

# Searching for a neutron EDM using Superthermal Sources and Cryogenics:

*PanEDM, SuperSUN, and  $(EDM)^n$*

Skyler Degenkolb, Institut Laue-Langevin  
on behalf of the PanEDM collaboration

# The PanEDM Collaboration

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Open lecture series, at student level, beginning in 2 weeks:  
Sept. 30 – Oct. 6 (jointly organized on Zoom by ILL and TUM)

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\*co-spokespersons

# Neutrons, as atoms or nuclei

can also bind two H nuclei and possibly also one H nucleus. In the one case, this entails the possible existence of an atom of mass nearly 2 carrying one charge, which is to be regarded as an isotope of hydrogen. In the other case, it involves the idea of the possible existence of an atom of mass 1 which has zero nucleus charge. Such an atomic structure seems by no means impossible. On present views, the neutral hydrogen atom is regarded as a nucleus of unit charge with an electron attached at a distance, and the spectrum of hydrogen is ascribed to the movements of this distant electron.

*—prediction by Rutherford (1920 Bakerian lecture)*

mass = 1.0087 amu  
spin =  $\frac{1}{2}$  ( $\mu = -1.9 \mu_N$ )  
 $\tau_\beta = 880$  s

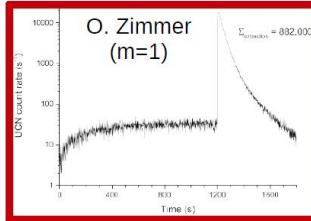
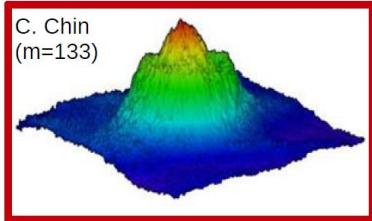
$mgh = 103$  neV ( $h = 1$  m)  
 $\mu B = 60$  neV ( $B = 1T$ )  
 $U_S = 168$  neV (copper in vacuum)

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the  $\alpha$ -particle by the

— *observation by Chadwick*  
*Nature 129, 312 (1932)*

Velocity	“Temperature”	Energy
$10^0 - 10^1$ m/s	Ultracold	5 neV – 500 neV
$10^1 - 10^2$ m/s	Very cold	0.5 $\mu$ eV – 50 $\mu$ eV
$10^2 - 10^3$ m/s	Cold	50 $\mu$ eV – 5 meV
$2.2 \times 10^3$ m/s	Thermal	25 meV
$2 \times 10^3 - 2 \times 10^4$ m/s	Hot	20 meV – 2 eV

# “Ultracold” and “Superthermal”



Number of Particles	$10^4$	$90 \times 10^4$
“Temperature”	$10^{-5}$ mK	1 mK
Wavelength	$1.5 \mu\text{m}$	$0.1 \mu\text{m}$
Velocity	$10^{-3}$ m/s	4 m/s
Phase Space Density	2.5	$2 \times 10^{-13}$

## Production rate density, and storage losses

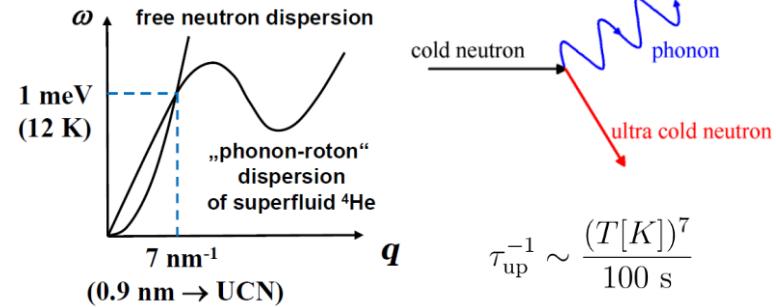
$$R \sim \left( \frac{5 \times 10^{-8}}{\text{cm}^3 \text{s}} \right) \times \frac{d\Phi}{d\lambda} \Big|_{8.9\text{\AA}} \times \left( \frac{V_{\text{trap}}}{233 \text{ neV}} \right)^{\frac{3}{2}} \rightarrow 5-15 /(\text{cm}^3 \text{s})$$

$$\frac{1}{\tau} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\text{up}}} + \frac{1}{\tau_{\text{capture}}} + \frac{1}{\tau_{\text{wall}}} + \dots \rightarrow \text{limited by decay, wall interactions}$$

16/09/2020

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## Superthermal conversion in SF He



Moderation vs. “conversion”  
 phase space compression  
 need for dissipative physics  
 flux vs. density (beam vs. storage)  
*-important for next generation*

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# Topics in nEDM Statistics/Systematics



## Statistics

- Flux vs. *density*: we want to count a large number after storage
  - Transport losses and dilution
- Storage time (including  $T_1/T_2$ )
- Total measurement time/repetitions
  - Long-term stability becomes important
- Polarization (and analyzing power)
- Electric field



$$N_{\text{cell}} \sim \rho_{\text{cell}} V_{\text{cell}} \sim \frac{\rho_{\text{source}} V_{\text{cell}}}{1 + \frac{V_{\text{cell}} + V_{\text{guide}}}{V_{\text{source}}}}$$



$$\frac{1}{\tau} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\text{up}}} + \frac{1}{\tau_{\text{capture}}} + \frac{1}{\tau_{\text{wall}}} + \dots$$

## Systematics (non-exhaustive)

- Cell size and quality
- Field stability, monitor quality
- Magnetic screening
- Environment/backgrounds

# Superthermal (He-II) UCN Sources



**High-density** sources (cf. more common, high-flux sources)

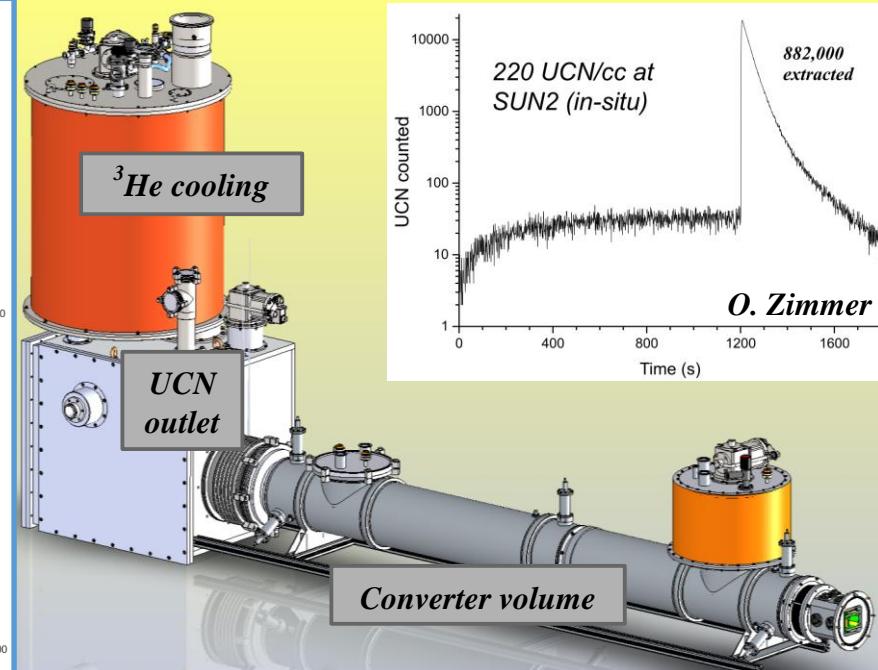
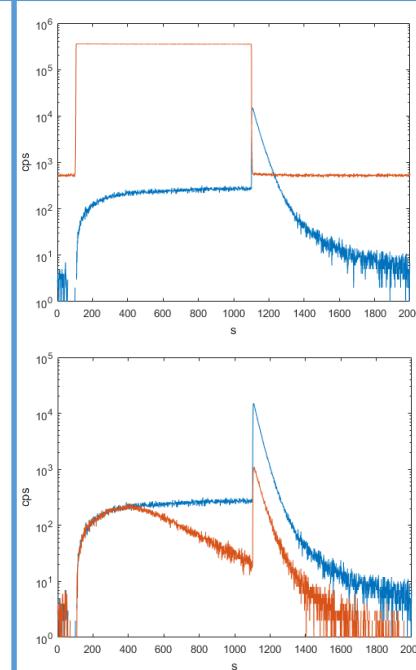
- phase space density
- beam current

Two basic issues:  $\rho_{UCN} = P\tau$

- production rate
- UCN loss

Experimentally, we might improve:

- cold neutron flux (usage?)
- storage/transport losses



## Characteristic output:

$$\lambda \sim 900 \text{ \AA} \quad (v \sim 4 \text{ m/s})$$

$$\Phi \sim 500 \text{ n/s/cm}^2 \quad (\sim 3 \times 10^{-13} \Phi_{pool})$$

$$\rho \sim 2 \text{ cm}^{-3} \quad (\sim 1 \times 10^{-10} \rho_{rest-gas})$$

$$\rho_{phase-space} < 10^{-13} \sim (900 \text{ \AA})^3 (220 \text{ cm}^{-3})$$

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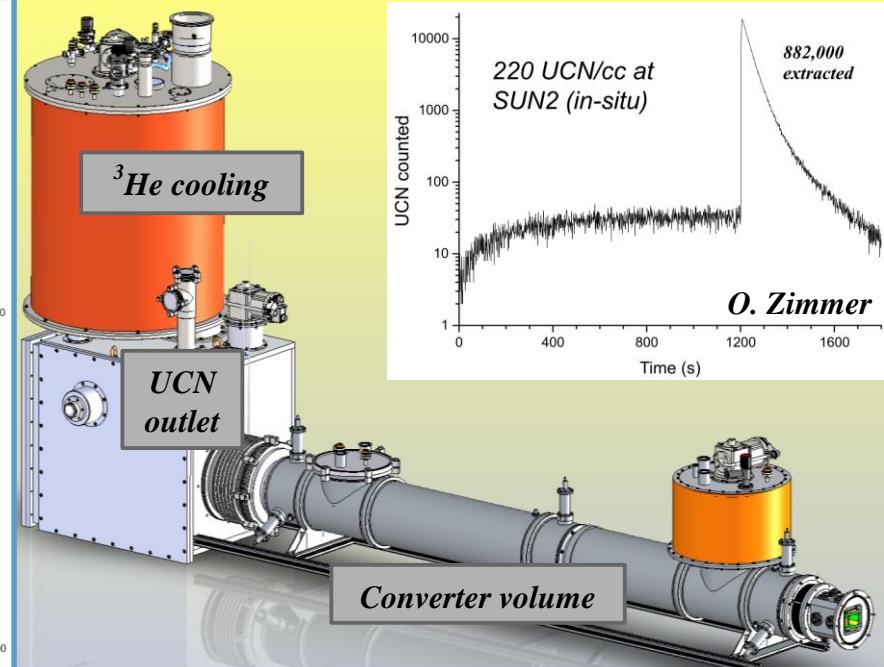
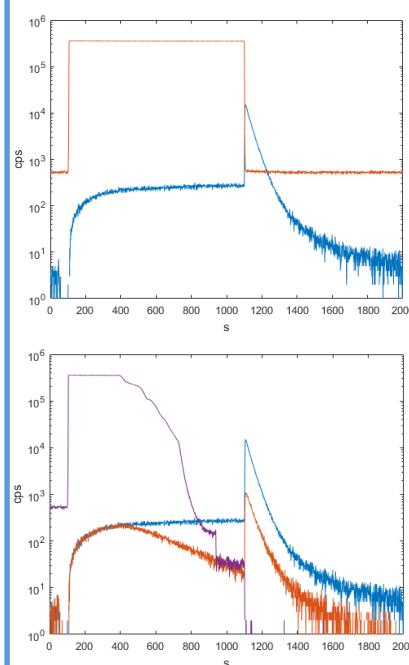
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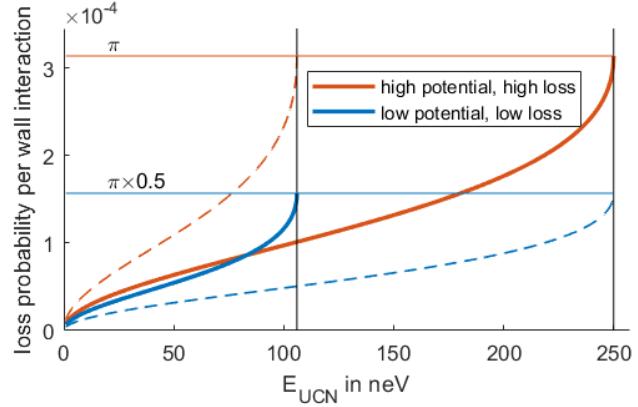
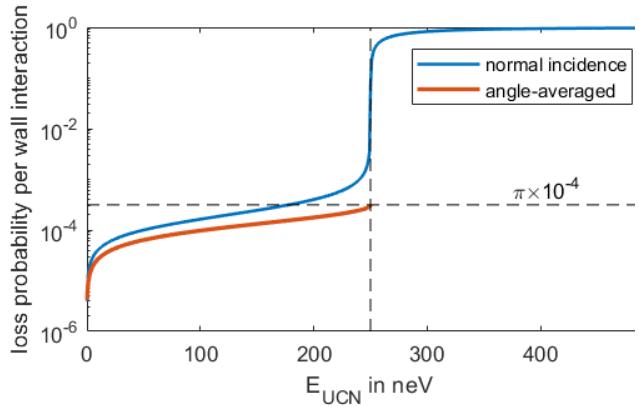
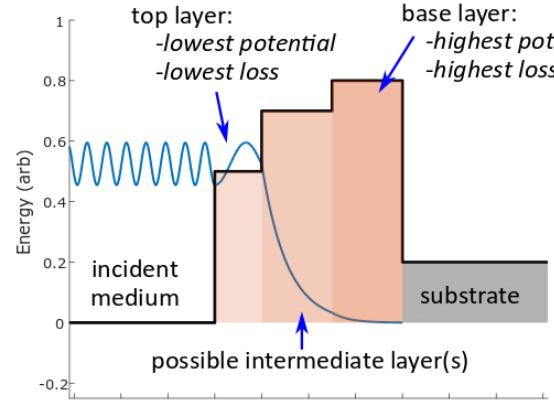


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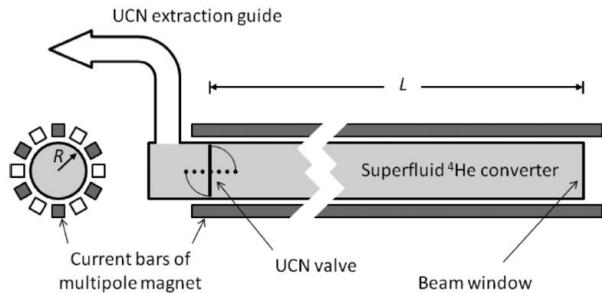
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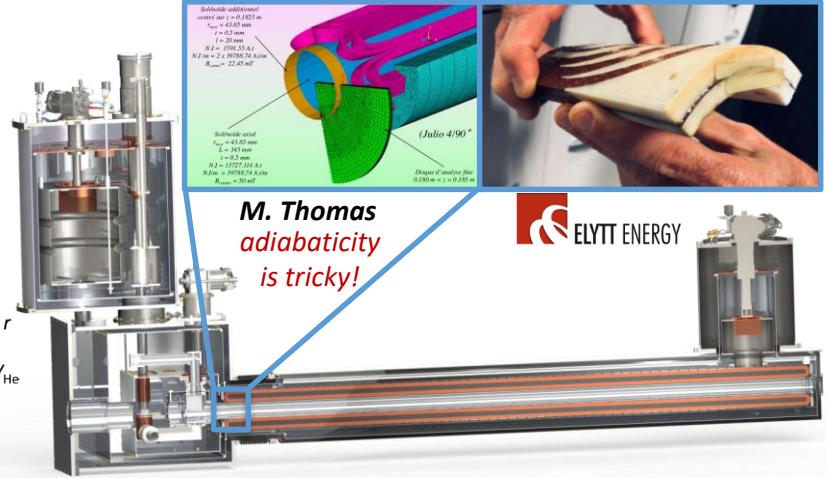
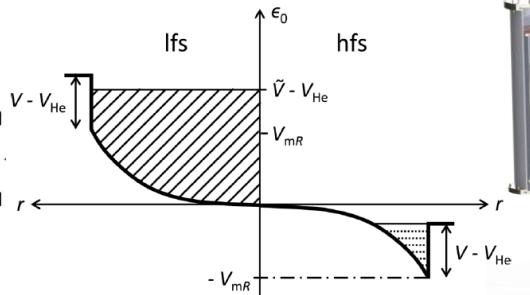
# Optimizing Coatings and Source Vessels



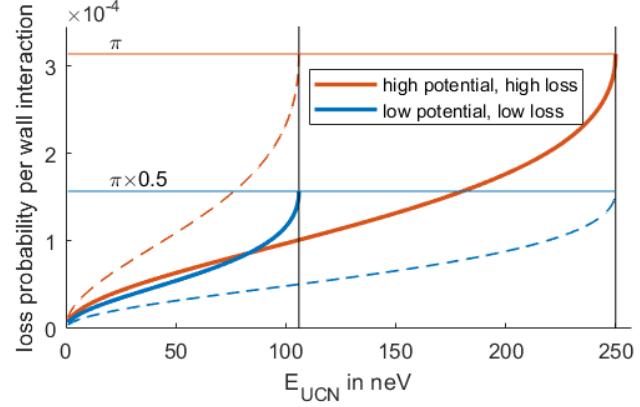
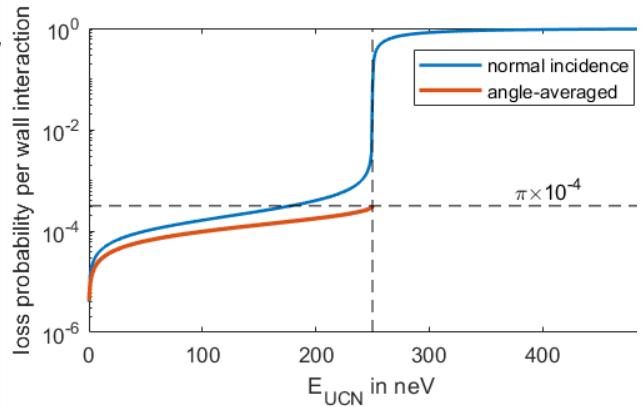
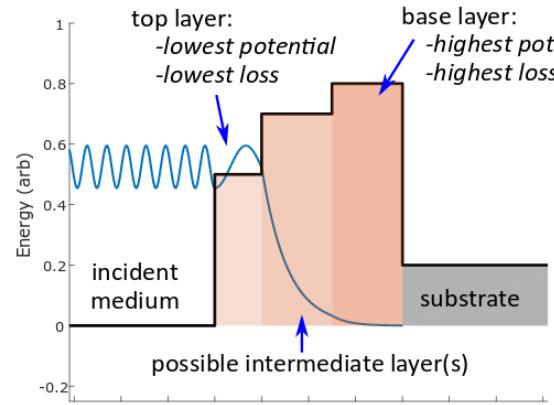
## SuperSUN phase II: magnetic octupole reflector



PHYSICAL REVIEW C 92, 015501 (2015)

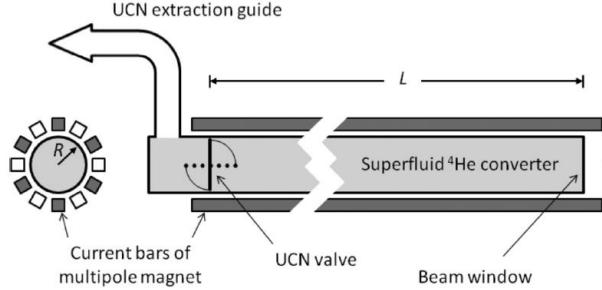


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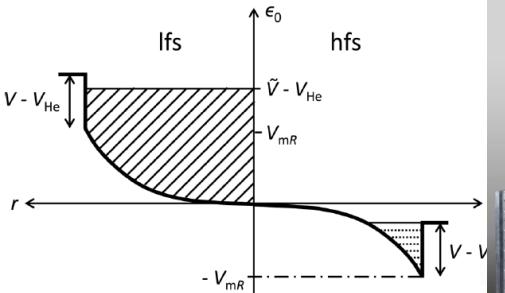


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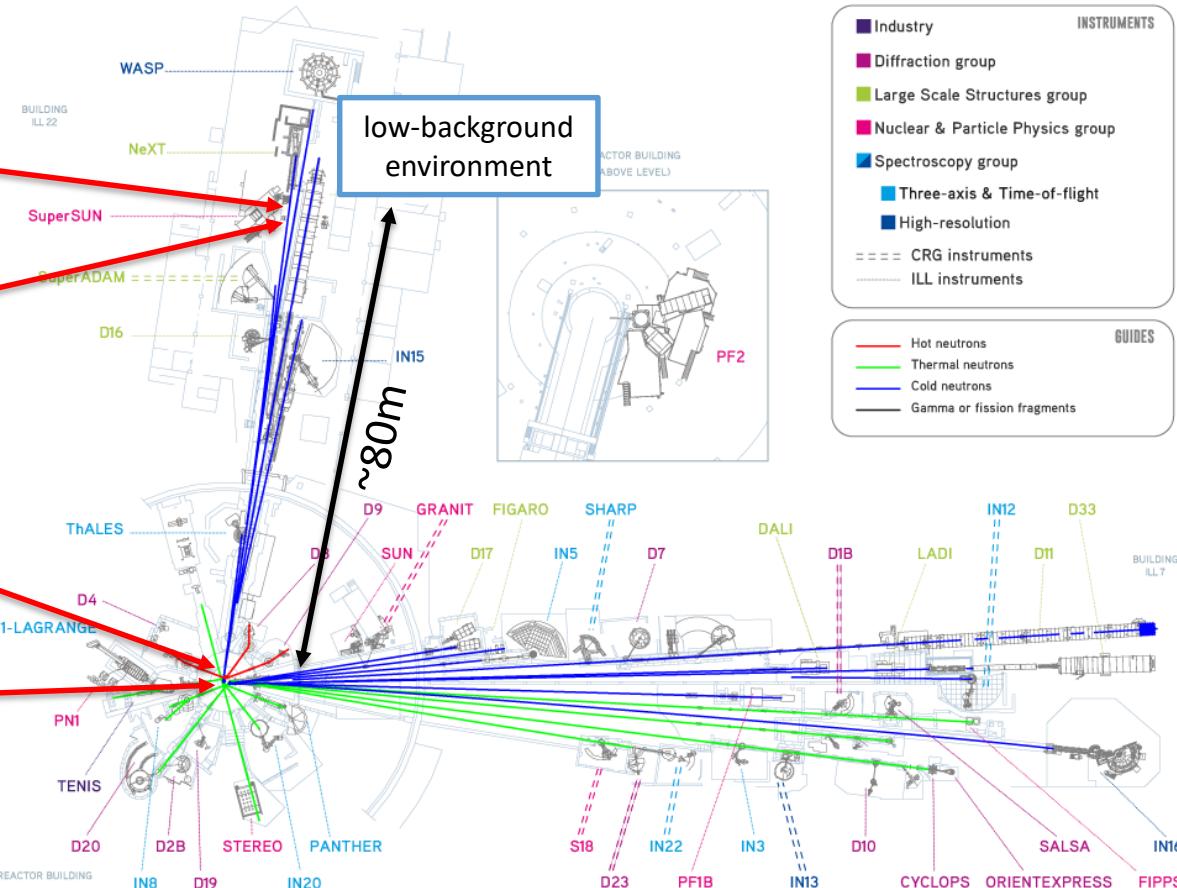
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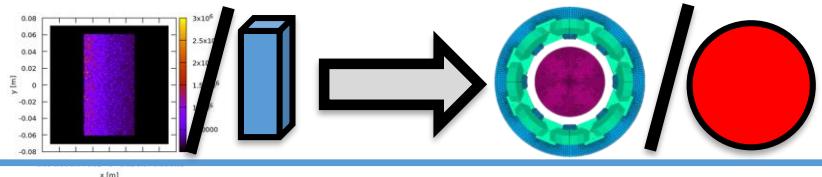
# Neutron delivery at the ILL

## In SuperSUN's converter vessel:

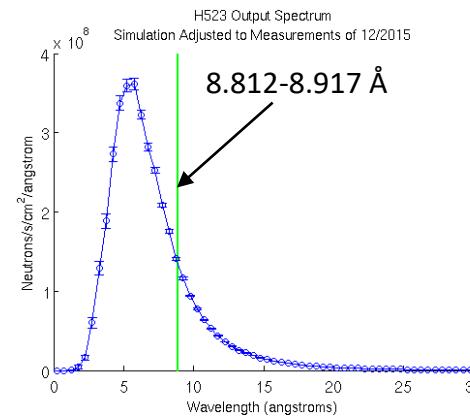
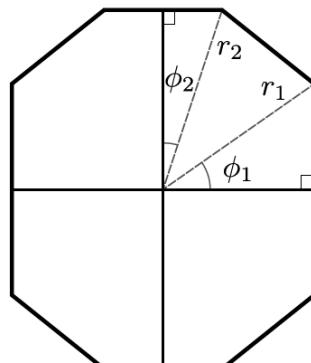
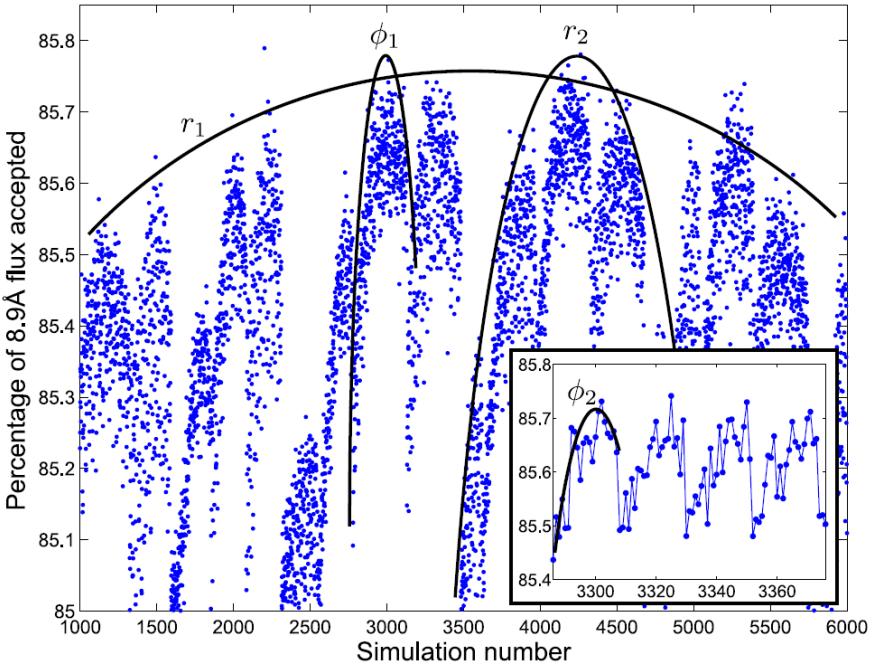
- $R \sim 15 \text{ UCN}/(\text{cm}^3 \text{ s})$



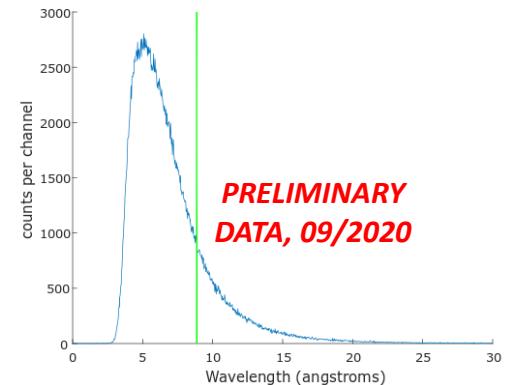
# SuperSUN Cold Neutron Guide:



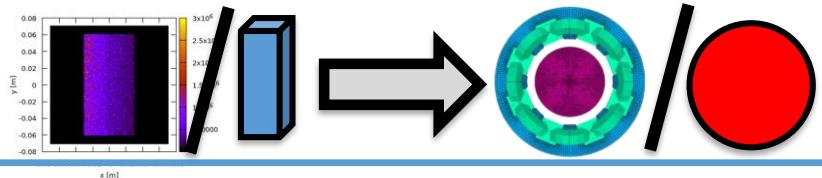
Each point:  $10^7$  particles / 5min



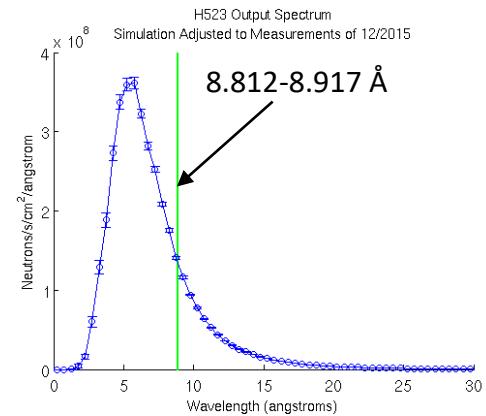
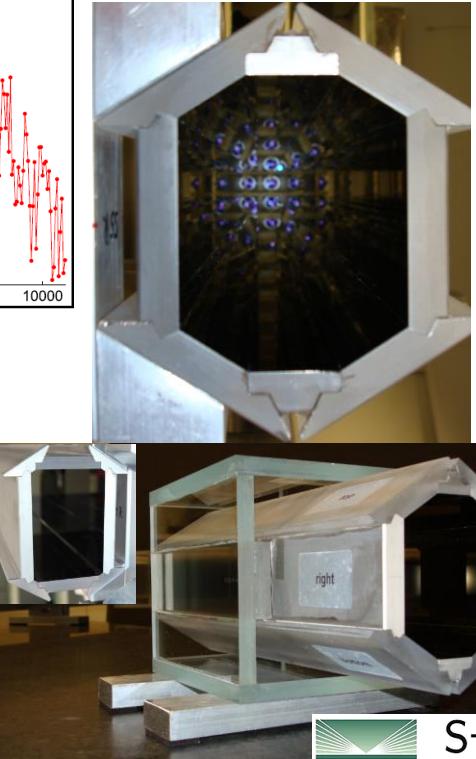
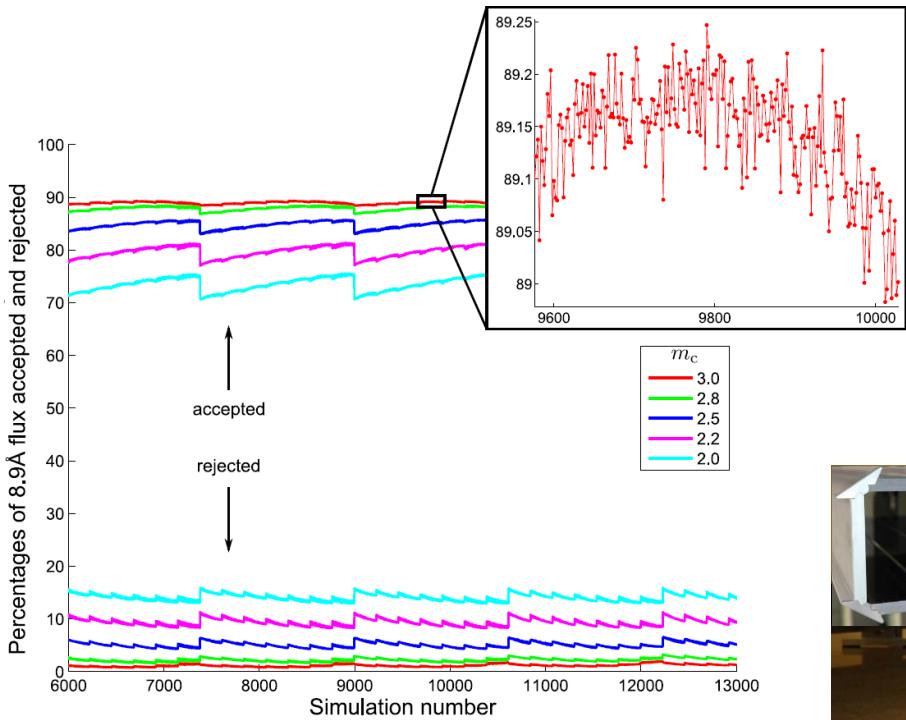
Capture-weighted flux (03/2020):  
 $2 \times 10^{10} \text{ n}/(\text{cm}^2 \text{ s})$



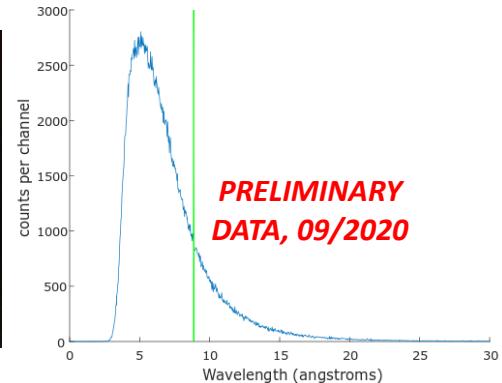
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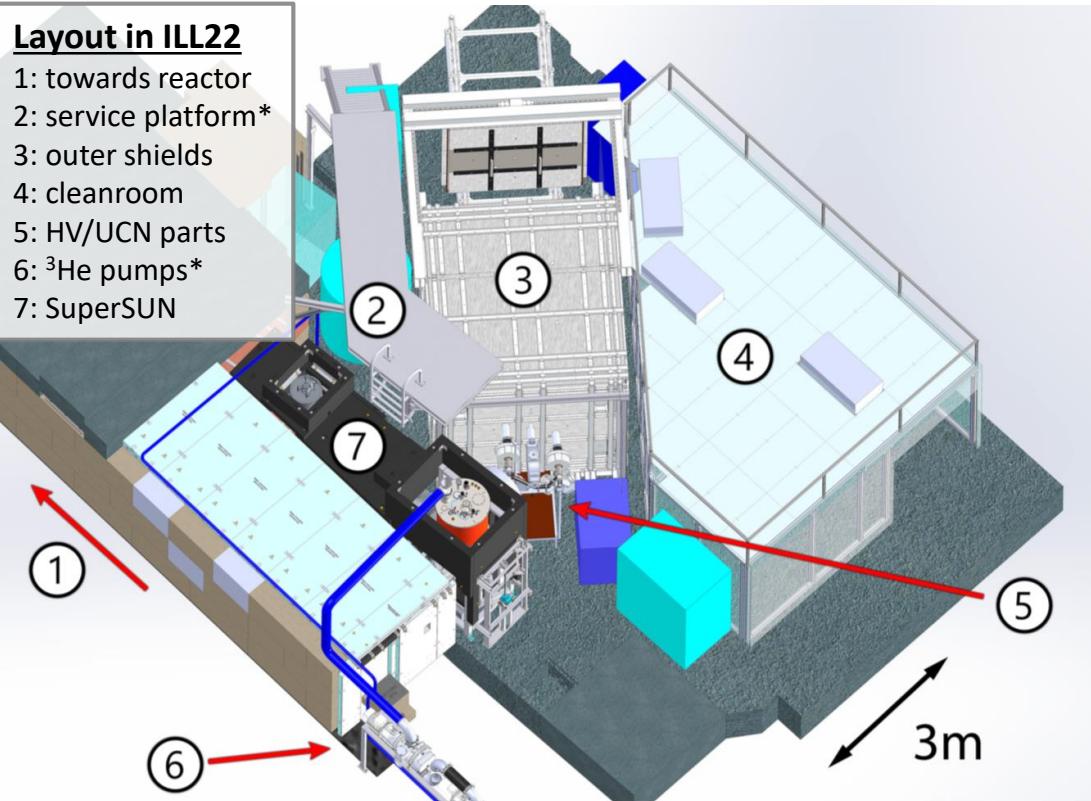
Capture-weighted flux (03/2020):  
 $2 \times 10^{10} \text{ n}/(\text{cm}^2 \text{ s})$



# Experimental Zone, Major Elements

## Layout in ILL22

- 1: towards reactor
- 2: service platform\*
- 3: outer shields
- 4: cleanroom
- 5: HV/UCN parts
- 6:  $^3\text{He}$  pumps\*
- 7: SuperSUN



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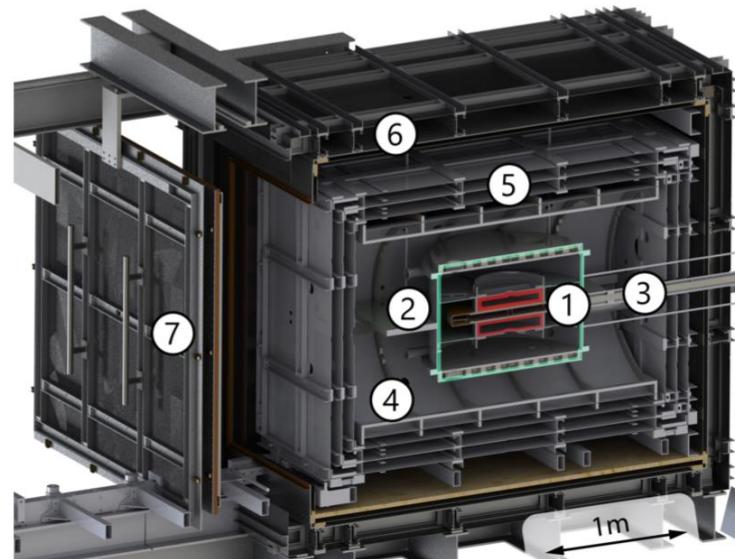
Skyler Degenkolb, for PanEDM

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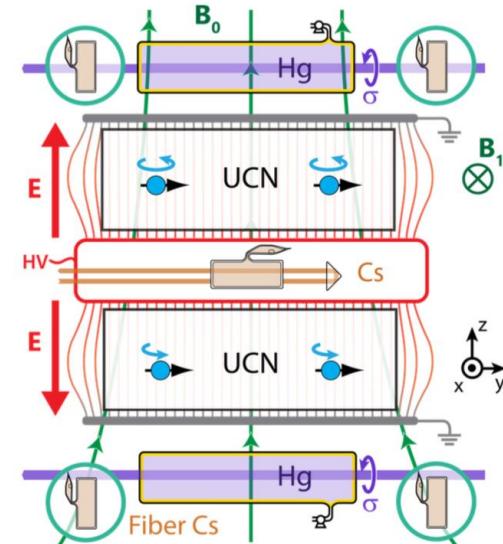
NEUTRONS  
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## PanEDM Magnetic and RF Shielding

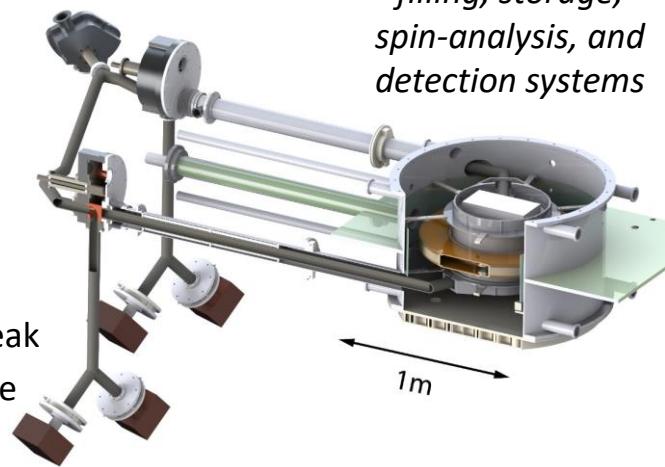
- 1: UCN cells
- 2: vacuum chamber
- 3: HV insertion
- 4: cylindrical shield
- 5: inner shields (3)
- 6: outer MSR (2+1)
- 7: MSR door



# Key Components



- Two chambers, at room temperature
- $^{199}\text{Hg}$  magnetometers with few-fT resolution
- Cs magnetometers (also at HV)
- Magnetic shield (SF:  $6 \times 10^6$  at 1 mHz)
- Simultaneous spin detection
- SuperSUN UCN source at ILL, in 2 phases:
  - Phase I: unpolarized UCN with 80 neV peak
  - Phase II: polarized UCN, magnetic storage
- Ongoing installation/commissioning



$^3\text{He}/^4\text{He Heat exchanger}$

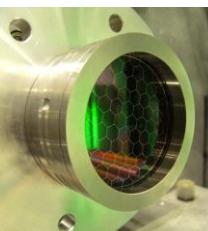
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$m=4$  "replica"



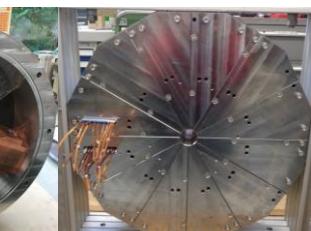
PP foil



3-way switch



$\text{H}_2\text{O}-\text{cooled polarizer}$



vacuum chamber



"Suniño" test vessel



# Schedule and Sensitivity Estimate

Statistical sensitivity:

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

extraction losses...

## Systematic effects: magnetic field, soft spectrum

Nondynamical phases (field control, spectrum)  
No comagnetometer (phase I; magnetic stability)  
Gradiometer stack + Cs sensor(s) in HV electrode  
Optically decoupled leakage current monitor  
On-site magnetic screening

## Phase II: superconducting octupole trap

Lower source losses, so higher UCN density  
UCN pre-polarized in the source

## Schedule:

Highly dependent on ILL cycle planning  
Try for first UCN in 2021  
Fortunately, we can do a lot in the meantime...

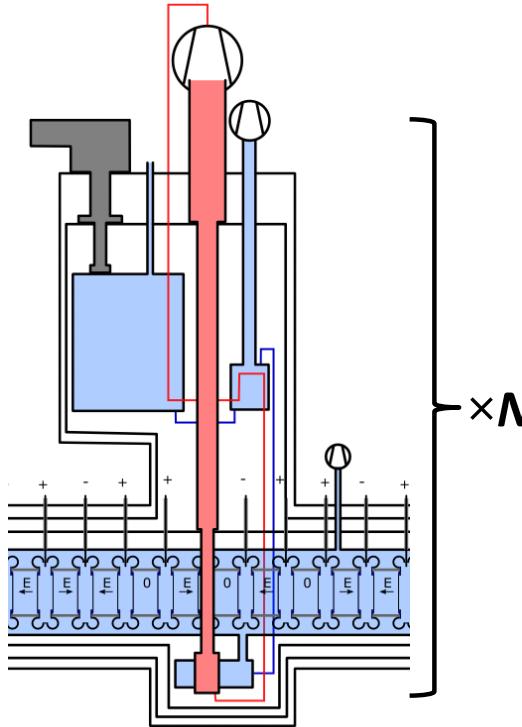
# Challenges in the Next Generation

How to get around the problems of production rate and loss rate?

- Statistical limitations: low source **phase-space** density, inefficient transport
  - *In-situ* experiments are challenging → why?
- Systematic limitations: imperfect knowledge/control of experimental conditions
  - Can source and spectrometer use the same prototypes?
  - Can we avoid some challenges already faced by others who tried this?
- Thought experiment: what is the ultimate limit within existing means?

# Where has there already been progress?

## Cryogenics (SuperSUN, SNS)

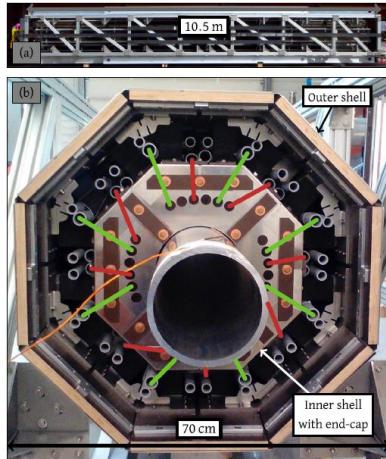


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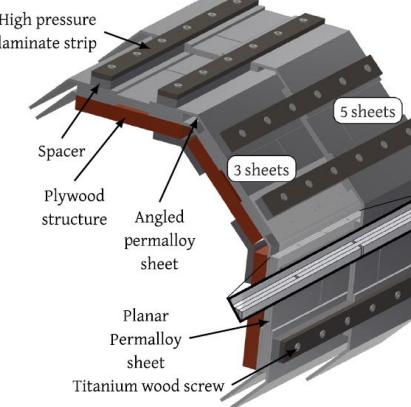
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## Magnetic Shielding (pEDM and AMO)

see e.g., *Rev. Sci. Instrum.* 91, 035117 (2020)



notice we like octagons...



## HV (SNS, CryoEDM)

see Brad Filippone's talk, yesterday

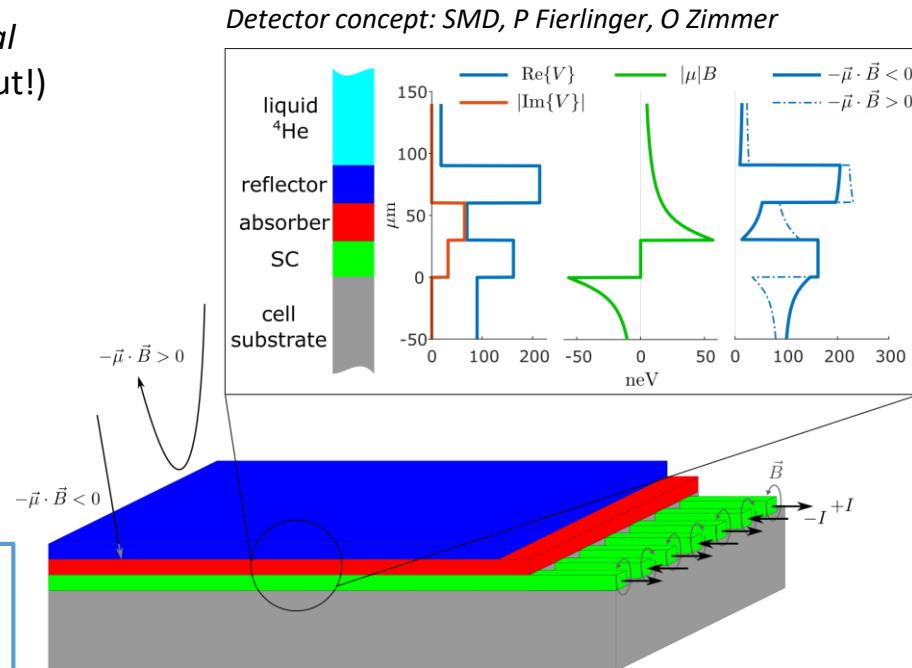


**Missing: in-situ polarization, detection, analysis**

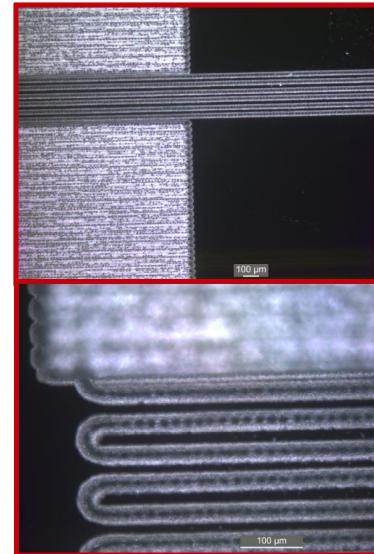
# New Detection Methods (*in-situ*)

- UCN get many chances to be detected
- Meander field creates strong *local* gradient at wall surface (watch out!)
- Limitations:
  - Slowest UCN never penetrate
  - Fastest UCN always penetrate
  - Cell dimensions
  - Holding time
  - Readout efficiency
- Remember the theme...

Central element:  
**in-situ, polarization sensitive**  
UCN detectors

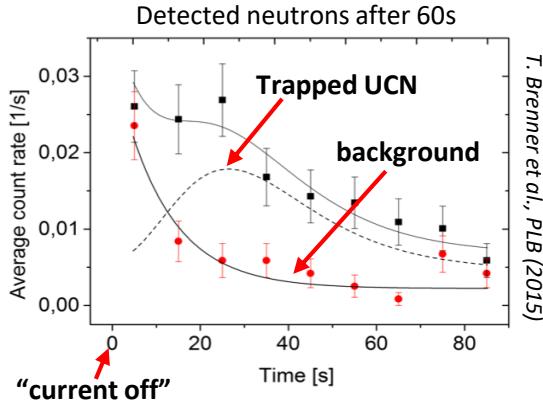


*Nb meanders on Si wafers:*  
R Gernhäuser, S Winkler

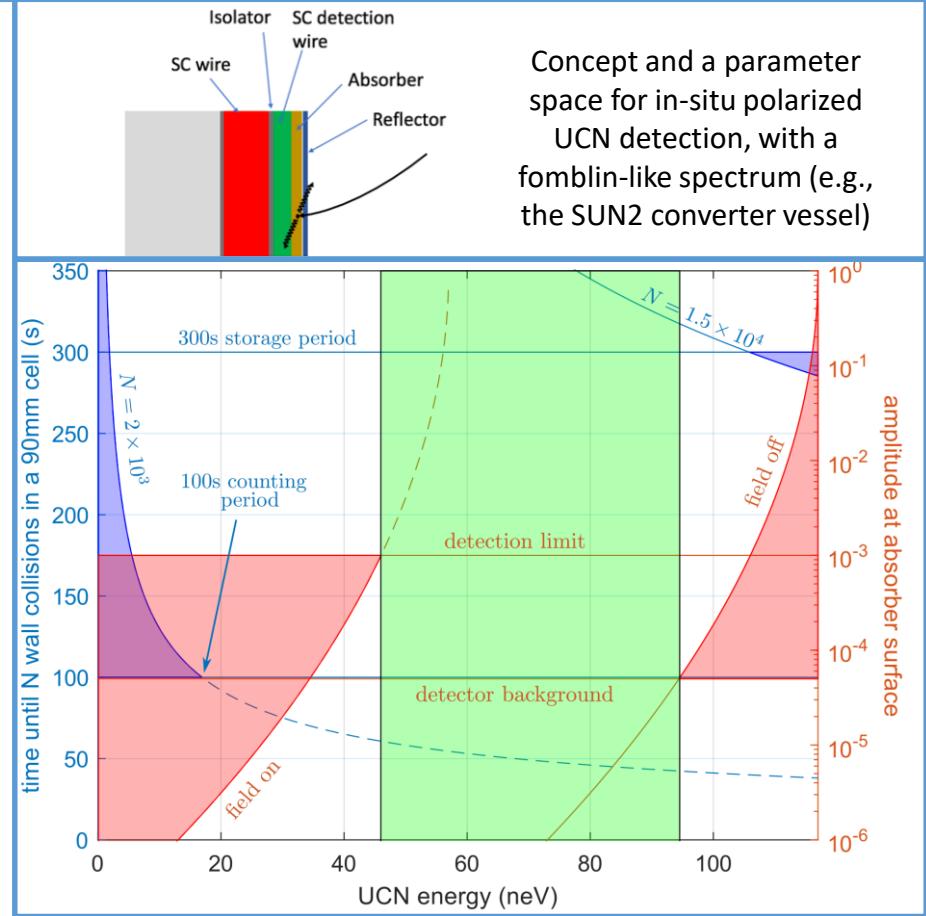


# Further Detector Development

- CB-KID preferred to TES ( $T < T_c$  raises  $J_c$ )
- Testable in small/scalable experiments
  - First: simple cryo environment (dry)
  - Next:  $\sim 1\text{K}$  by pumping on LHe
  - Later:  $T < 1\text{K}$  w/  $^3\text{He}$  or dilution fridge
  - Develop robust cells before scaling up
- Systematically test new materials (cf. Suniño)



Inspiration:  
Trapping/detection  
of high-field-seekers  
...at PF2/TES (flux source)



# Ultimate Reach

## Main chances for meaningful improvements:

- Density (via extraction/transfer loss)
  - Requires in-situ polarization, analysis, detection
  - Watch out for systematics...
- Full use of cold neutron beam
  - Also brighter beams, new moderators\*
- Electric field (limited)
- Storage time (limited\*)
  - Also leads to some gain in density, via accumulation
- Systematics
- Total measurement time...

	Full Version	Small Scale
E	8.5 MV/m	7 MV/m
T	300s	250s
UCN/cc	1000	55
UCN/cell pair	$4.4 \times 10^6$	$6 \times 10^4$
N(T)/cell pair	$1.6 \times 10^6$	$2 \times 10^4$
M (per day)	$170 \times 144 = 24480$	1440 (10 cells)
$\alpha$	0.85	0.85
$\sigma_d$ (95% CL)	$2.1 \times 10^{-29} e \text{ cm}$	$7 \times 10^{-27} e \text{ cm}$

## Special thanks to:

P Fierlinger  
H Filter  
D Wurm

O Zimmer  
X Tonon  
M Kreuz

D Beck  
T Neulinger  
??? (Post-Doc)

R Gernhäuser  
S Winkler  
R Georgii

M Thomas  
Elytt Energy  
S-DH, GmbH



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# Modified targets for 2020 & 2021

Reference reactor schedule (dates are tentative)

