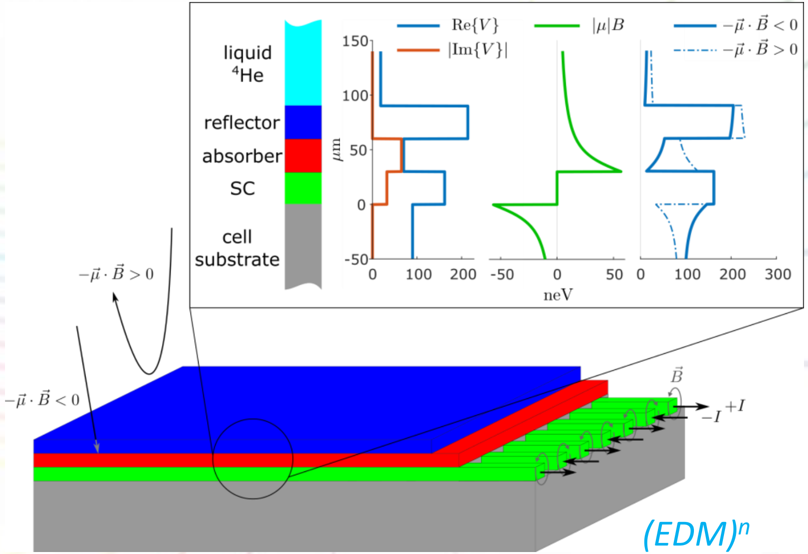
New platforms for ultracold neutron production: SuperSUN and beyond

SuperSUN



(EDM)^n

Skyler Degenkolb, Institut Laue-Langevin

Neutron delivery at the ILL

<u>In SuperSUN's converter vessel:</u>

- $R \sim 15$ UCN/(cm^3 s) expected

<u>End of guide H523:</u>

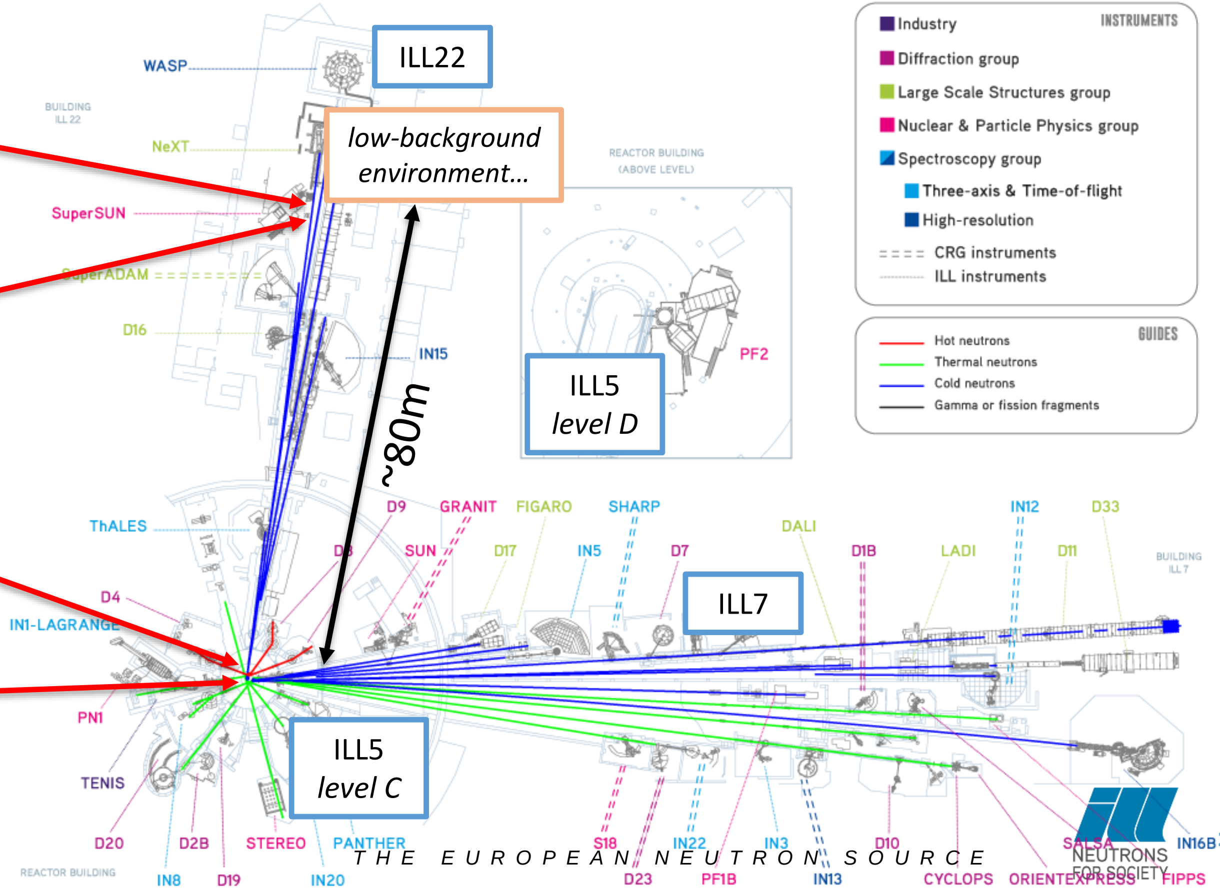
- $\Phi \sim 2\times10^{10}$ n/(cm^2 s)

<u>Horizontal Cold Source:</u>

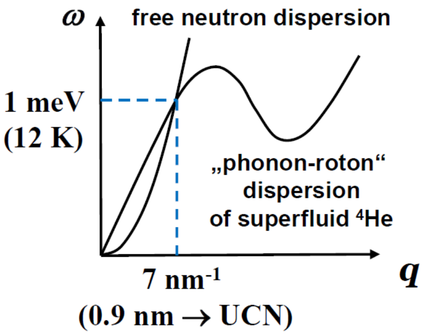
- $\Phi \sim 10^{14}$ n/(cm^2 s)

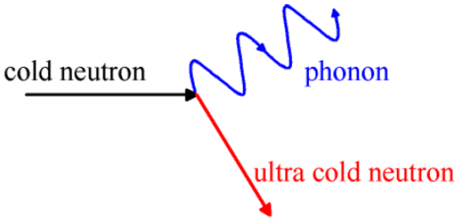
<u>In pile:</u>

- $\Phi \sim 1.5\times10^{15}$ n/(cm^2 s)



“Ultracold” and “Superthermal”





$$\tau_{\rm up}^{-1} \sim \frac{(T[K])^7}{100\ {\rm s}}$$

Velocity	“Temperature”	Energy
$10^0 - 10^1$ m/s	Ultracold	5 neV – 500 neV
$10^1 - 10^2$ m/s	Very cold	0.5 μeV – 50 μeV
$10^2 - 10^3$ m/s	Cold	50 μeV – 5 meV
2.2×10^3 m/s	Thermal	25 meV
$2\times10^3 - 2\times10^4$ m/s	Hot	20 meV – 2 eV

“Conversion” in Superfluid ^{4}He

- -phase space compression
- -requires dissipative physics
- -flux vs. density (beam vs. storage)
  - *-important for next generation*

Production rate density, and storage losses

5-15 /(cm³ s) ⟵ $$R \sim \left(\frac{5\times10^{-8}}{{\rm cm}^3\ {\rm s}}\right) \times \left.\frac{d\Phi}{d\lambda}\right|_{8.9\text{Å}} \times \left(\frac{V_{\rm trap}}{233\ {\rm neV}}\right)^{\frac{3}{2}}$$

limited by decay, wall interactions ⟵ $$\frac{1}{\tau} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\rm up}} + \frac{1}{\tau_{\rm capture}} + \frac{1}{\tau_{\rm wall}} + \cdots$$

UCN Storage (and nEDM)

Statistics

- Flux vs. *density*
  - want to count many UCN, after storage
  - transport losses and dilution
- Storage time (including T_1/T_2)
- Total measurement time/repetitions
  - duty factor vs. accumulation time
  - long-term stability becomes important
- Polarization (incl. analyzing power)
- Electric field

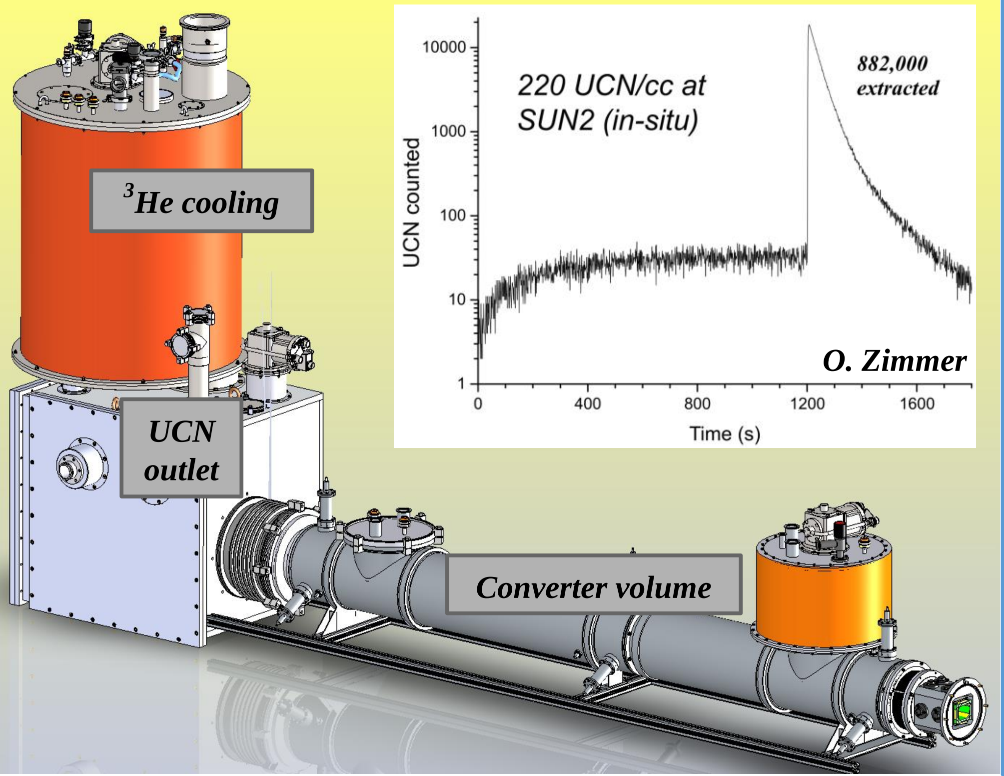
$$N_{\mathrm{cell}} \sim \rho_{\mathrm{cell}} V_{\mathrm{cell}} \sim \frac{\rho_{\mathrm{source}} V_{\mathrm{cell}}}{1 + \frac{V_{\mathrm{cell}} + V_{\mathrm{guide}}}{V_{\mathrm{source}}}}$$

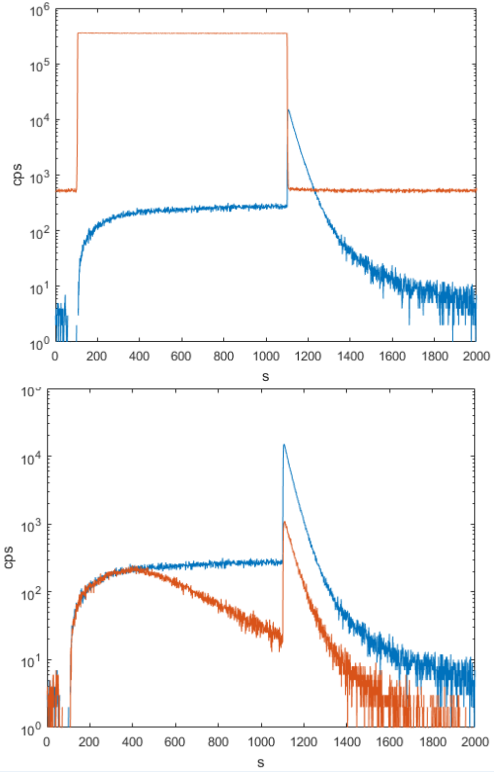
$$\frac{1}{\tau} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\mathrm{up}}} + \frac{1}{\tau_{\mathrm{capture}}} + \frac{1}{\tau_{\mathrm{wall}}} + \cdots$$

Systematics (not exhaustive)

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

Superthermal (He-II) UCN Sources





High-density sources

(high-flux: more common)

-phase space density
-beam current

Two basic issues:

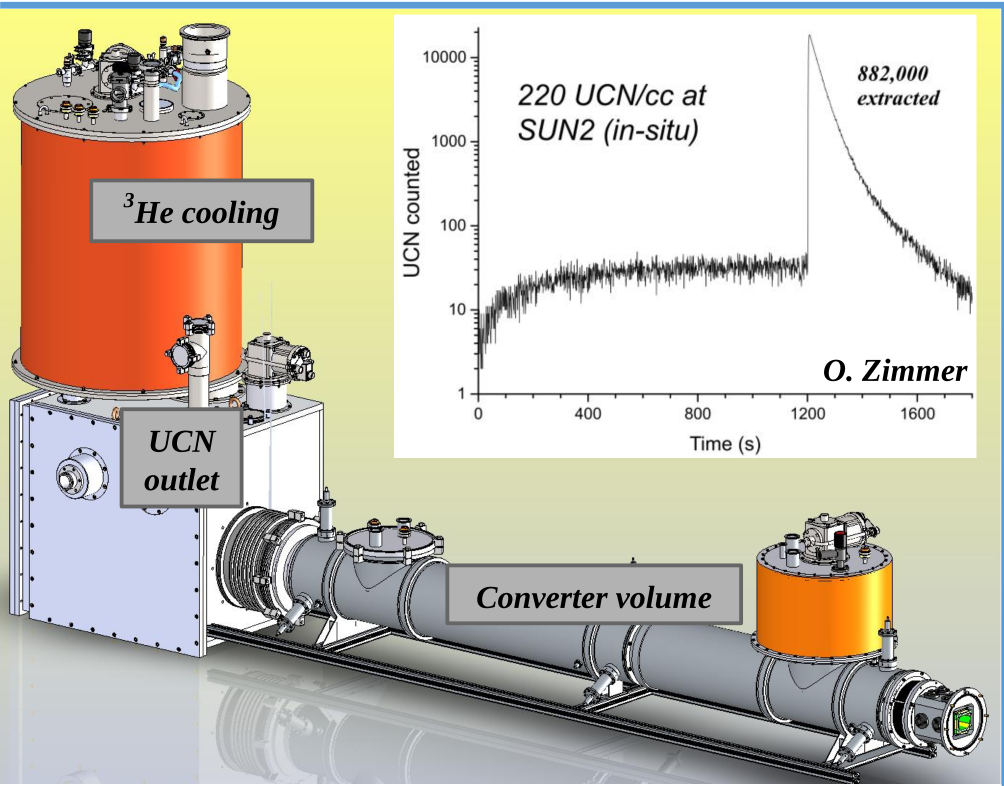
$$\rho_{UCN} = P\tau$$

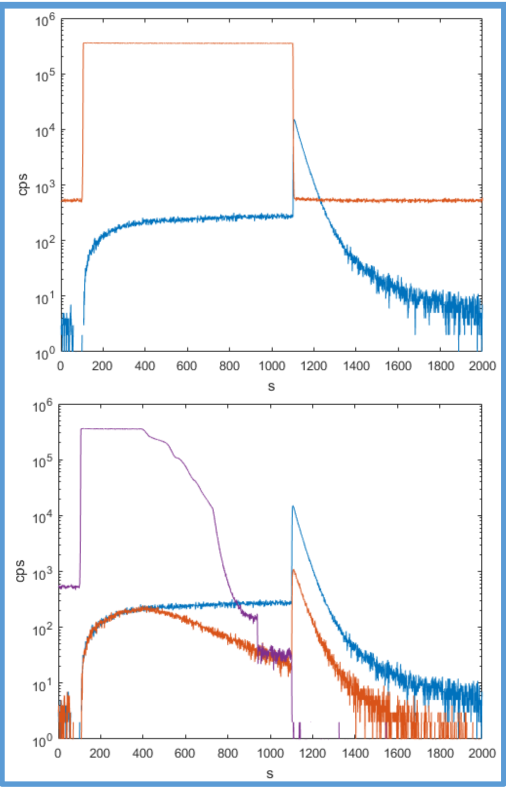
-production rate
-UCN loss

We might improve:

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

Superthermal (He-II) UCN Sources





Characteristic output:

$\lambda \sim 900$ Å

$(v \sim 4$ m/s$)$

$\rho \sim 2$ cm^{-3}

$(\sim 1\times10^{-10}\ \rho_{rest\text{-}gas})$

$\Phi \sim 500$ n/s/cm^2

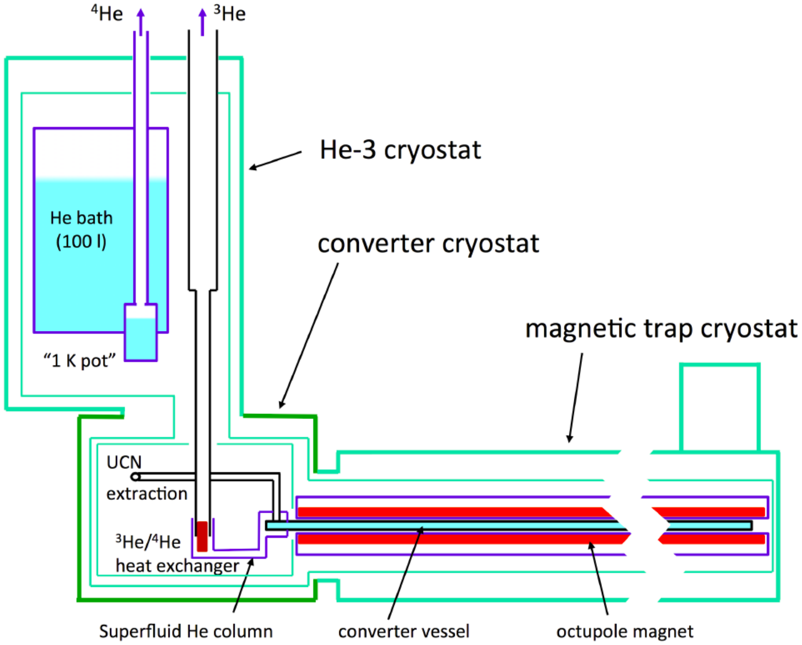
$(\sim 3\times10^{-13}\ \Phi_{pool})$

$\rho_{phase\text{-}space} < 10^{-13}$

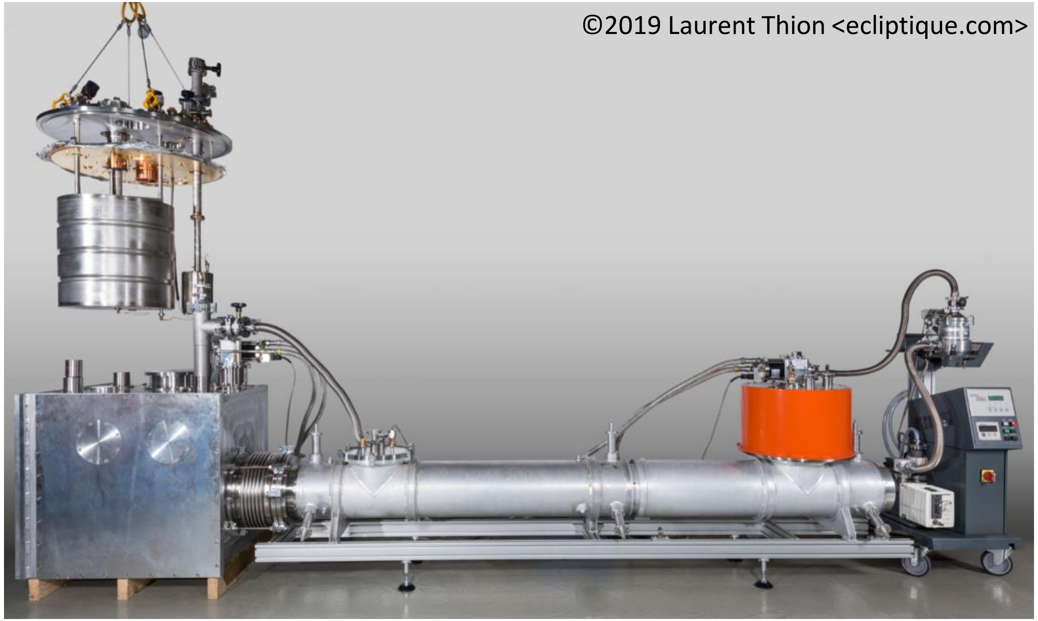
$\sim (900\ \text{Å})^3(220\ \text{cm}^{-3})$

SuperSUN (in two phases)

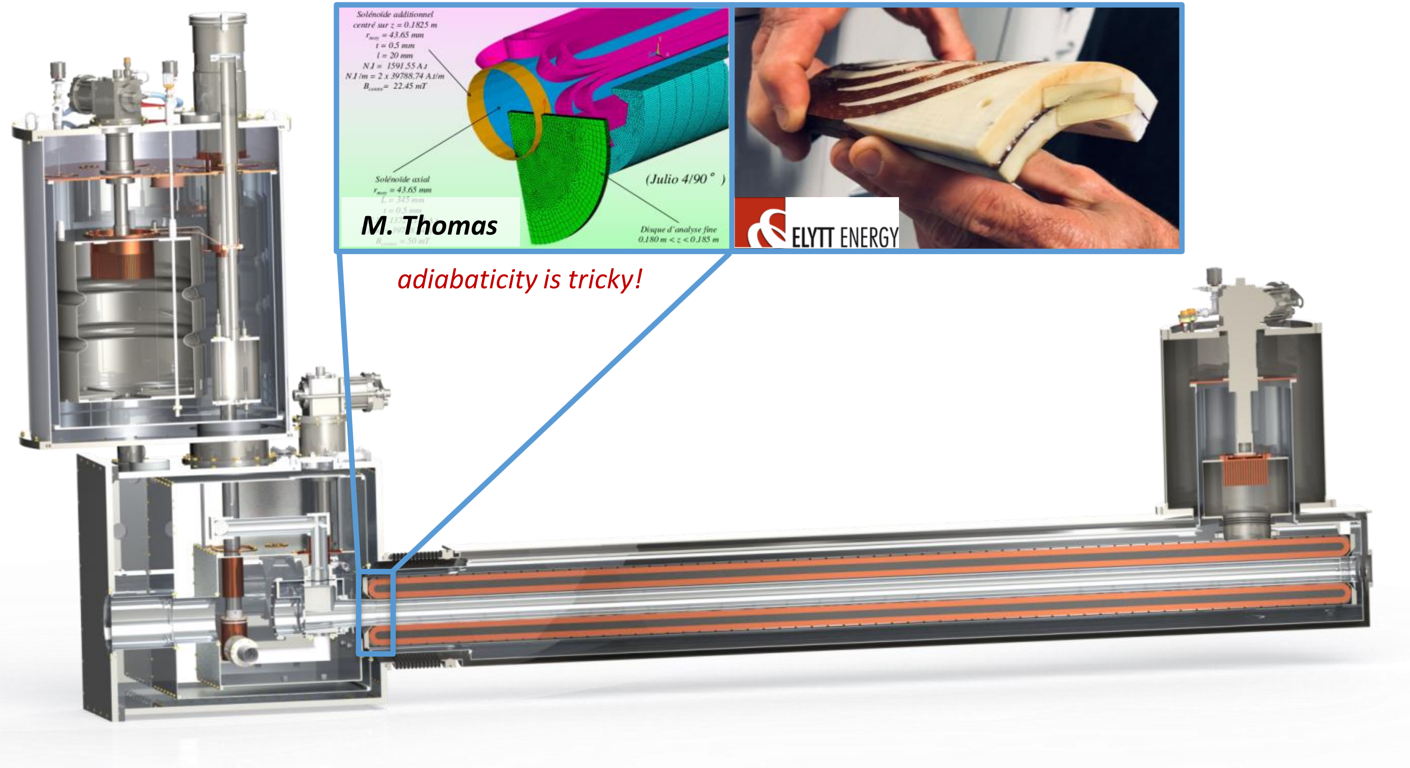
Cryogenic concept:



Present status:

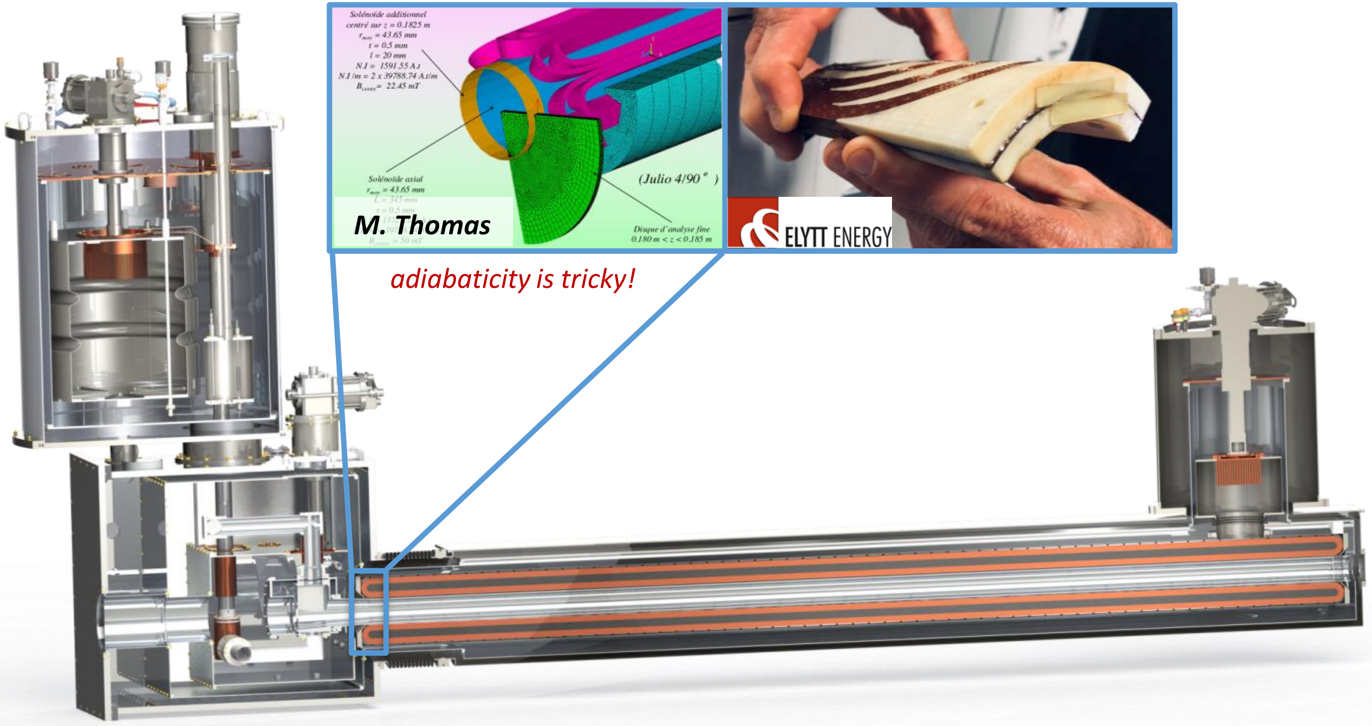


Magnet and Accumulation Vessel



cold neutrons in

Magnet and Accumulation Vessel



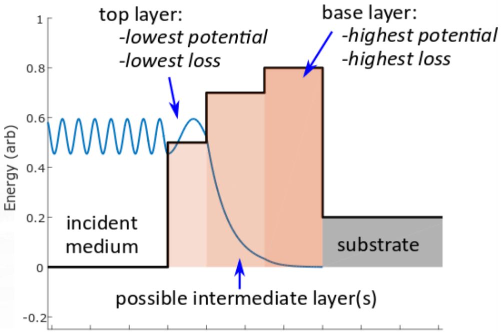
M. Thomas

ELYTT ENERGY

adiabaticity is tricky!

"Suniño" test vessel

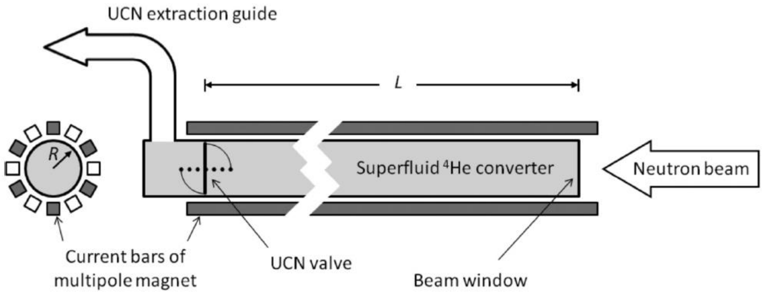
J. Hingerl, MSc.

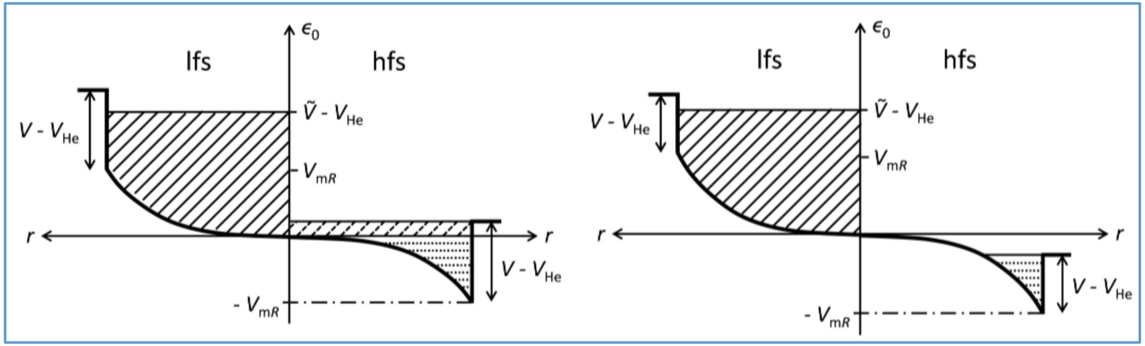


Optimizing Coatings and Vessels

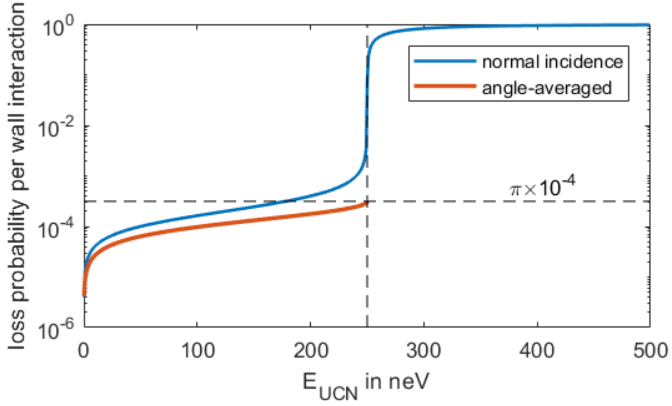
SuperSUN phase II: magnetic octupole reflector

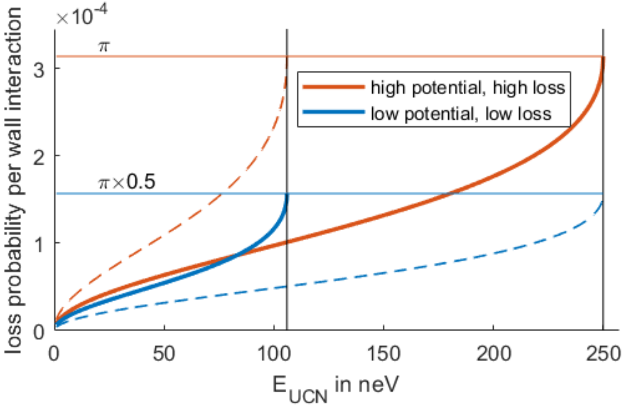
PHYSICAL REVIEW C **92**, 015501 (2015)



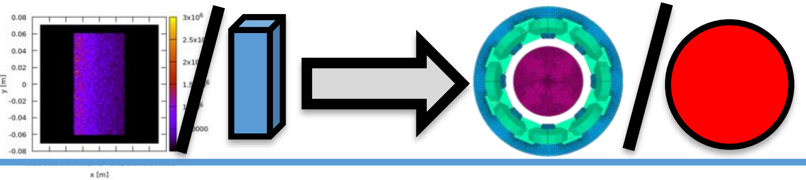


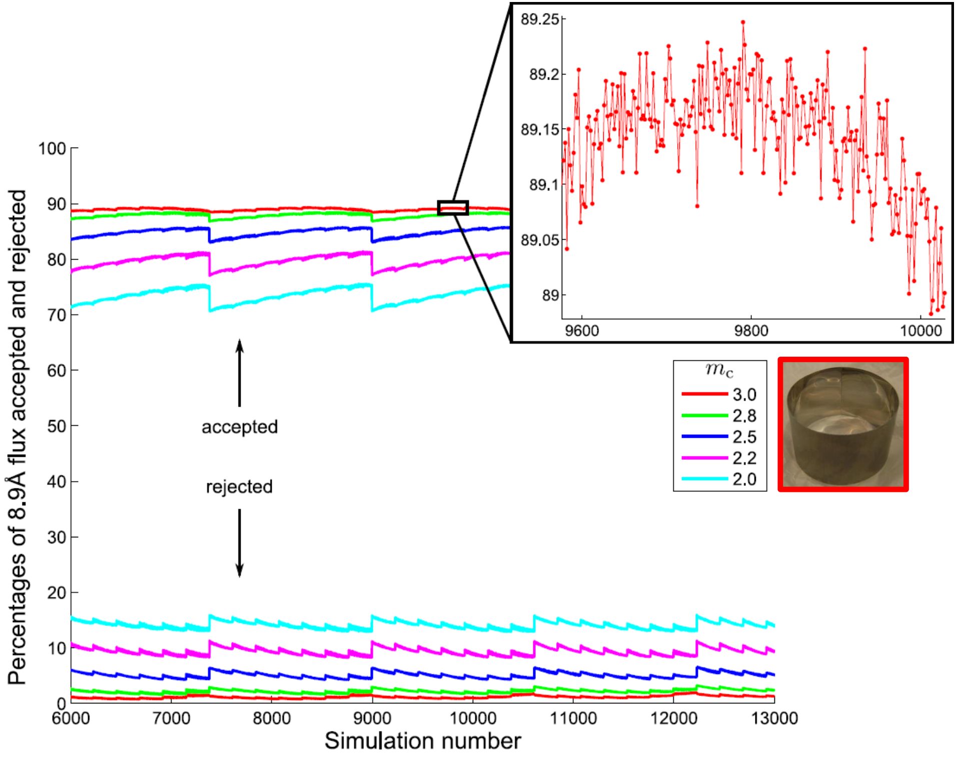
Material wall potentials

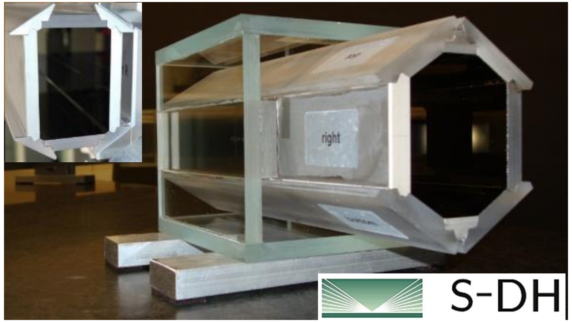




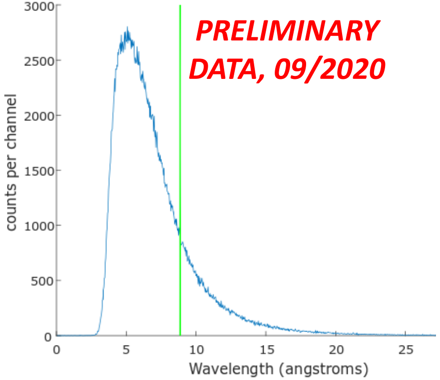
SuperSUN Cold Neutron Guides:

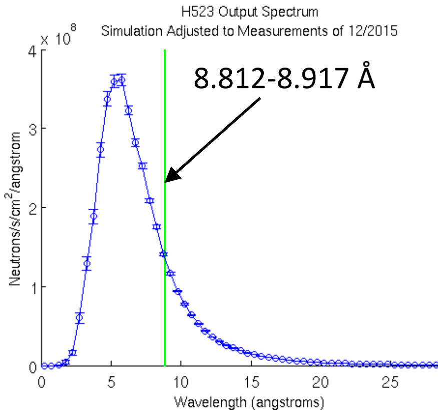




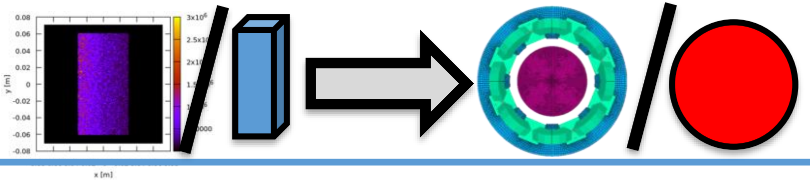


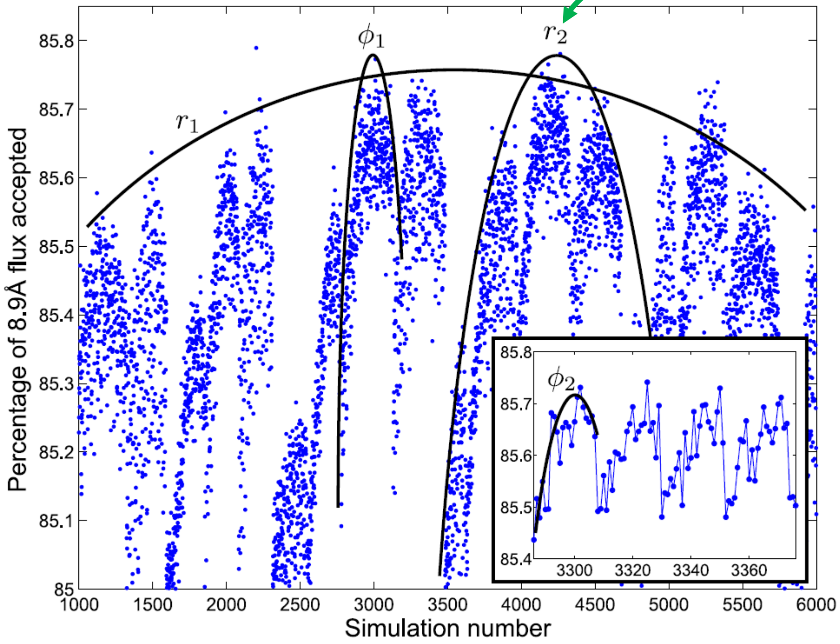
Capture-weighted flux (03/2020): 2×10^{10} n/(cm^2 s)

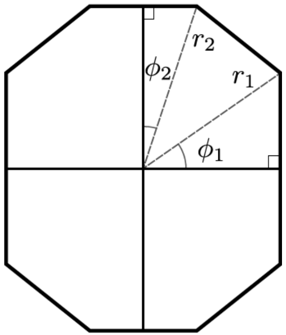


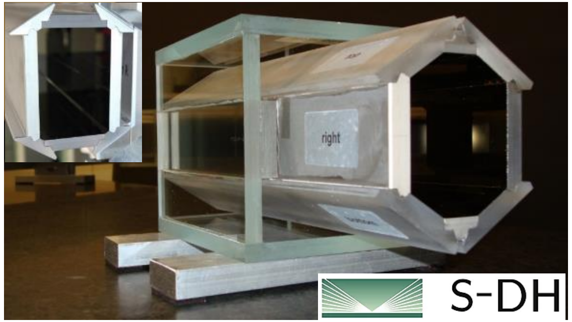


SuperSUN Cold Neutron Guides:









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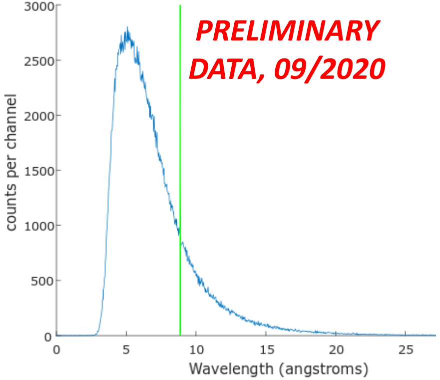
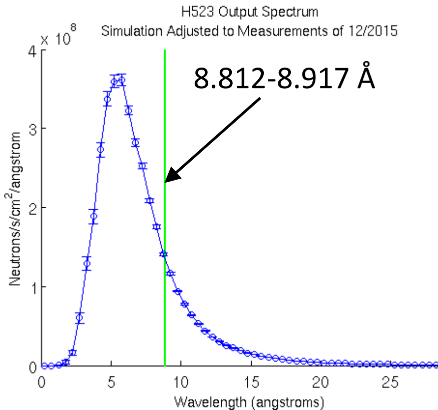
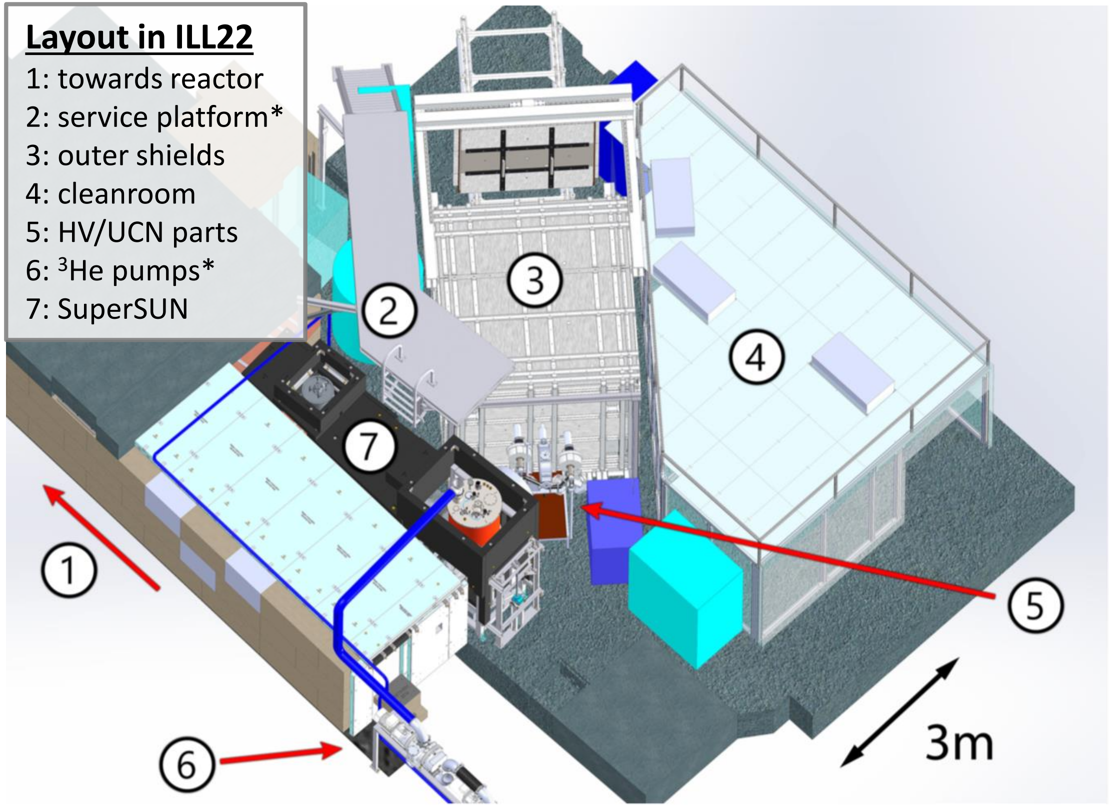


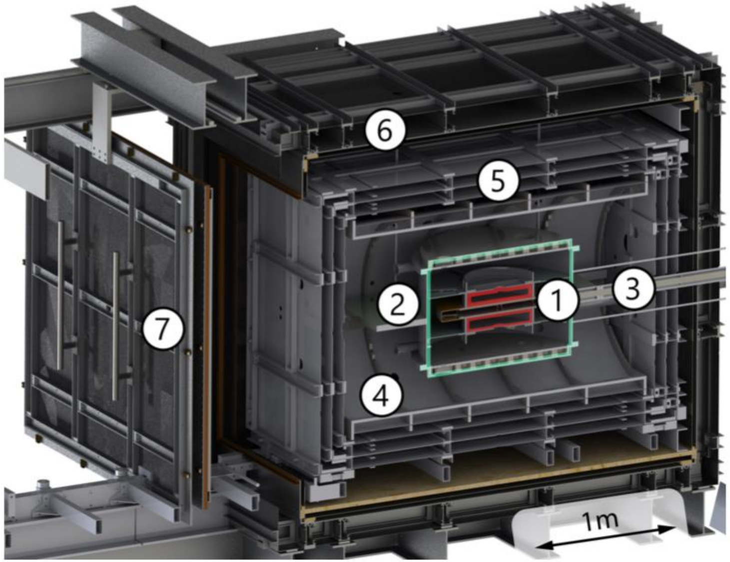


Experimental Zone, PanEDM

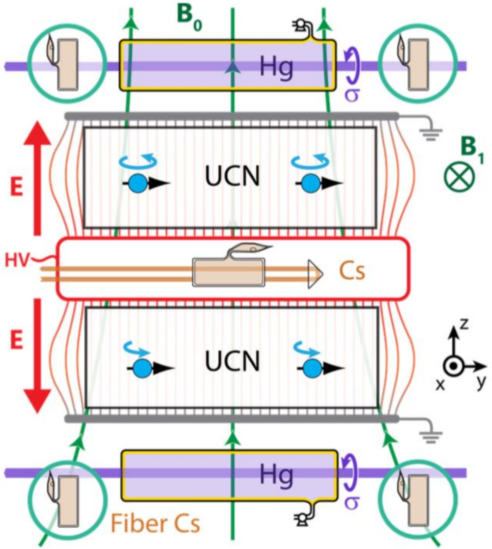
Layout in ILL22
1: towards reactor
2: service platform*
3: outer shields
4: cleanroom
5: HV/UCN parts
6: ^{3}He pumps*
7: SuperSUN



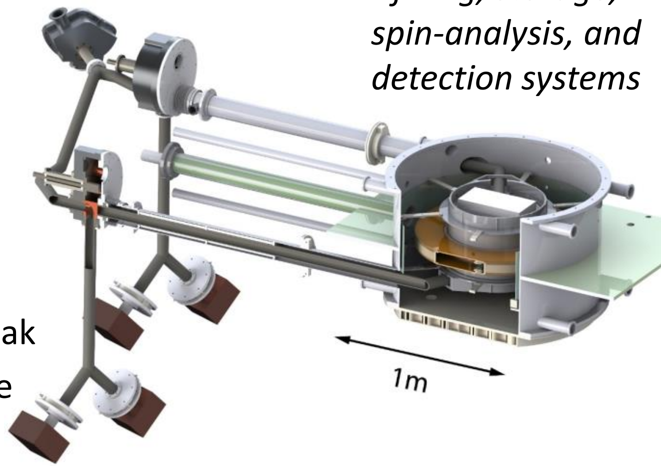
PanEDM Magnetic and RF Shielding
1: UCN cells
2: vacuum chamber
3: HV insertion
4: cylindrical shield
5: inner shields (3)
6: outer MSR (2+1)
7: MSR door



SuperSUN-PanEDM: Key Components



- Two chambers, at room temperature
- ^{199}Hg magnetometers with few-fT resolution
- Cs magnetometers (also at HV)
- Magnetic shield (SF: 6×10^6 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

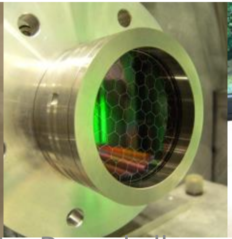


filling, storage, spin-analysis, and detection systems

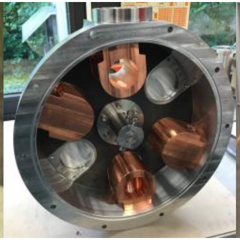
^{3}He/^{4}He Heat exchanger

m=4 "replica"

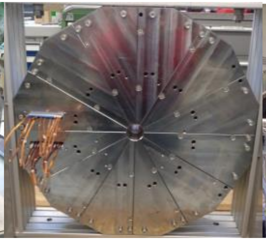
PP foil



3-way switch



H_2O-cooled polarizer



vacuum chamber

"Suniño" test vessel

Schedule and Sensitivity Estimate

Statistical sensitivity:

SuperSUN	Phase I
Saturated source density [cm^{-3}]	330
Diluted density [cm^{-3}]	63
Density in cells [cm^{-3}]	3.9
PanEDM Sensitivity [1σ, e cm]	
Per run	5.5×10^{-25}
Per day	3.8×10^{-26}
Per 100 days	3.8×10^{-27}

extraction losses…

More details, including phase II:

EPJ Web of Conferences **219**, 02006 (2019)
https://doi.org/10.1051/epjconf/201921902006

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…

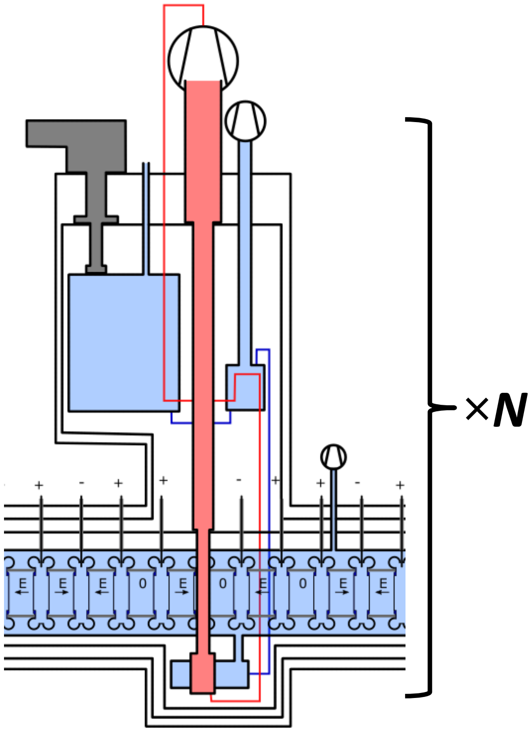
Challenges in the Next Generation

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?
  - **Modularity and Scalability**
- 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?

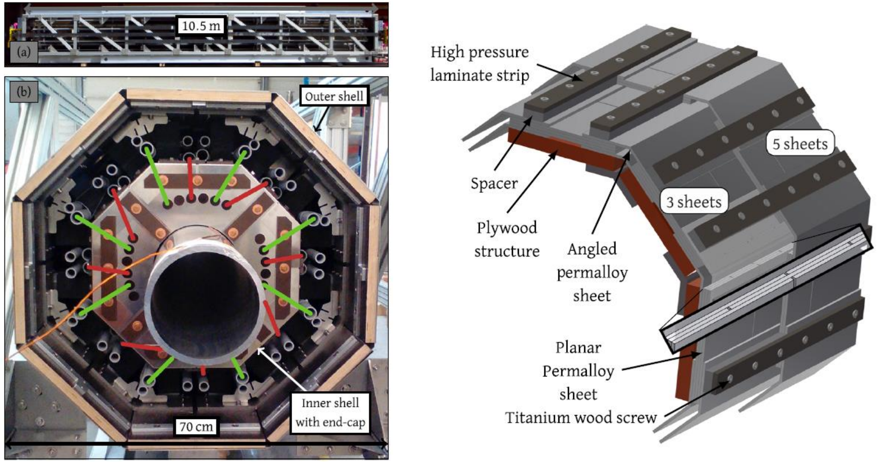
Where has there already been progress?

Cryogenics (SuperSUN, SNS)



Magnetic Shielding (pEDM and AMO)

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



notice we like octagons…

HV (SNS, CryoEDM)

Image: Brad Filippone

Missing: in-situ polarization, detection, analysis

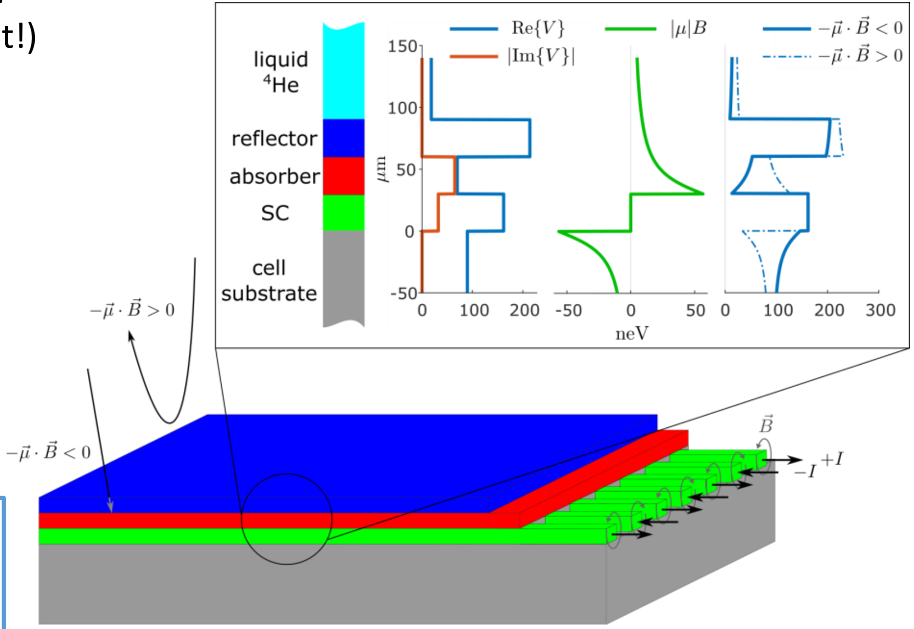
New Detection Methods (*in-situ*)

- Many chances for UCN 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

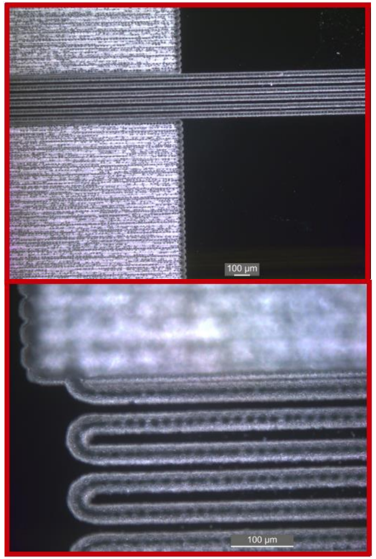
- Remember the themes…

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

Detector concept: SMD, P Fierlinger, O Zimmer



Nb meanders on Si wafers:
R Gernhäuser, S Winkler



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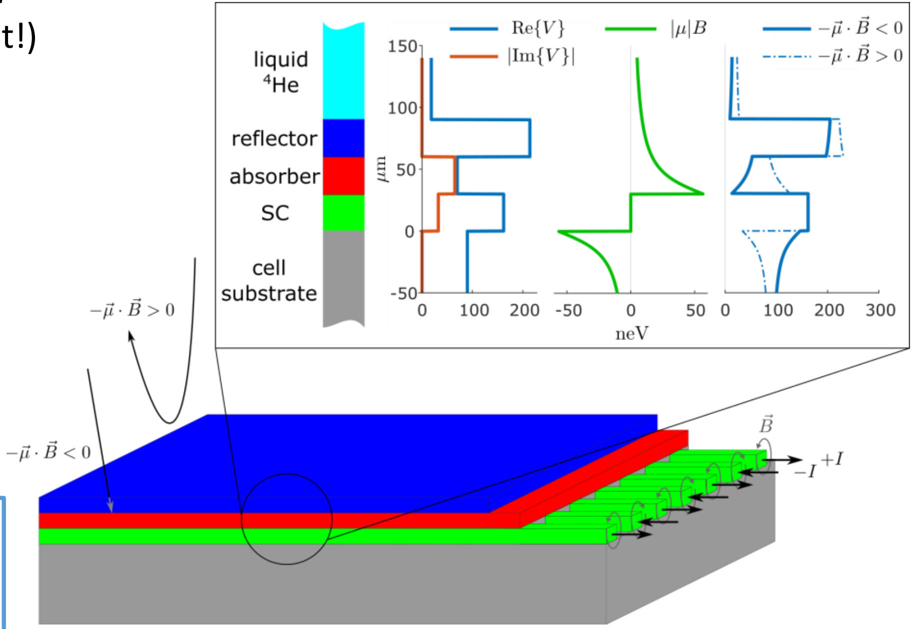

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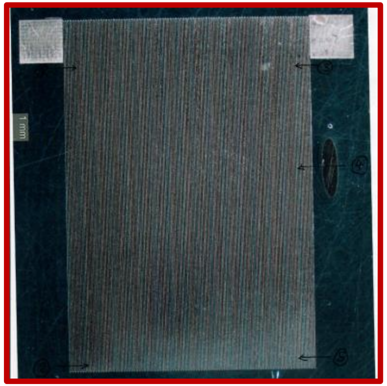
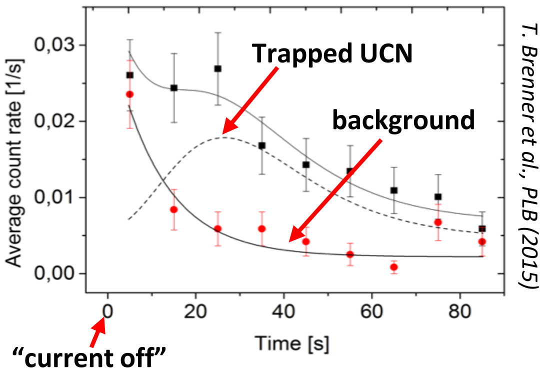


(EDM)^n: Further Detector Development

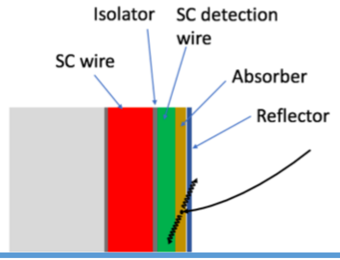
- CB-KID preferred to TES ($T<T_c$ raises J_c)
- Testable in small/scalable experiments
  - First: simple cryo environment (dry)
  - Next: ~1K by pumping on LHe
  - Later: T<1K w/ ^{3}He or dilution fridge
  - Develop robust cells before scaling up
- Systematically test new materials (cf. Suniño)

Detected neutrons after 60s

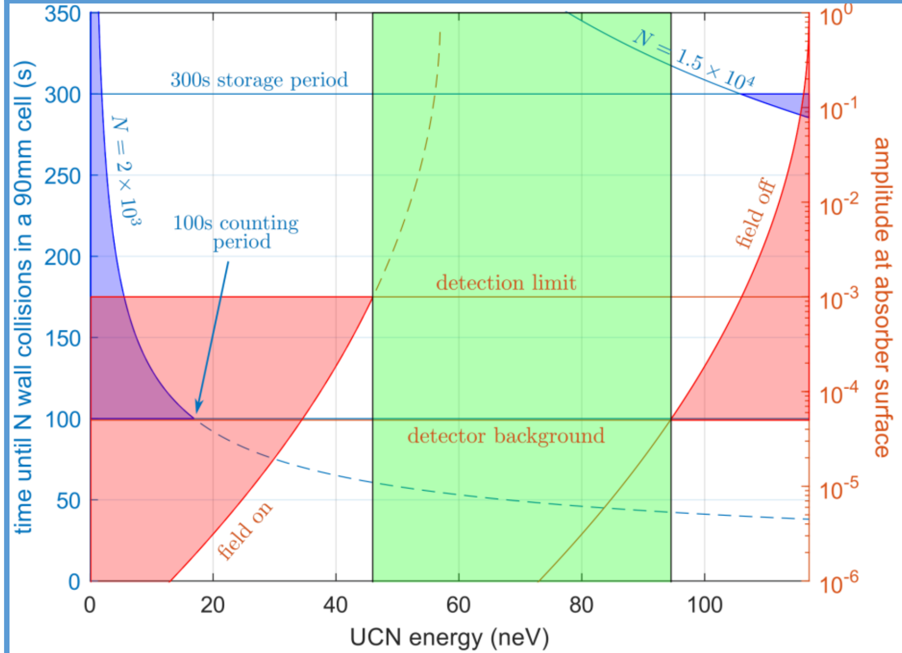


Inspiration:
Trapping/detection of high-field-seekers

…at PF2/TES (flux source)



Concept and a parameter space for in-situ polarized UCN detection, with a fomblin-like spectrum (e.g., the SUN2 converter vessel)



$(EDM)^n$: 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	4.4×10^6	6×10^4
N(T)/cell pair	1.6×10^6	2×10^4
M (per day)	170 × 144 = 24480	1440 (10 cells)
α	0.85	0.85
σ_d (95% CL)	2.1×10^{-29} *e* cm	7×10^{-27} *e* cm

Special thanks to:

P Fierlinger	O Zimmer	D Beck	R Gernhäuser	M Thomas
H Filter	X Tonon	T Neulinger	S Winkler	Elytt Energy
D Wurm	M Kreuz	??? (Post-Doc)	R Georgii	S-DH, GmbH

NEUTRONS FOR SOCIETY

INSTITUT LAUE LANGEVIN

Modified targets for 2020 & 2021

Reference reactor schedule (dates are tentative)

NEUTRONS FOR SOCIETY

The PanEDM Collaboration

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