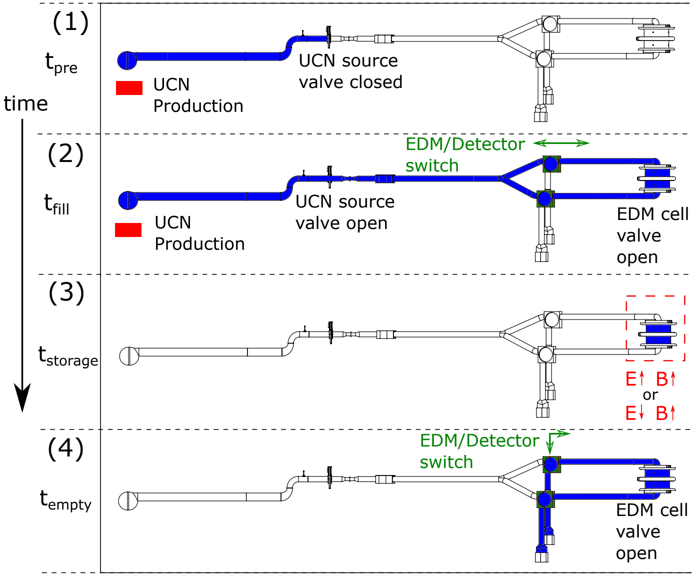

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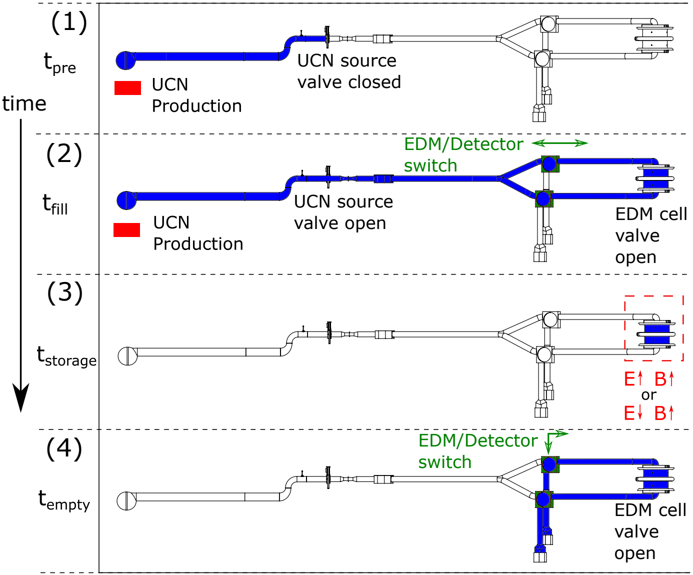

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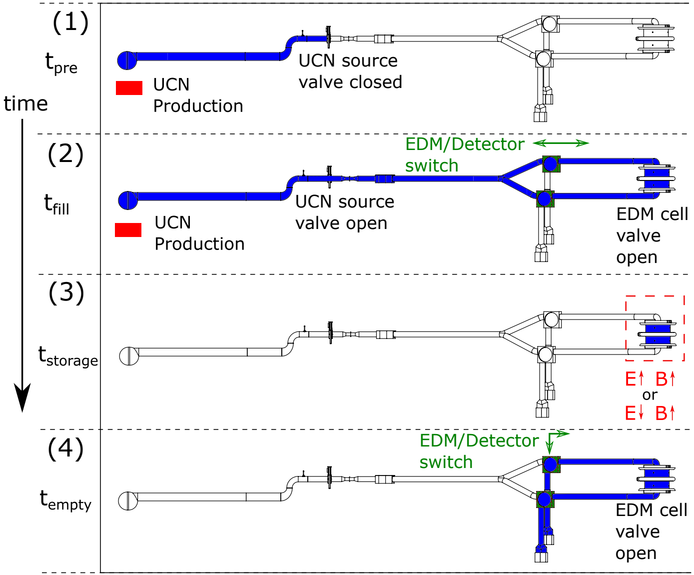
- Varying these timings changes the spectrum of UCN energies at the end of each period. (overloading)
- For each configuration, T_{meas} is minimized by optimizing the timings together.



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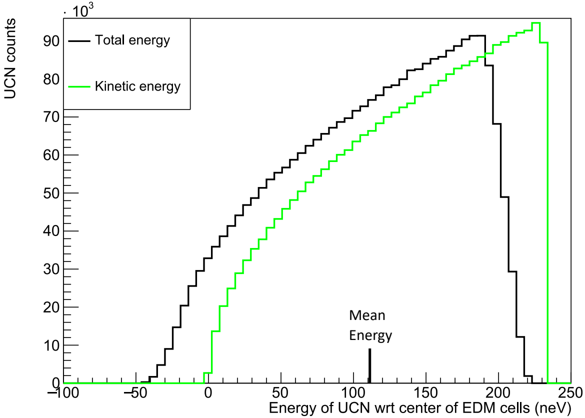
- **Key point**: the operational timings of the entire experiment must be optimized together.

$$T_{\mathrm{meas}} \propto \frac{t_{\mathrm{cycle}}}{\alpha_{\mathrm{det}}^2 E^2 T_{\mathrm{Ramsey}}^2 N_{\mathrm{det}}},$$

where $t_{\mathrm{cycle}} = t_{\mathrm{pre}} + t_{\mathrm{fill}} + T_{\mathrm{Ramsey}} + t_{\mathrm{empty}}$ + constant operational timings.

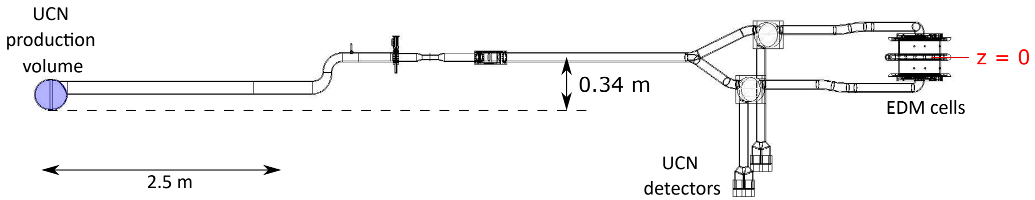
This is because we are dealing with dependant variables,
e.g. A longer T_{Ramsey} decreases N_{det} and α_{det}.

Starting energy spectrum in the production volume



- Total energy: $H = E_{\mathrm{kin}} + V_g + V_B + V_F$.
- Starting simulated-spectrum of UCN in production volume.
- $V_g = 0$ at the center of the EDM cells. V_F(He) = 18.5 neV.

Starting energy spectrum in the production volume



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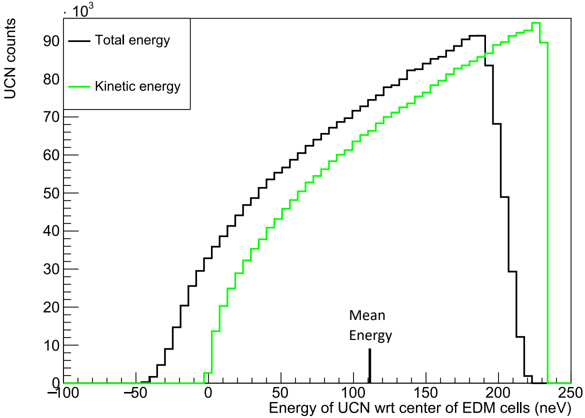

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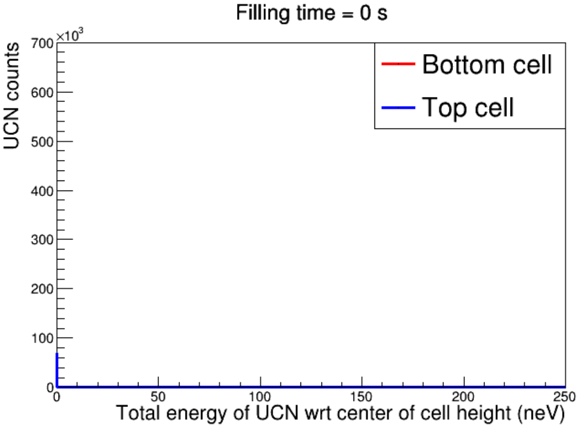
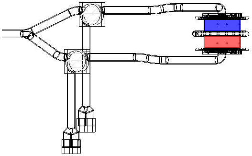
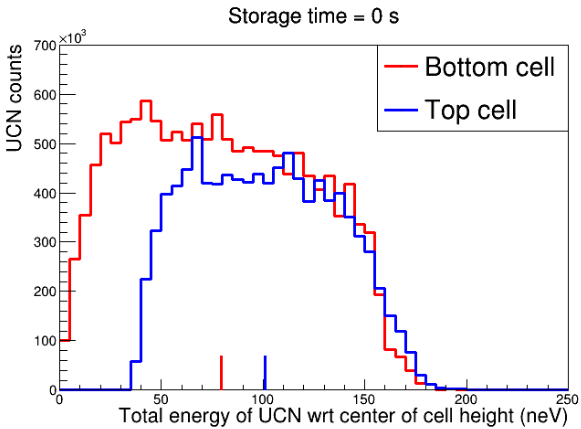
Filling of EDM cells

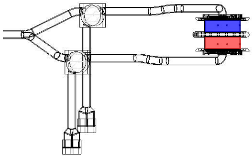




The energy spectrum of UCNs that fill the EDM cells. Vertical lines indicate mean energy.
This includes a $t_{\mathrm{pre}} = 99$ s.

Storage in EDM cells

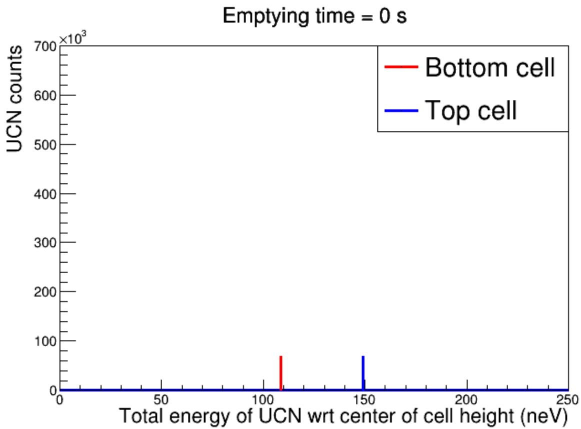


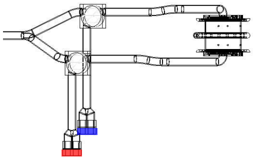


Energy spectrum of UCNs that survive in the EDM cells during the free precession. Vertical lines indicate mean energy.

Assumed timings: $t_{\mathrm{pre}} = 99$ s, $t_{\mathrm{fill}} = 99$ s.

Detection of UCN from EDM cells





The energy spectrum of UCN that are detected. Vertical lines indicate mean energy.
Assumed timings: $t_{\text{pre}} = 99$ s, $t_{\text{fill}} = 99$ s, $t_{\text{storage}} = 100$ s.

Impact of optimization methods

Comparison of optimization methods for the same configuration:

Method	t_{pre} (s)	t_{fill} (s)	T_{Ramsey} (s)	t_{empty} (s)	T_{meas} (d)
Filling only	0	62.5	140	100	$451(14)$

- Filling only: fit $N_{\text{filled}}(t)$ to $1 - e^{-t/\tau_{\text{fill}}}$ and choosing t_{fill} to be 2.5 filling lifetimes ($\sim$ 90 $\%$ maximal filling).

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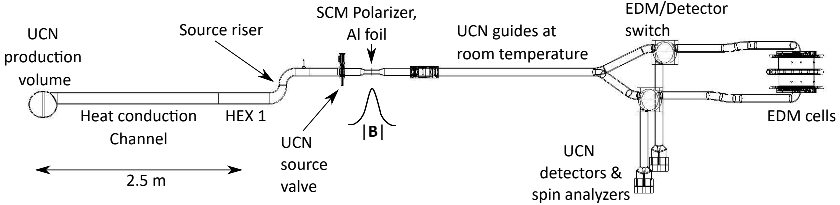
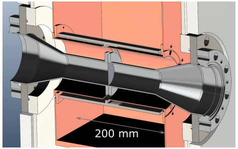
- Using TUCAN MESA method, which optimizes the entire experiment, results in a nearly 35 $\%$ shorter measurement time compared to the "filling only" method.
- This leads to a long t_{fill}, T_{Ramsey}, and is biased towards lower-energy UCNs.

Main results and outcomes

1. The operational timings of the entire experiment should be optimized together
2. Simulations indicate that our vacuum separation foil volume should be minimized (resulting in a small diameter guide through our SCM and a $\sim$ 20% reduction in T_{meas})
3. Simulations indicate that the vertical drop to our detectors from the cells should be almost double what we expected and a $\sim$ 35% reduction in T_{meas}



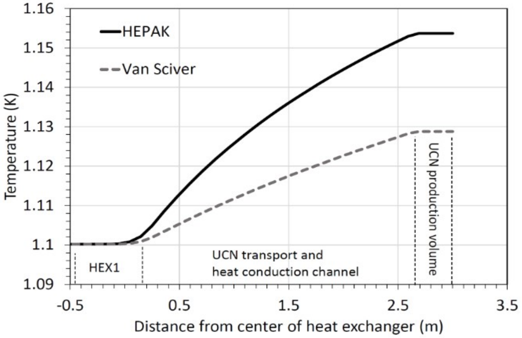
45 mm bore guide



Estimated performance - assumptions

- Yoshiki B parameter of 0.0161 $s^{-1}K^{-7}$
- Temperature of He-II in HEX1: 1.1 K
- Model of heat transport in He-II: HEPAK
- Fermi potential of
  - He-II: U_F = (19 - $i\frac{\hbar}{2}BT^7$) neV
  - NiP: U_F = $(213 - i0.07)$ neV
  - dPS: U_F = $(171 - i0.05)$ neV
  - Al: U_F = $(54 - i0.003)$ neV
- Lambert diffuse reflection probability of
  - cryogenic region $P_L = 0.15$
  - room temperature guides $P_L = 0.03$
- spin-flip prob. per wall bounce: 3×10^{-5}
- Total spin coherence lifetime $T_2 :> 800$s
- Avg E-field in EDM cells of 12.5 kV/cm

Comparison of HEPAK and Van Sciver parameterizations of the temperature profile in He-II.



See our paper for details, `https://doi.org/10.1051/epjconf/202328201015`.

Estimated performance

Description	Value	Comment
Production with valve closed	20 s	Optimized timing
Filling with production	105 s	Optimized timing
Ramsey time	188 s	Optimized timing
UCN collection time	49 s	Optimized timing
Source lifetime	19.2 $\pm$ 0.2 s	with valve closed
Neutrons filled into cells	$1.38 \pm 0.02 \times 10^7$	
Corresponding density	$\mathbf{213 \pm 3}$ **UCN/cc**	
EDM cell lifetimes	$\mathbf{119 \pm 4}$ s, $\mathbf{116 \pm 4}$ s	top and bottom
UCN detected	$\mathbf{1.43 \pm 0.02 \times 10^6}$	
Detected visibility	0.60 ± 0.02	
Sensitivity per cycle	$\mathbf{1.94 \pm 0.06 \times 10^{-25}}$ $e\mathrm{cm}$	
Quiet time per day	16 h on avg	excluding 7am to 6pm weekdays
Time to reach 10^{-27} $e\mathrm{cm}$ (1σ)	$\mathbf{281 \pm 16}$ **days**	

For more details, please see my thesis,
`https://summit.sfu.ca/item/36485`
and our paper,
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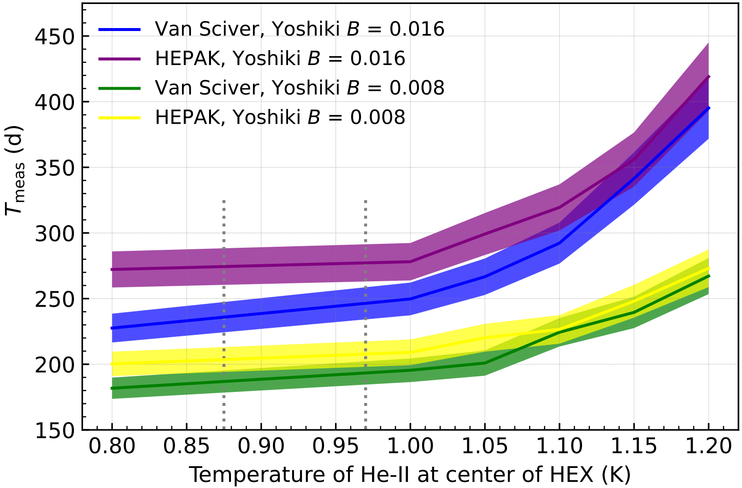
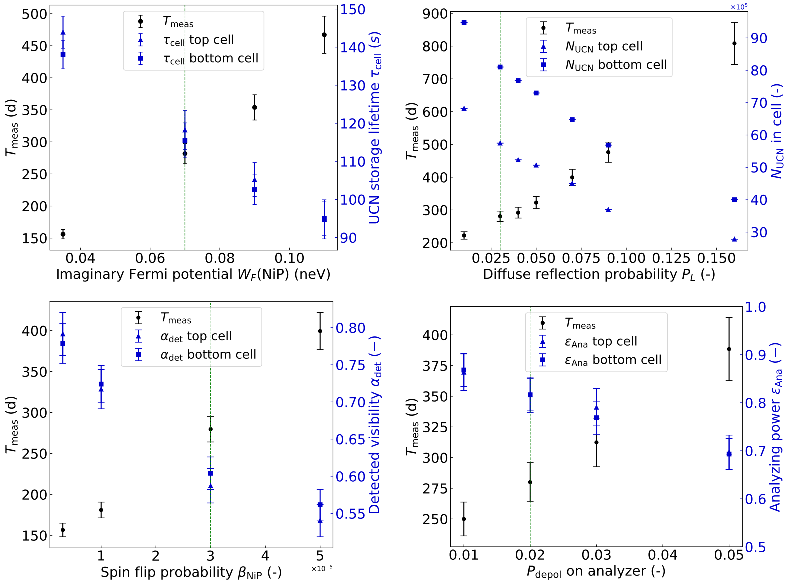
Thank you.

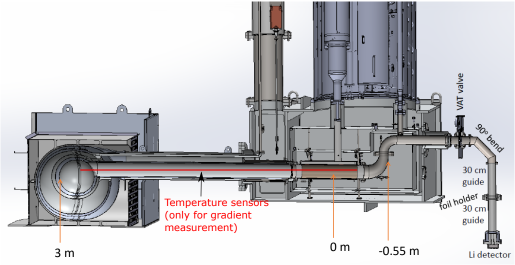
Sensitivity to He-II temperature

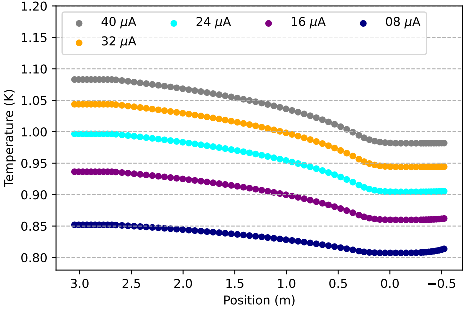


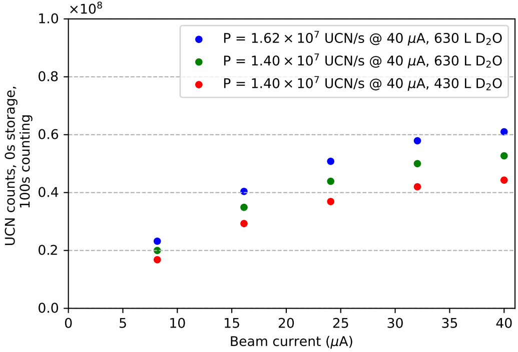
Sensitivity to global parameters



Source commissioning predictions

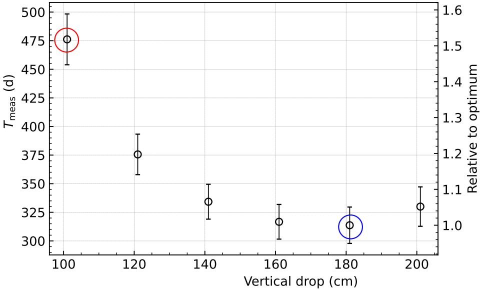


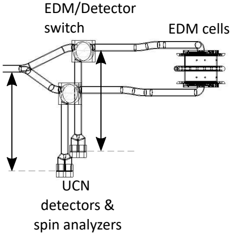




Vertical drop to the detectors

- UCNs can be reflected off the glass windows of the UCN detectors: not detected.





$$E_{\text{kin}} > V_F(\text{det window})$$

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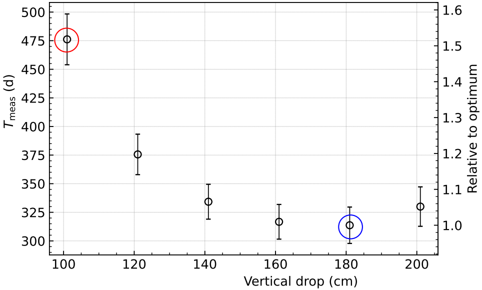
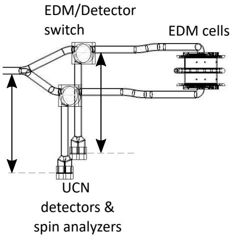
- Analytical calculations indicate that the vertical drop should be around 100 cm.





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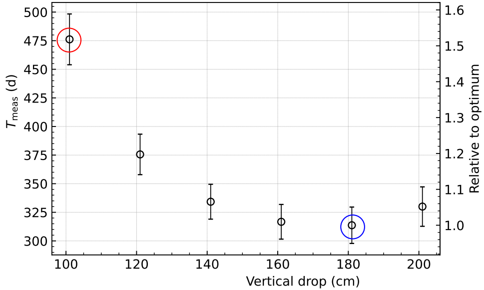
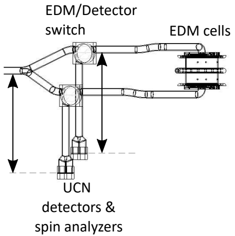
- Simulations indicate an optimal of 180 cm, a $\sim 35\%$ reduction in T_{meas}.





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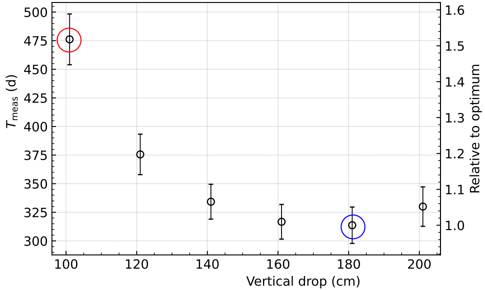
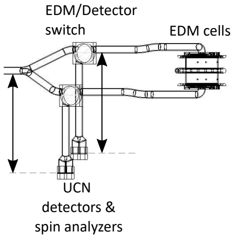
- My calculation assumes specular reflections.





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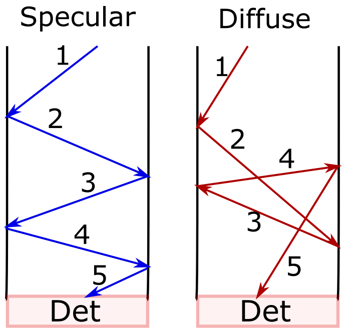
Vertical drop to the detectors

- If we ignore non-specular (diffuse) reflection, the analytical calculation should be correct.
- Only specular reflection: vertical momentum is conserved.
- Diffuse reflection: vertical momentum is not conserved.



SCM bore guide I

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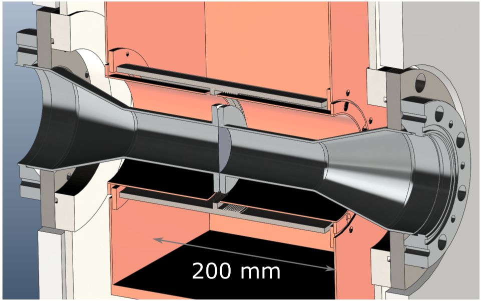

V_F(Al) = 54 neV

SCM bore guide I

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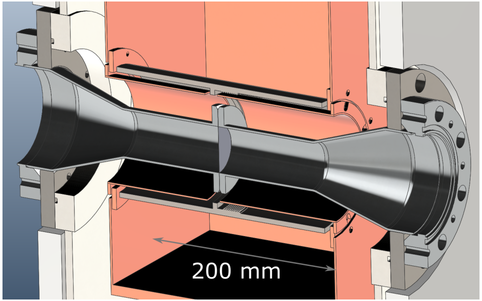

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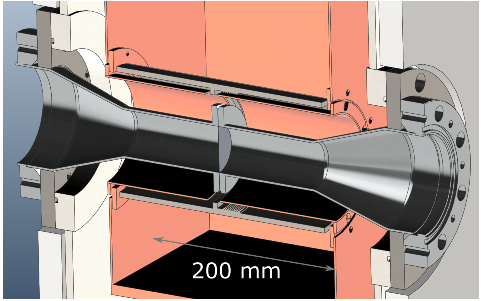

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SCM bore guide I

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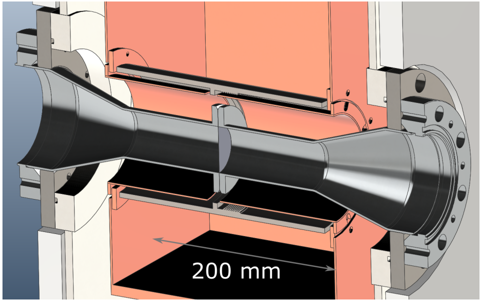
- Adding the foil inside the SCM increases the efficiency of UCN transport through the foil.
- The diameter of the SCM bore guide was varied.



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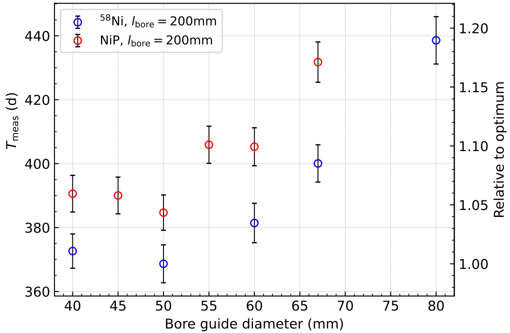
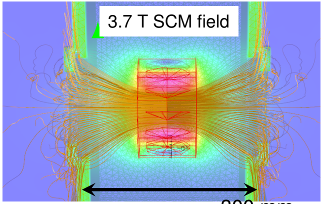
SCM bore guide II

- A smaller diameter results in a shorter T_{meas}. There were still large UCN losses in this region.





V_F(NiP) = 213 neV
$V_F(^{58}$Ni) = 345 neV

SCM bore guide II

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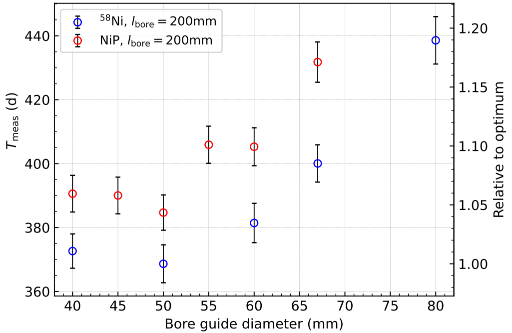
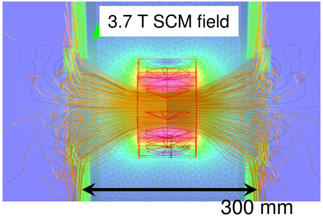
- **Hypothesis**: UCN are accelerated towards the walls $\rightarrow$ use different material.





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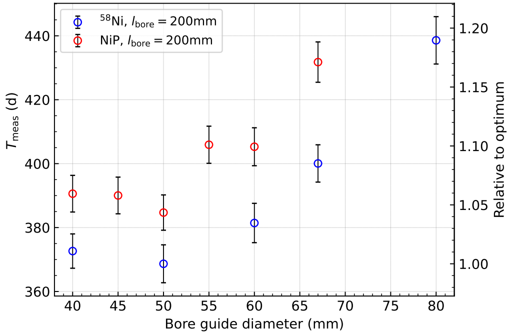
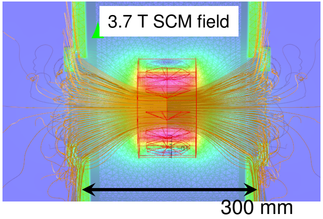
- I simulated ^{58}Ni coating on the walls, the trend was the same.





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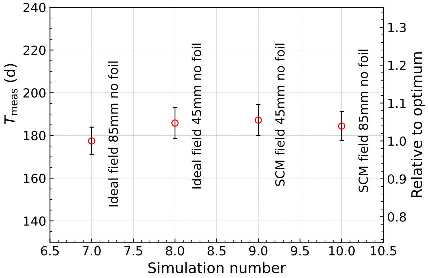
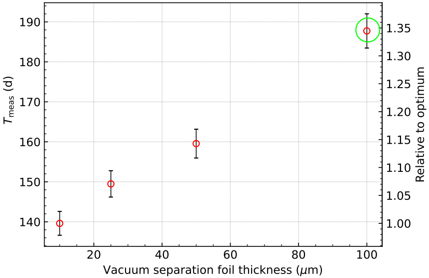
SCM bore guide III

- Simulations were performed to test,
  - reducing strength of $\mathbf{B}$,
  - eliminating the $\mathbf{B}$-field gradient (non-physical),
  - eliminating the foil,
  - reducing the thickness of the foil.





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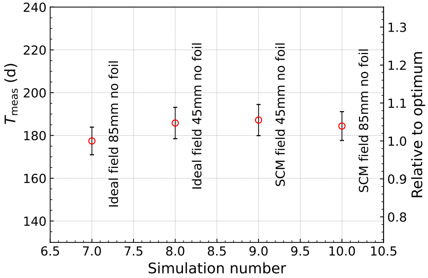
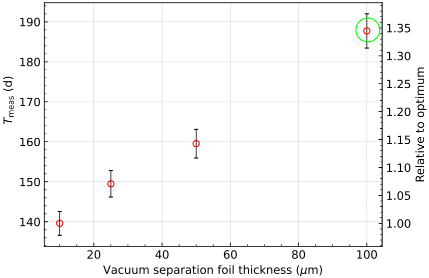
- With no foil, a small diameter does not yield a shorter measurement time.





SCM bore guide III

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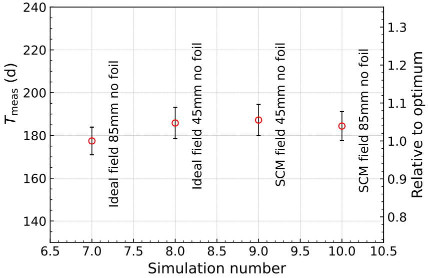
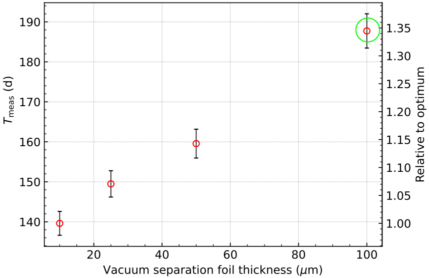
- With no foil, a small diameter does not yield a shorter measurement time.
- The foil is the largest source of UCN loss.





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  - reducing the thickness of the foil.
- With no foil, a small diameter does not yield a shorter measurement time.
- The foil is the largest source of UCN loss.
- **Conclusion: reduce the volume (diameter and thickness) of the foil.**