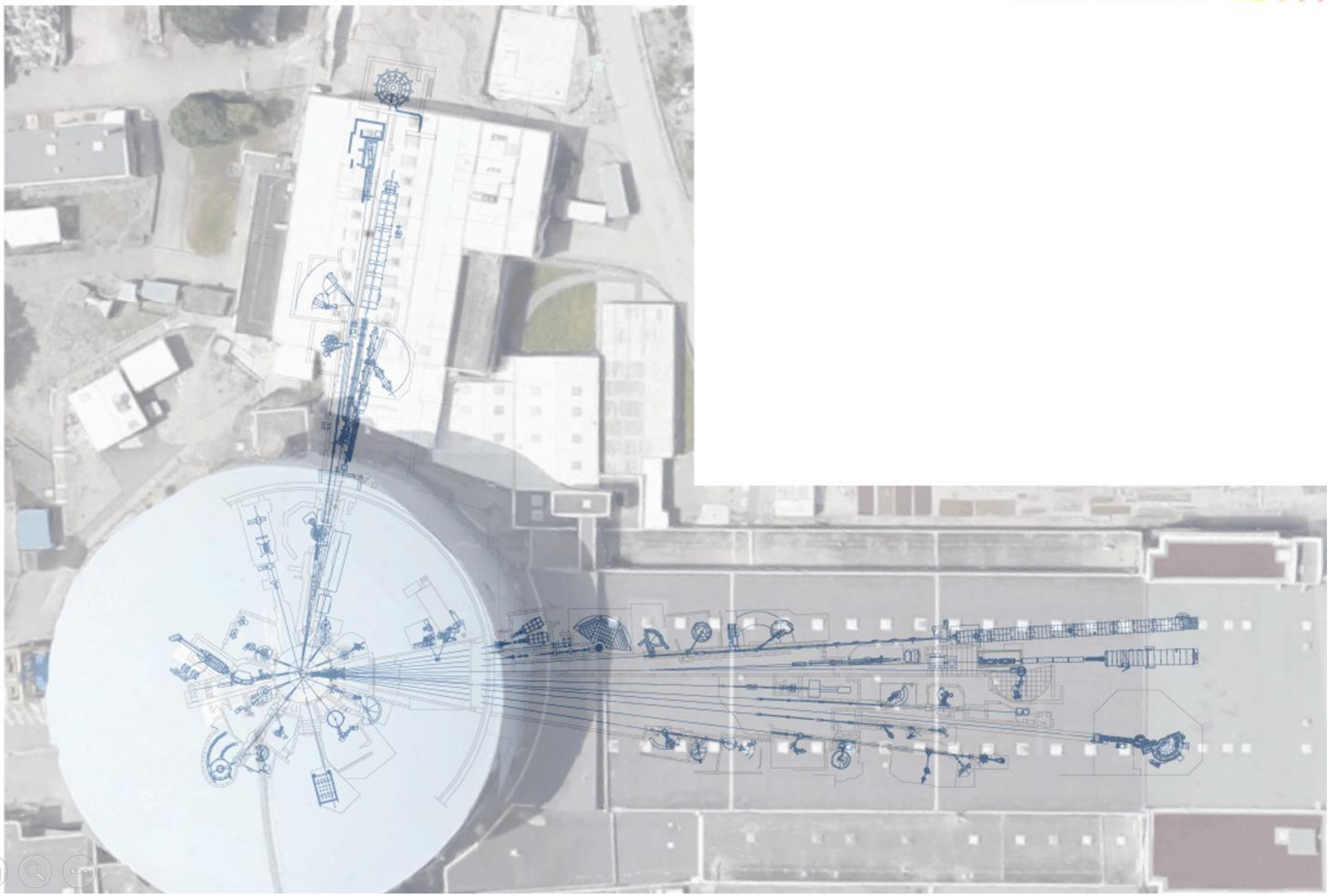
Overview of the PanEDM experiment at SuperSUN

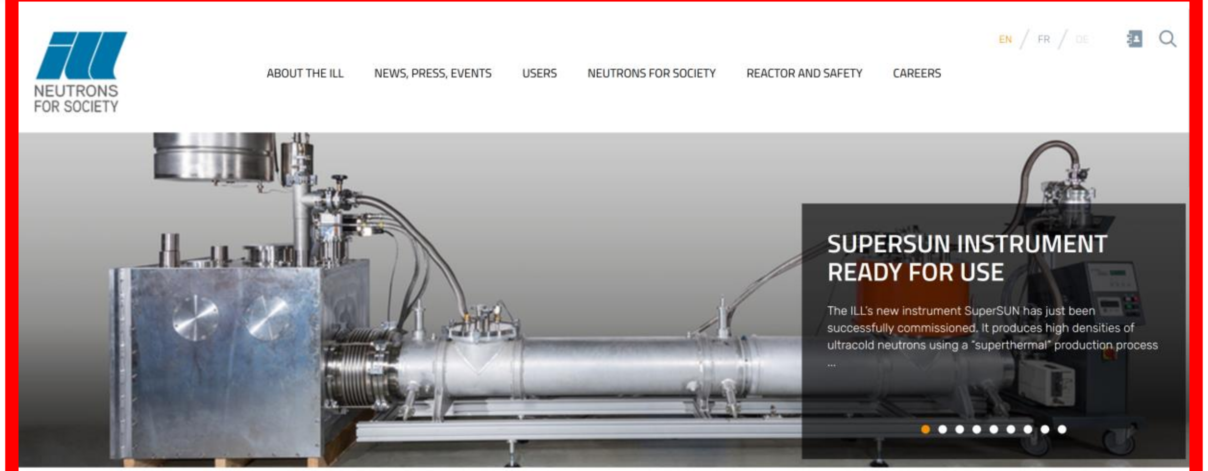
nEDM2023, Santa Fe
November 6, 2023

Skyler Degenkolb, Universität Heidelberg

Institut Laue-Langevin (ILL)



Institut Laue-Langevin (ILL)



→ See Estelle's talk, today at 17:05

Neutron Delivery to SuperSUN

In SuperSUN's converter vessel:

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

End of guide H523:

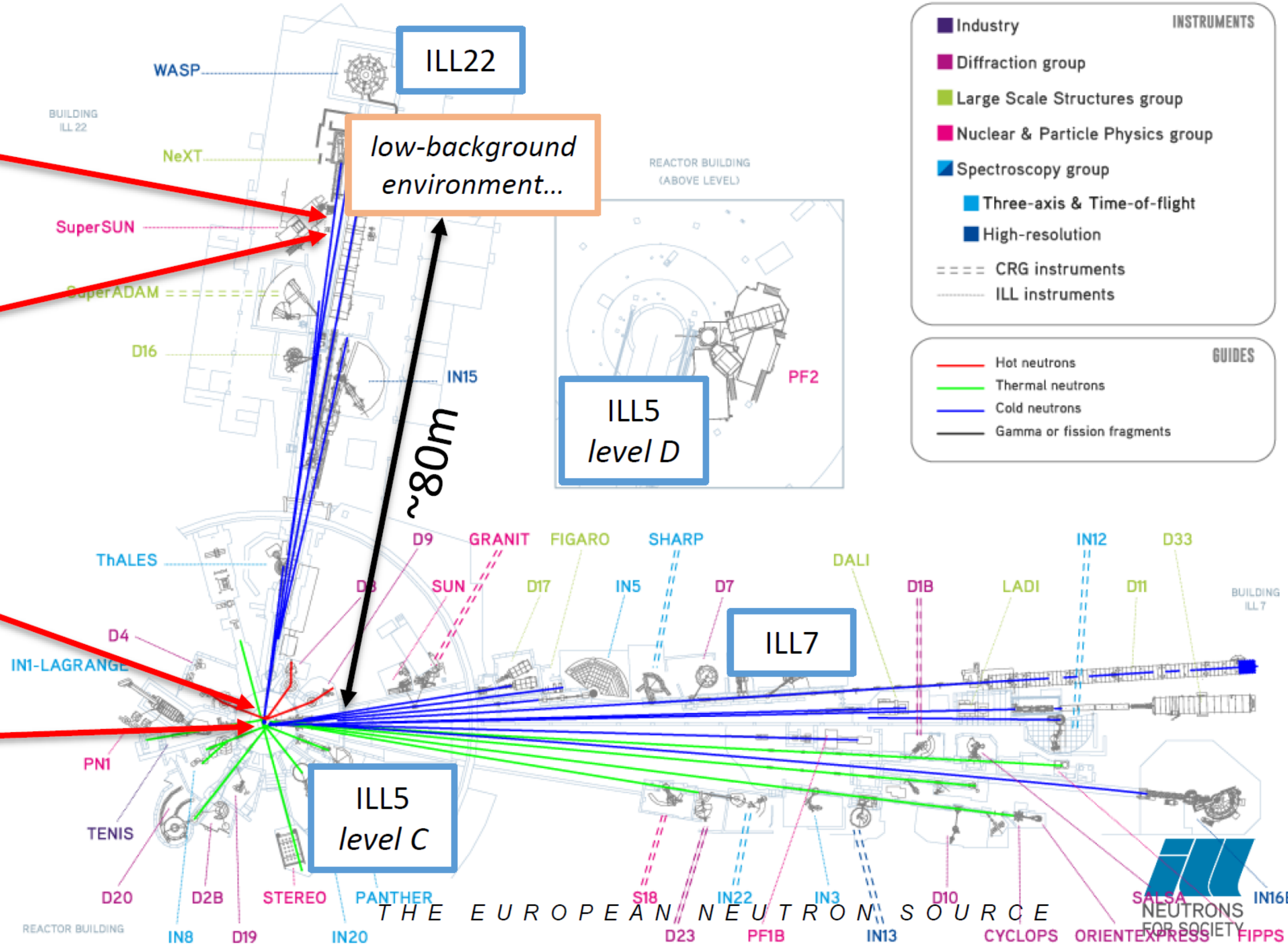
- $\Phi \sim 2\times10^{10}$ n/(cm^2 s)

Horizontal Cold Source:

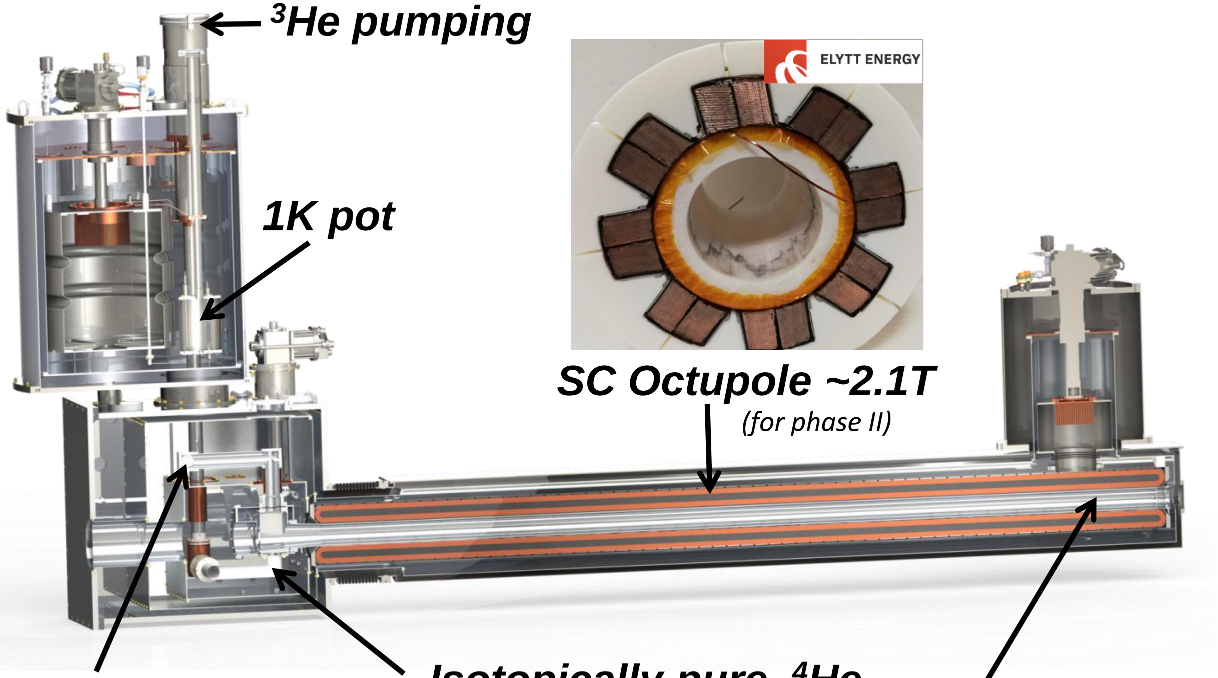
- $\Phi \sim 10^{14}$ n/(cm^2 s)

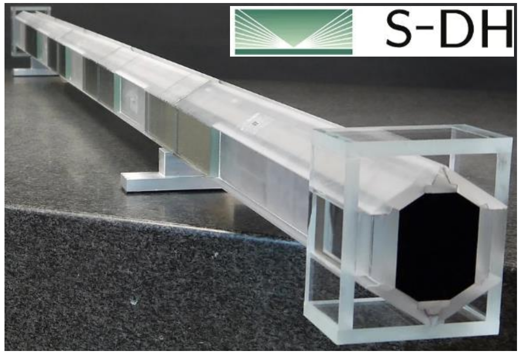
In pile:

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



The SuperSUN-PanEDM Installation



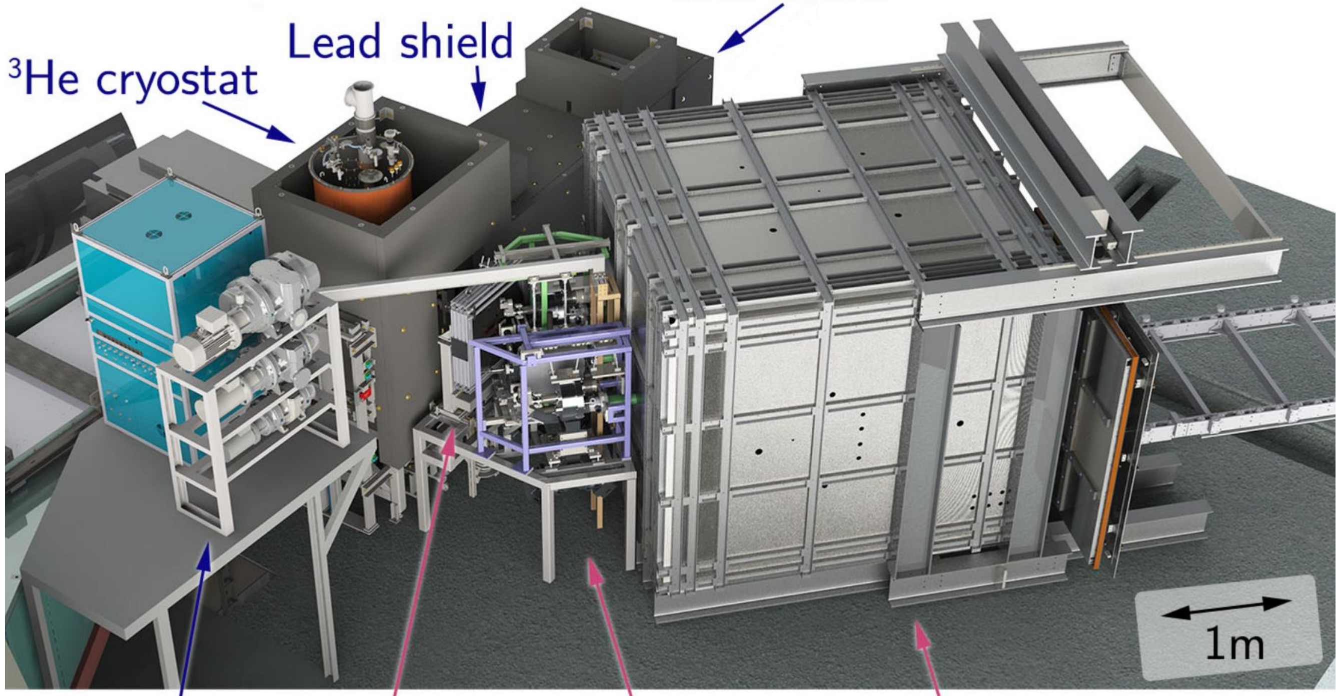


Cold neutrons delivered in a tapered octagonal guide:
[J. Neutron Research 20(4), 117-122 (2018)]

SuperSUN:
[J. Neutron Research **24**(2), 111-121 (2022)]

PanEDM:
[EPJ Web Conf. **219**, 02006 (2019)]

UCN density proportional to: (0.89nm flux) × (source storage time)
High *in-situ* density …but extracting to external volumes is <u>very penalizing</u>.
Unique circular "replica" supermirror for cold neutrons <u>inside ^{4}He converter</u>.



SuperSUN: High density UCN source

Phase I characterization

Measurement agrees with expectation (48 MW)

cf. EPJ Conf. 219, 02006 (2019)

Total UCN output: 3.8×10^6 (integral of blue peak)
Source density: 270 UCN/cm^3
Long storage times: 126000 UCN remaining after 20min
Expected density in PanEDM: 3.9 UCN/cm^3 (58 MW)
Source characterization, PanEDM commissioning ongoing

Phase II expectation

Peak field:	2.1 T
Source density:	1670 UCN/cm^3 (**x5 gain**)
Density in PanEDM:	40 UCN/cm^3 (**x10 gain**)

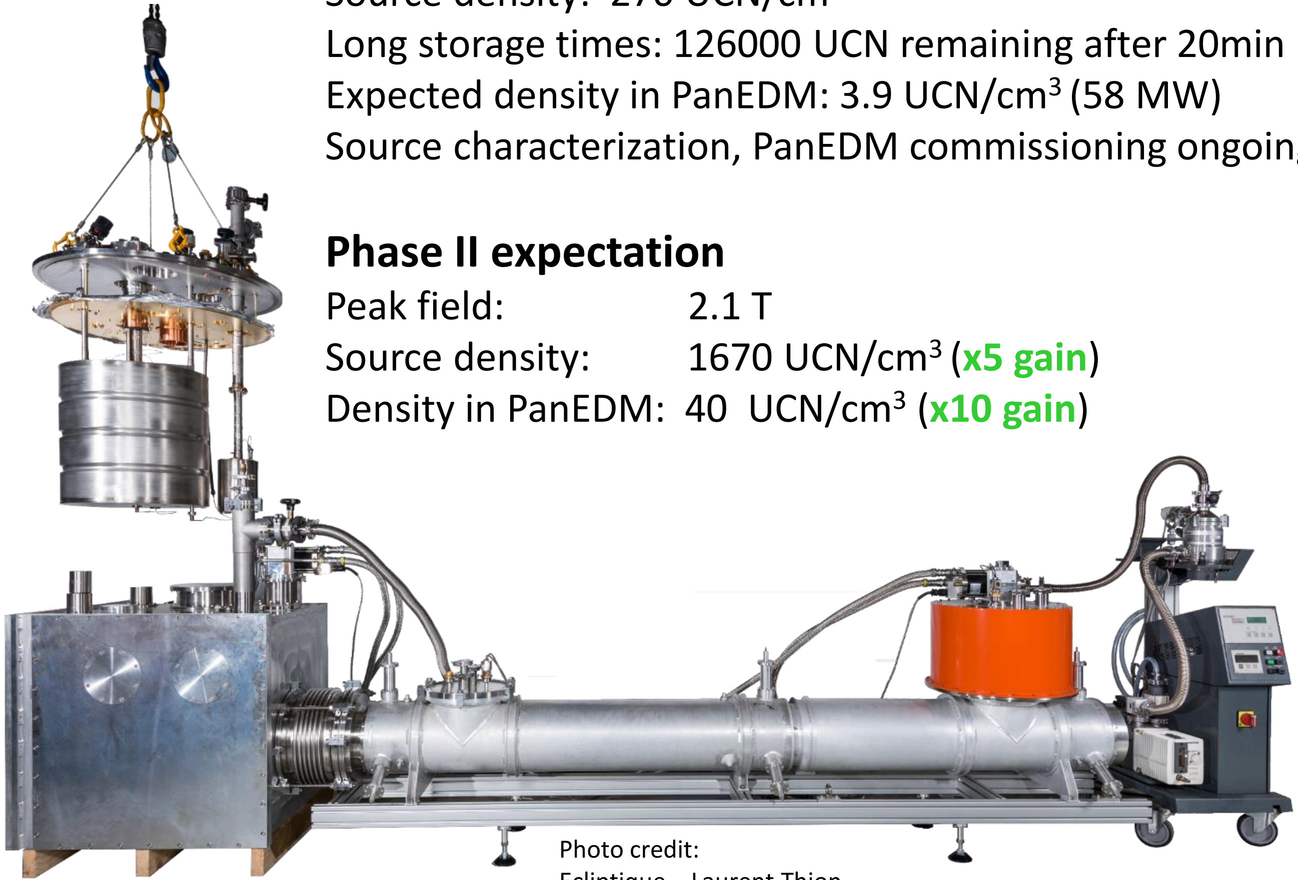
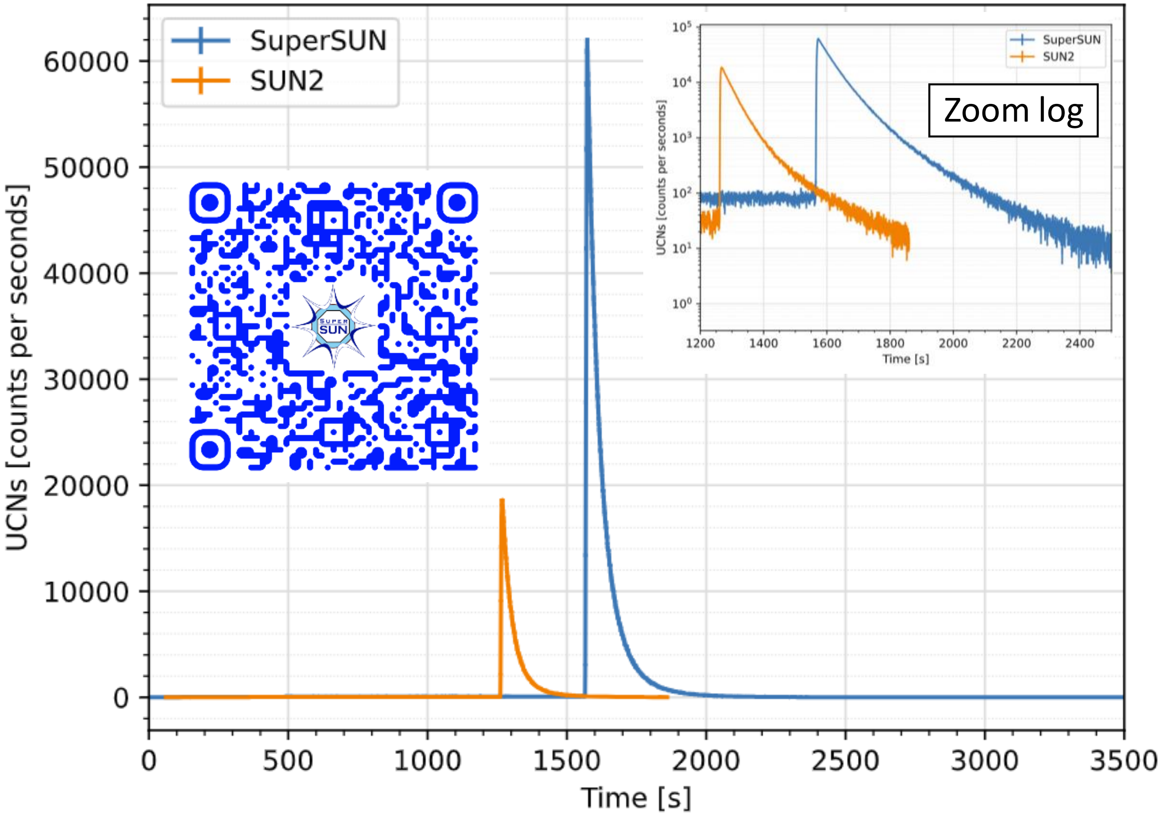


Photo credit:
Ecliptique – Laurent Thion.

Comparison to the prototype source SUN2



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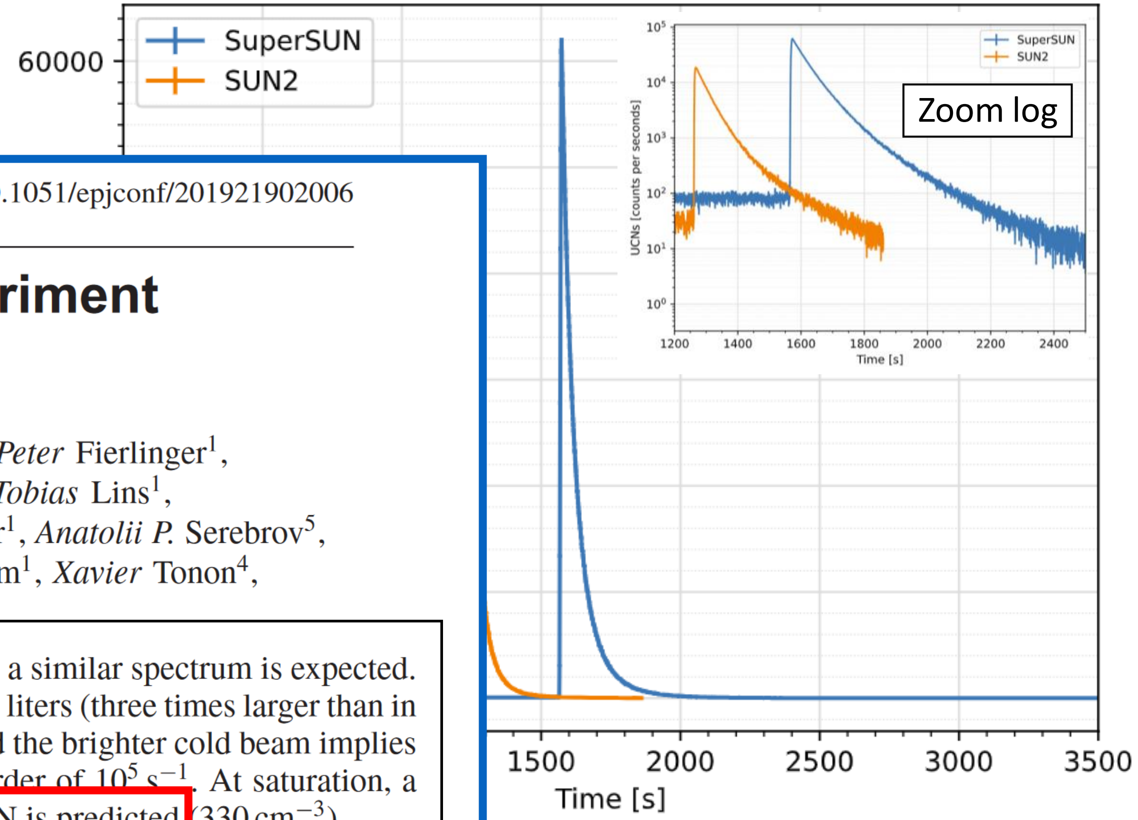

EPJ Web of Conferences **219**, 02006 (2019) https://doi.org/10.1051/epjconf/201921902006
PPNS 2018

The PanEDM neutron electric dipole moment experiment at the ILL

David Wurm[1], *Douglas H.* Beck[2], *Tim* Chupp[3], *Skyler* Degenkolb[4,a], *Katharina* Fierlinger[1], *Peter* Fierlinger[1], *Hanno* Filter[1], *Sergey* Ivanov[5], *Christopher* Klau[1], *Michael* Kreuz[4], *Eddy* Lelièvre-Berna[4], *Tobias* Lins[1], *Joachim* Meichelböck[1], *Thomas* Neulinger[2], *Robert* Paddock[6], *Florian* Röhrer[1], *Martin* Rosner[1], *Anatolii P.* Serebrov[5], *Jaideep Taggart* Singh[7], *Rainer* Stoepler[1], *Stefan* Stuiber[1], *Michael* Sturm[1], *Bernd* Taubenheim[1], *Xavier* Tonon[4], *Mark* Tucker[8], *Maurits* van der Grinten[8], and *Oliver* Zimmer[4]

by material walls only, and a similar spectrum is expected. The converter volume is 12 liters (three times larger than in SUN2); scaling for this and the brighter cold beam implies a production rate on the order of $10^5\ s^{-1}$. At saturation, a total of 4×10^6 stored UCN is predicted ($330\ cm^{-3}$).

3.8×10^6 UCN measured (fill-and-empty)

Ongoing work: spectrum, transfer efficiency and storage in external volumes, etc…

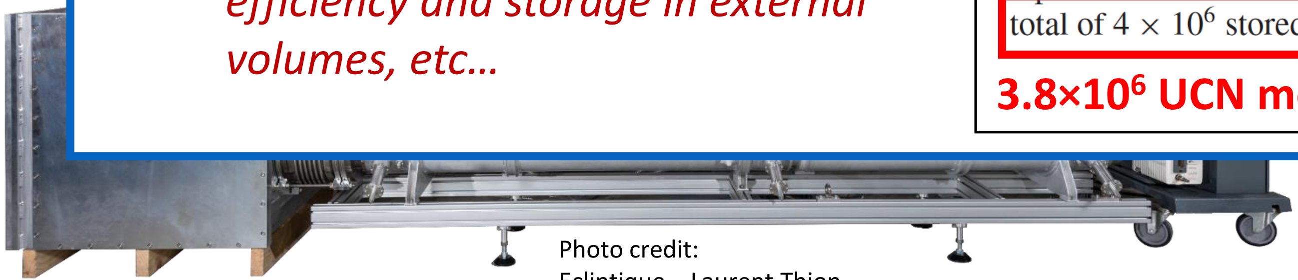

Photo credit:
Ecliptique – Laurent Thion.

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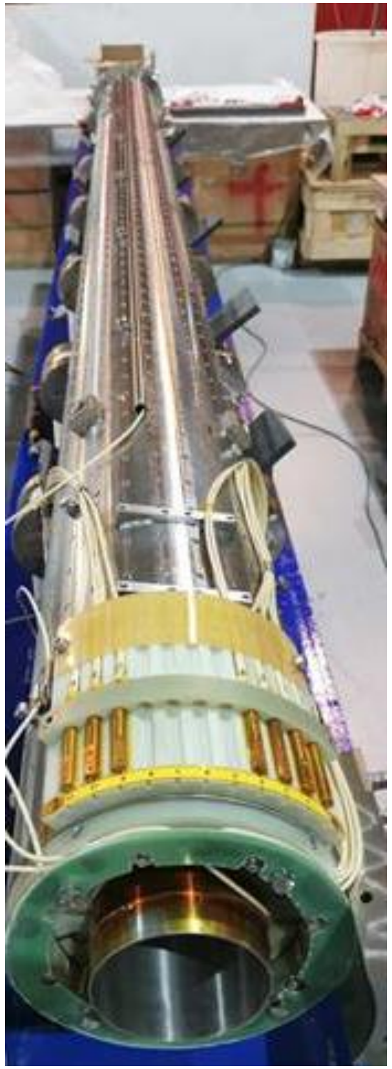
SuperSUN phase II: polarized UCN and magnetic storage



Benefits in phase II

- Increase storage potential for one spin state
- Decrease loss rate for stored UCN

→ UCN already polarized within the source

Phase II expectations (gain over phase I)

Peak field: 2.1 T

Source density: 1670 UCN/cm^3 (**x5 gain**)

Density in PanEDM: 40 UCN/cm^3 (**x10 gain**)

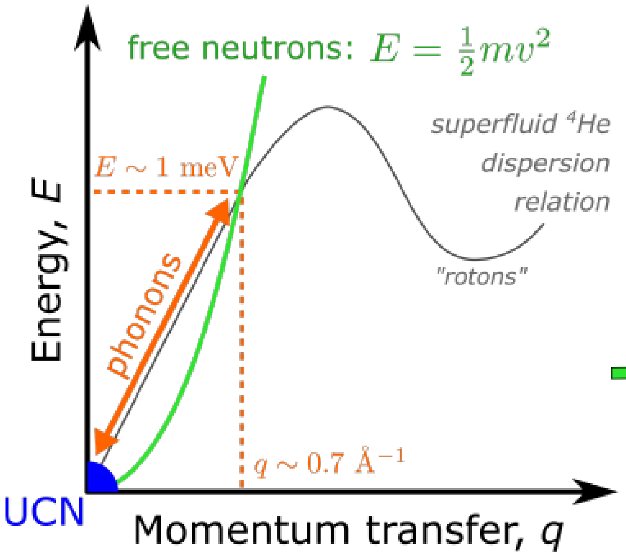
Status

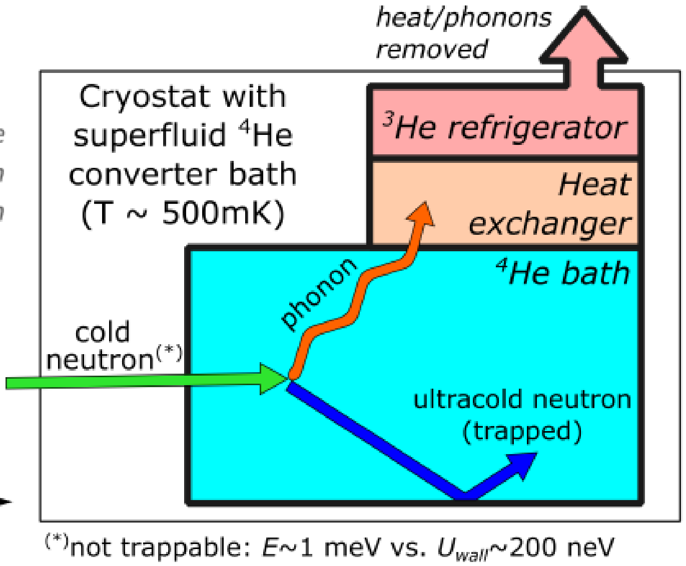
Quench protection validated

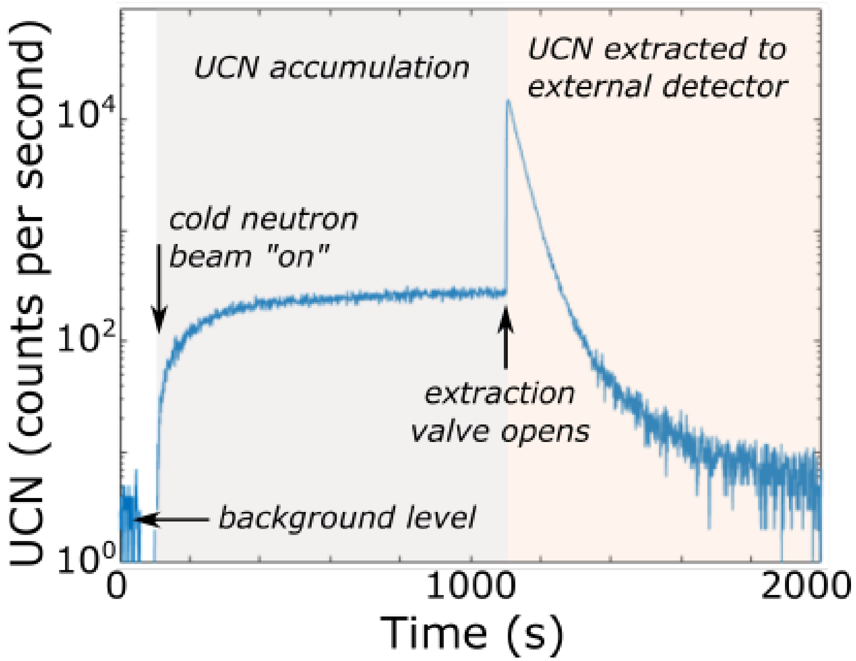
Octupole trained up to 1 T

Preparing impregnation of the octupole, to reach nominal field

UCN from Superfluid ^{4}He: Flux vs. Density





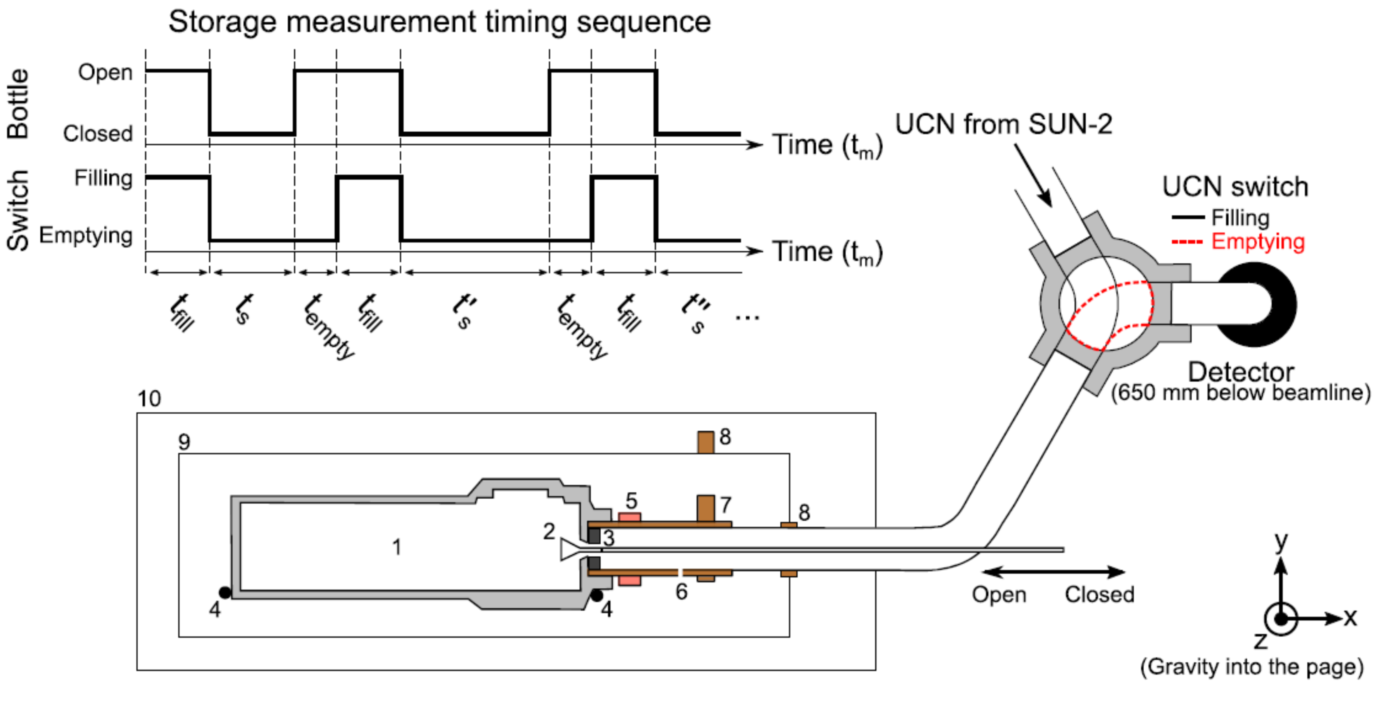


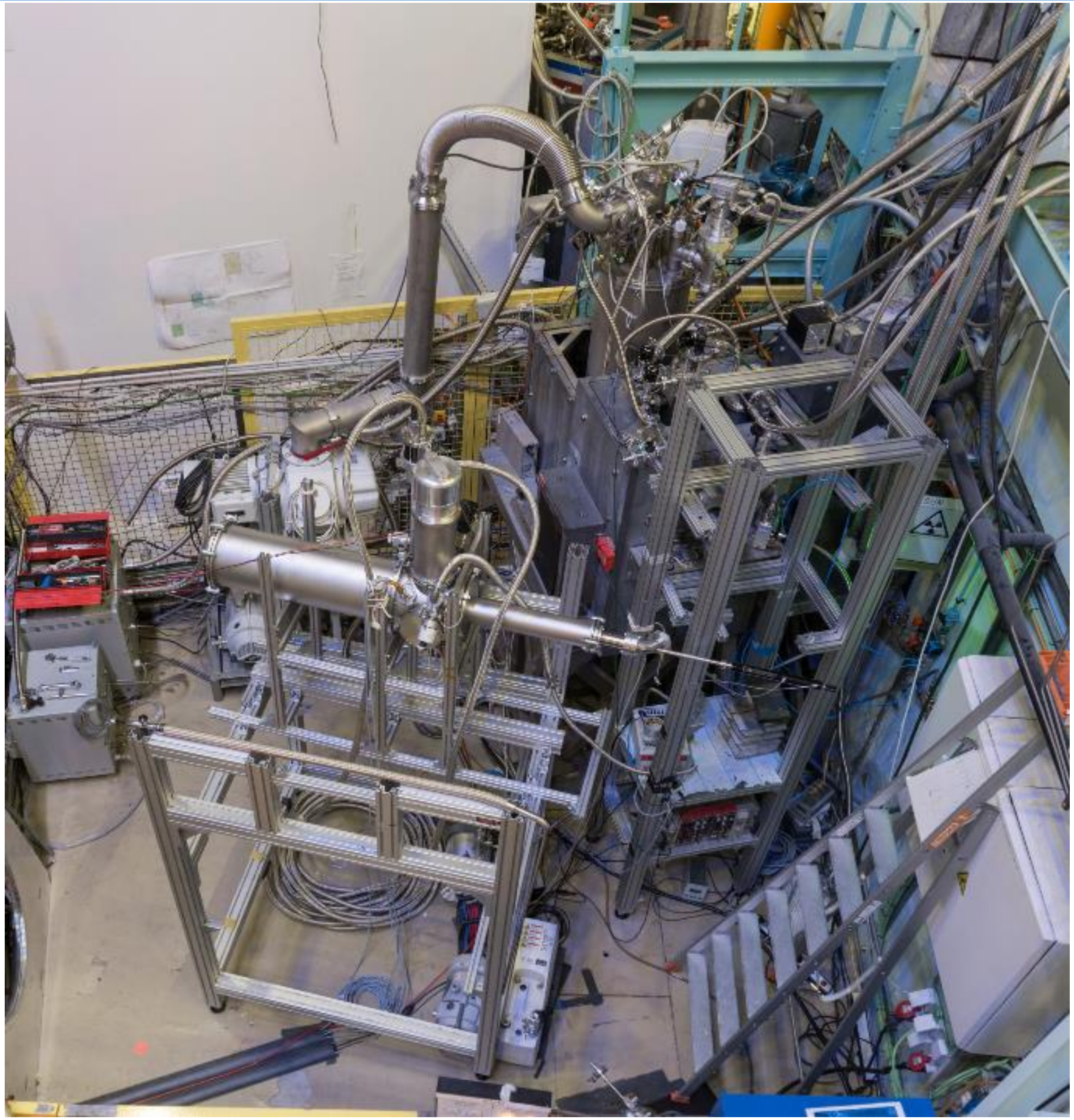
Velocity	"Temperature"	Energy
$10^0 - 10^1$ m/s	Ultracold	5 neV – 500 neV
$10^1 - 10^2$ m/s	Very cold	0.5 μeV – 50 μeV
$10^2 - 10^3$ m/s	Cold	50 μeV – 5 meV
2.2×10^3 m/s	Thermal	25 meV
$2{\times}10^3 - 2{\times}10^4$ m/s	Hot	20 meV – 2 eV

$$R \sim \left(\frac{5 \times 10^{-8}}{\text{cm}^3\ \text{s}}\right) \times \left.\frac{d\Phi}{d\lambda}\right|_{8.9\text{Å}} \times \left(\frac{V_{\text{trap}}}{233\ \text{neV}}\right)^{\frac{3}{2}}$$ **production**

$$\frac{1}{\tau} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\text{up}}} + \frac{1}{\tau_{\text{capture}}} + \frac{1}{\tau_{\text{wall}}} + \cdots$$ **loss**

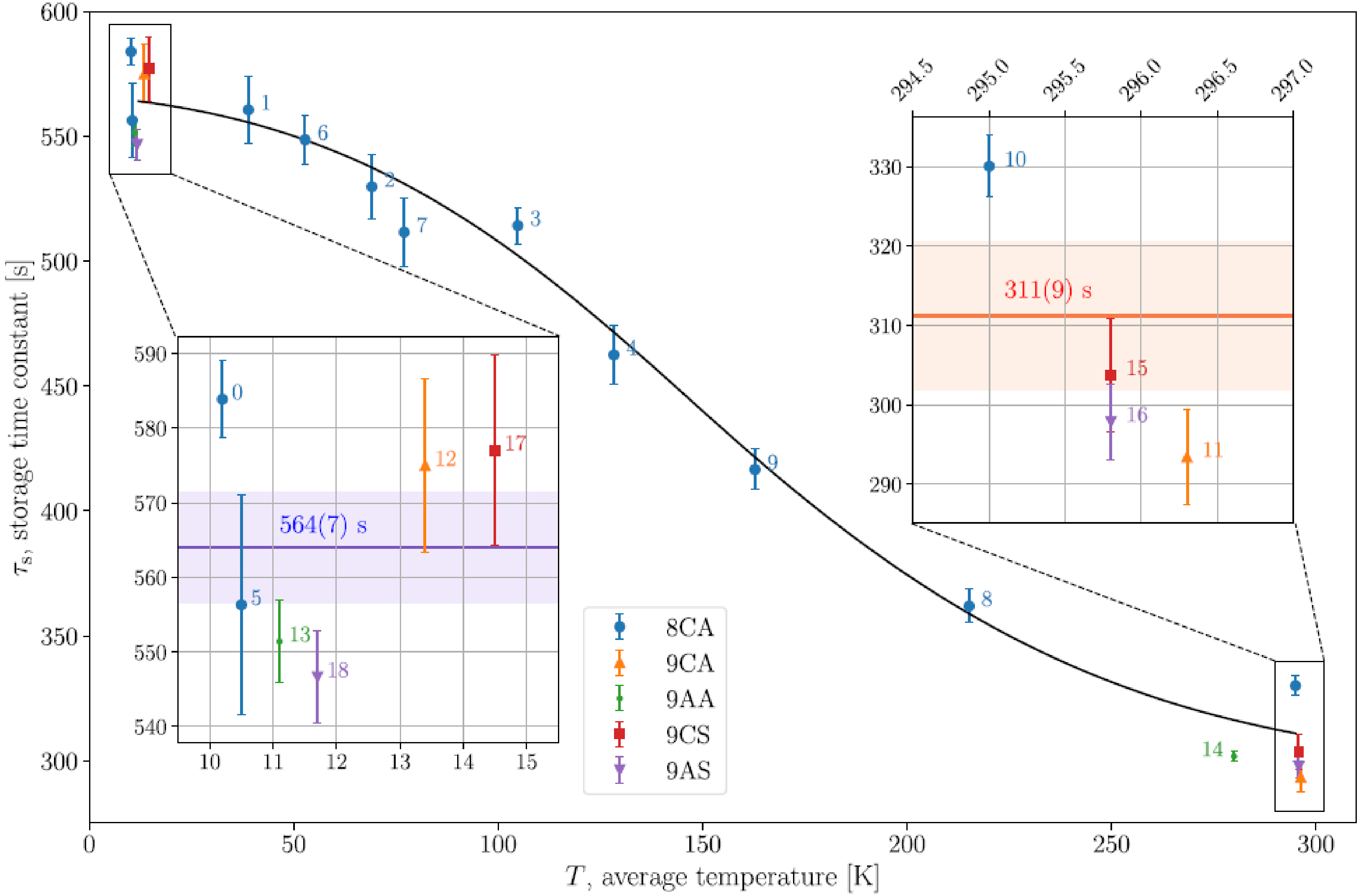
The need for UCN R&D facilities: using SUN-2

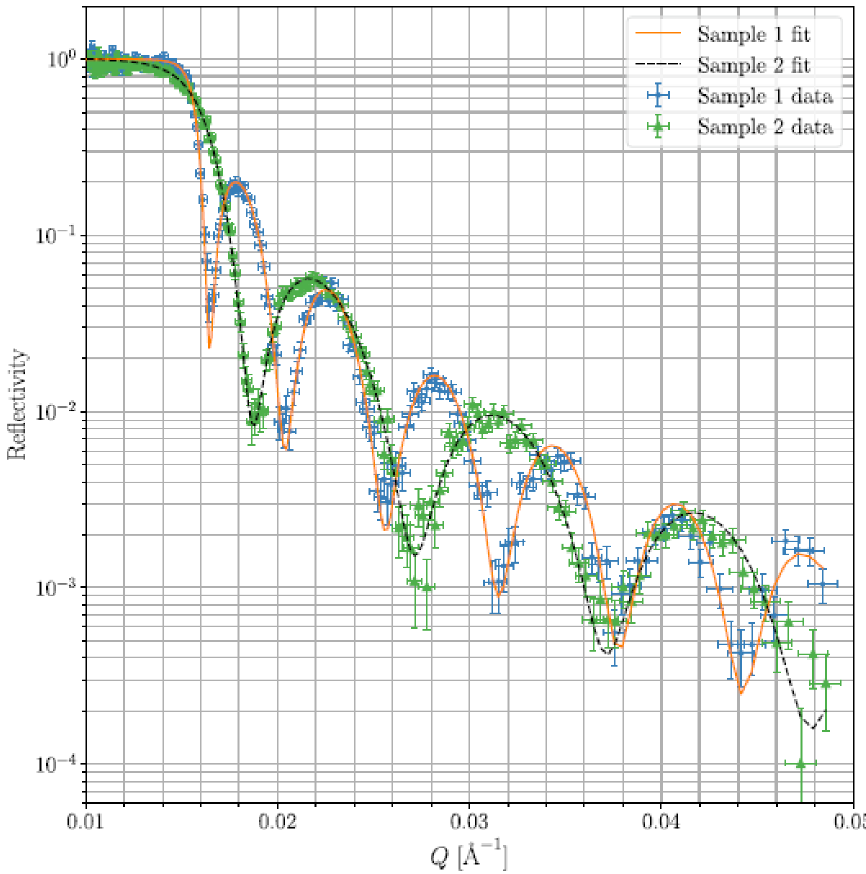




"Suniño" test vessel: J. Hingerl, MSc. 2019
Storage measurements: T. Neulinger, PhD 2021

CYTOP^{TM} as a UCN wall coating



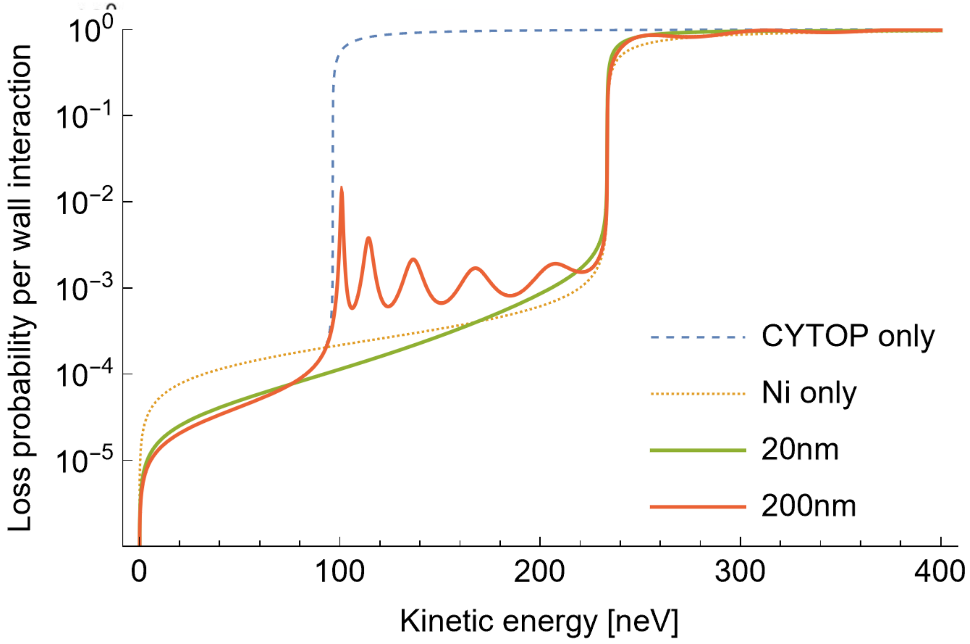


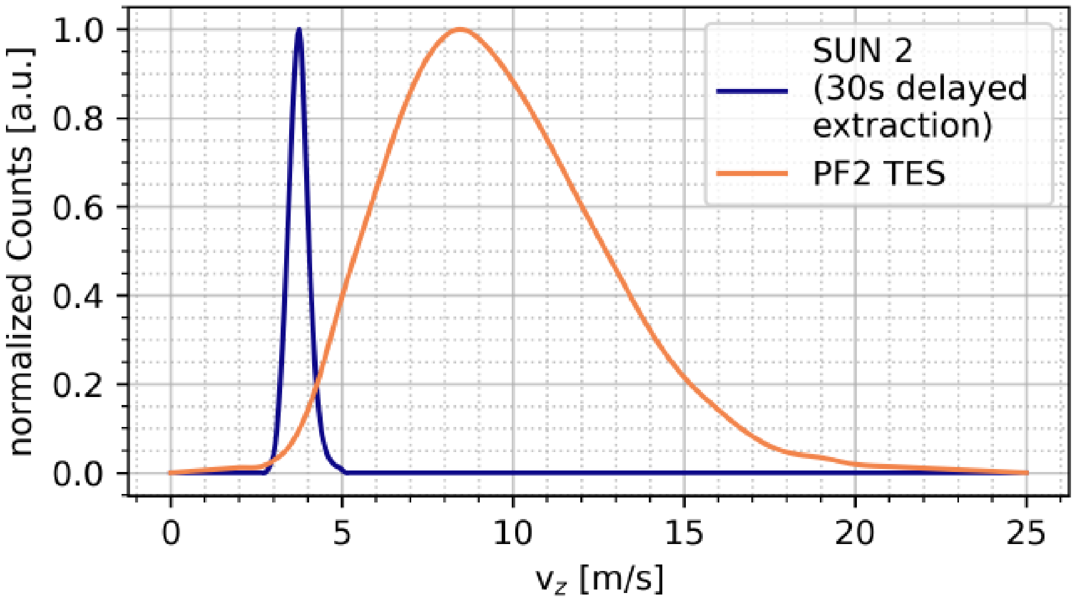
T. Neulinger, PhD 2021

Eur. Phys. J. A **58**: 141 (2022)

Soft Energy Spectra from ^{4}He sources*

**Time-of-flight measurements come with some caveats*





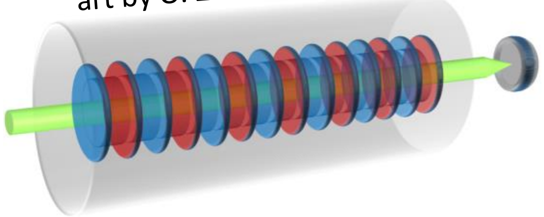
Development of these ideas for in-situ experiments:

[J. Neutron Research **24**(2), 123-143 (2022)]

[Physics Reports **1023**, 1-84 (2023)]

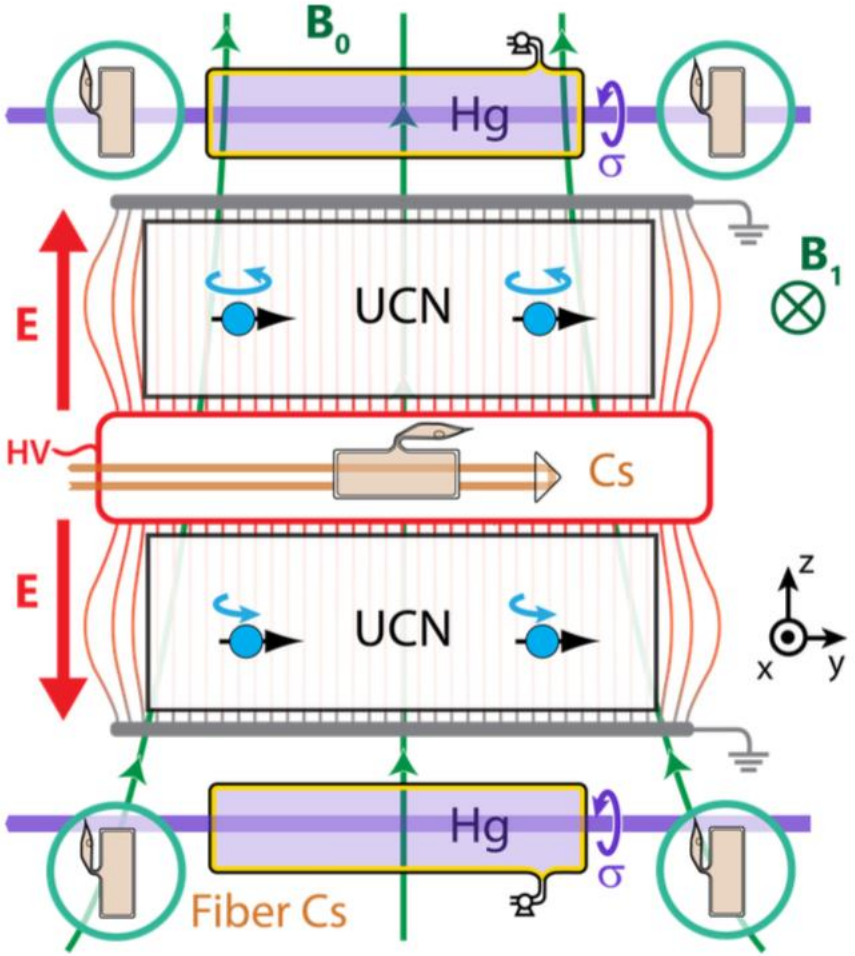
$$R \sim \left(\frac{5\times 10^{-8}}{\mathrm{cm}^3\ \mathrm{s}}\right) \times \left.\frac{d\Phi}{d\lambda}\right|_{8.9\text{Å}} \times \left(\frac{V_{\mathrm{trap}}}{233\ \mathrm{neV}}\right)^{\frac{3}{2}}$$ **production**

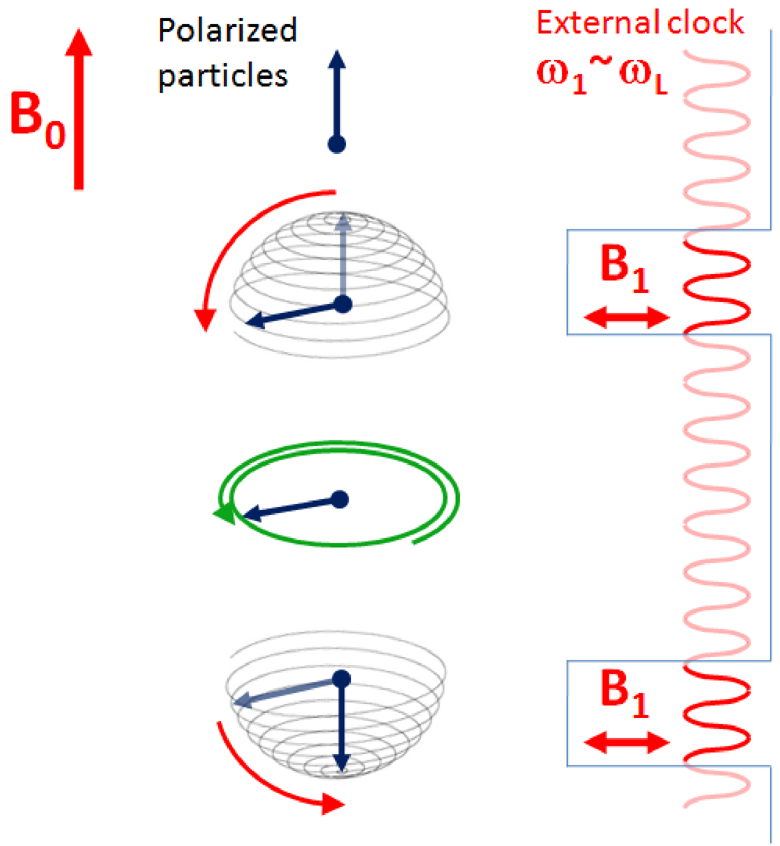
art by O. Zimmer



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

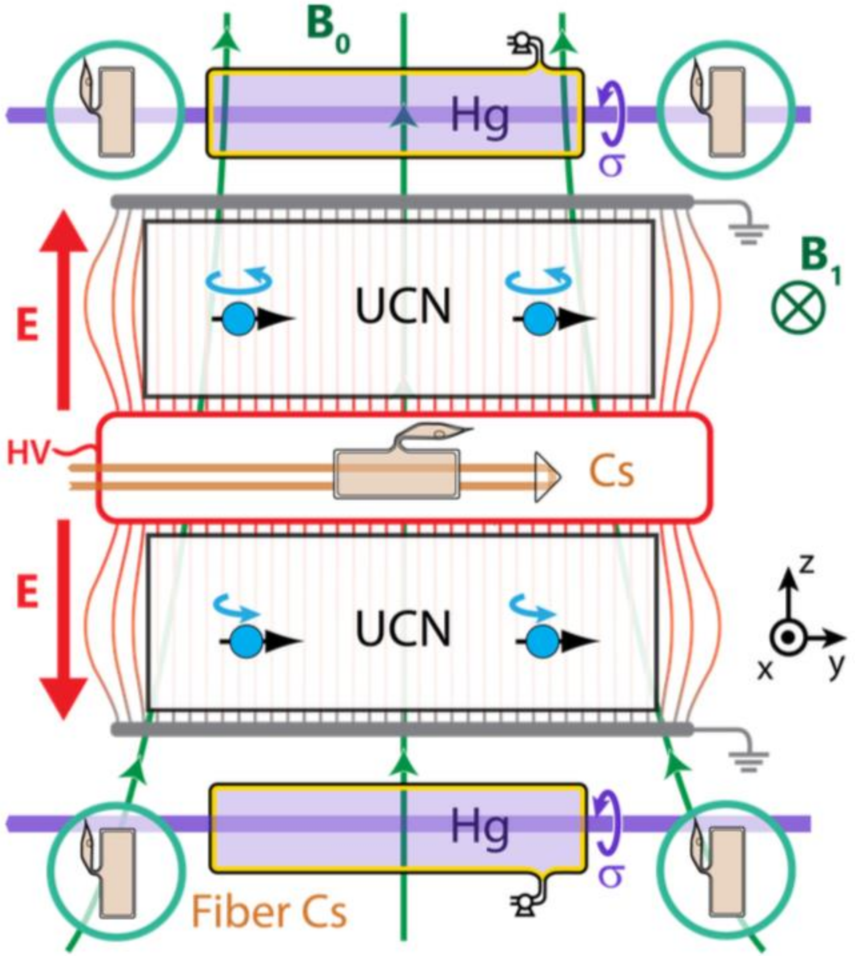
The PanEDM Experiment





EPJ Conf. 219, 02006 (2019)

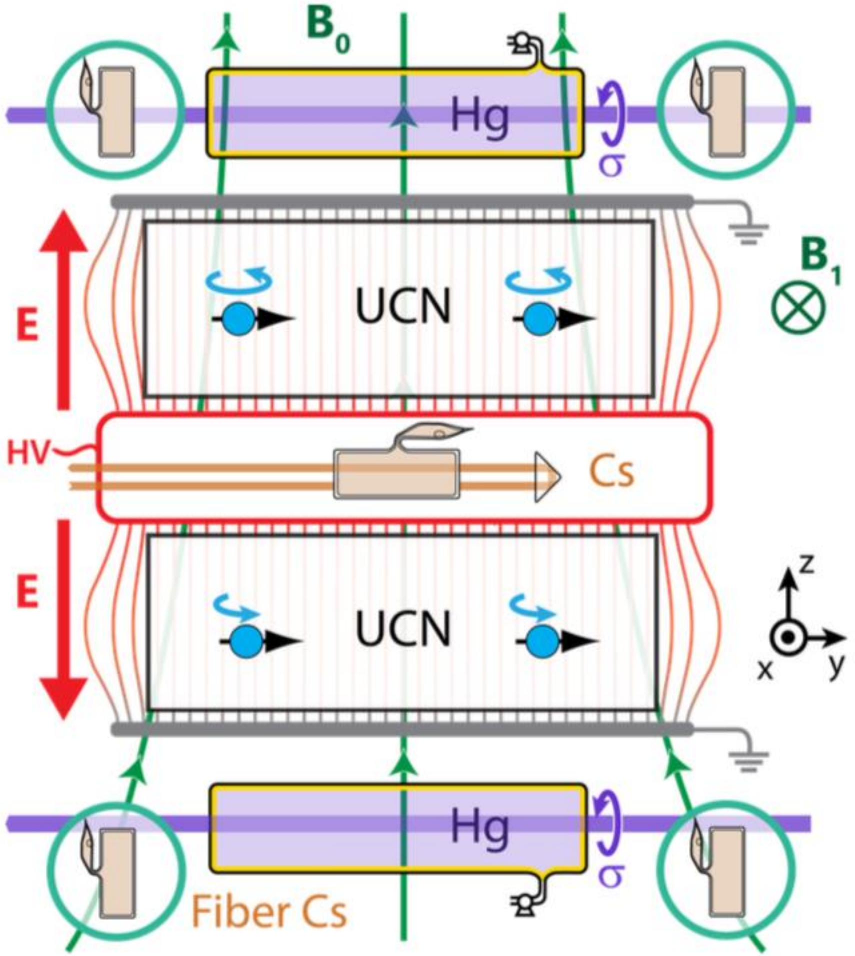
The PanEDM Experiment



- Double chamber Ramsey interferometer at room temperature (but T_{UCN} ~ 5mK)
- ^{199}Hg magnetometers with few-fT resolution
- Cs magnetometers (also at high voltage)
- Magnetic shielding factor: 6×10^{6} at 1 mHz
- Simultaneous spin detection for up/down
- SuperSUN UCN source at ILL in 2 phases:
  - Phase I: unpolarized UCN with 80 neV peak
  - Phase II: polarized UCN, magnetic storage
- Ongoing installation of parts, commissioning with UCN ongoing in 2023-2024

EPJ Conf. 219, 02006 (2019)

The PanEDM Experiment



Statistical sensitivity:

$$\sigma(d_n) \gtrsim \frac{\hbar}{2\alpha|\mathbf{E}|T\sqrt{N}}$$

Frequency measurement:

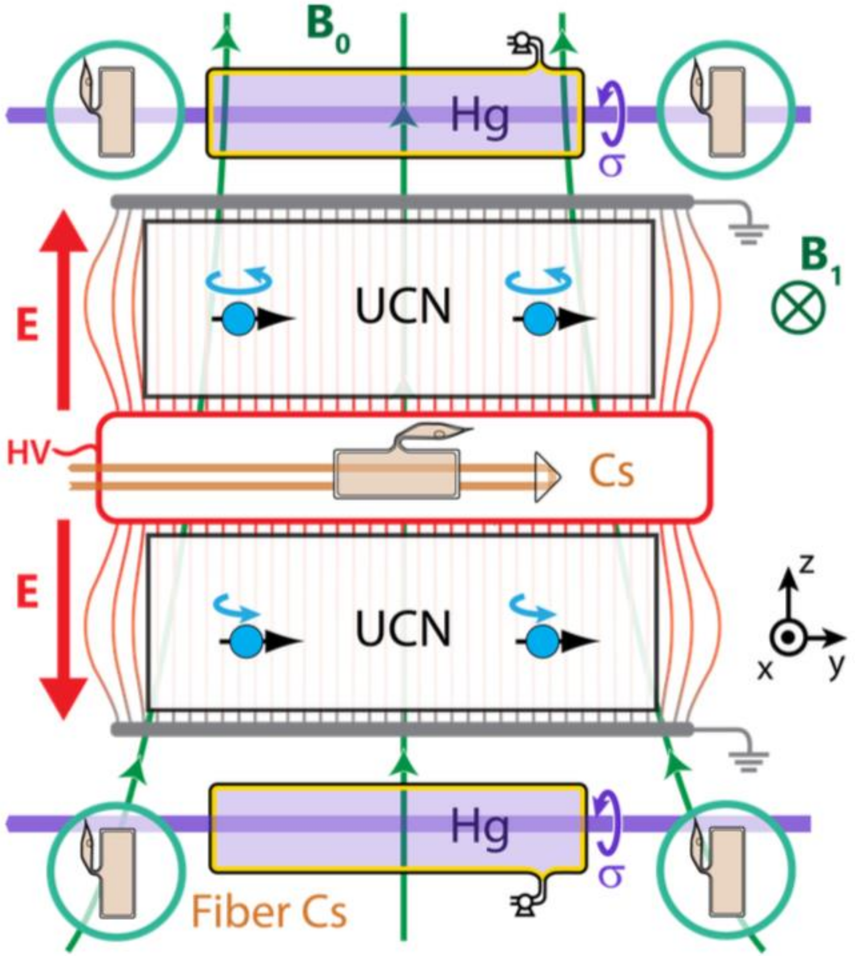
$$|\delta\omega| = \frac{|dE|}{\hbar F}$$

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}

$$\Delta E \Delta t \geq \hbar/2$$

EPJ Conf. 219, 02006 (2019)

Brighter UCN Sources vs. Lower Losses



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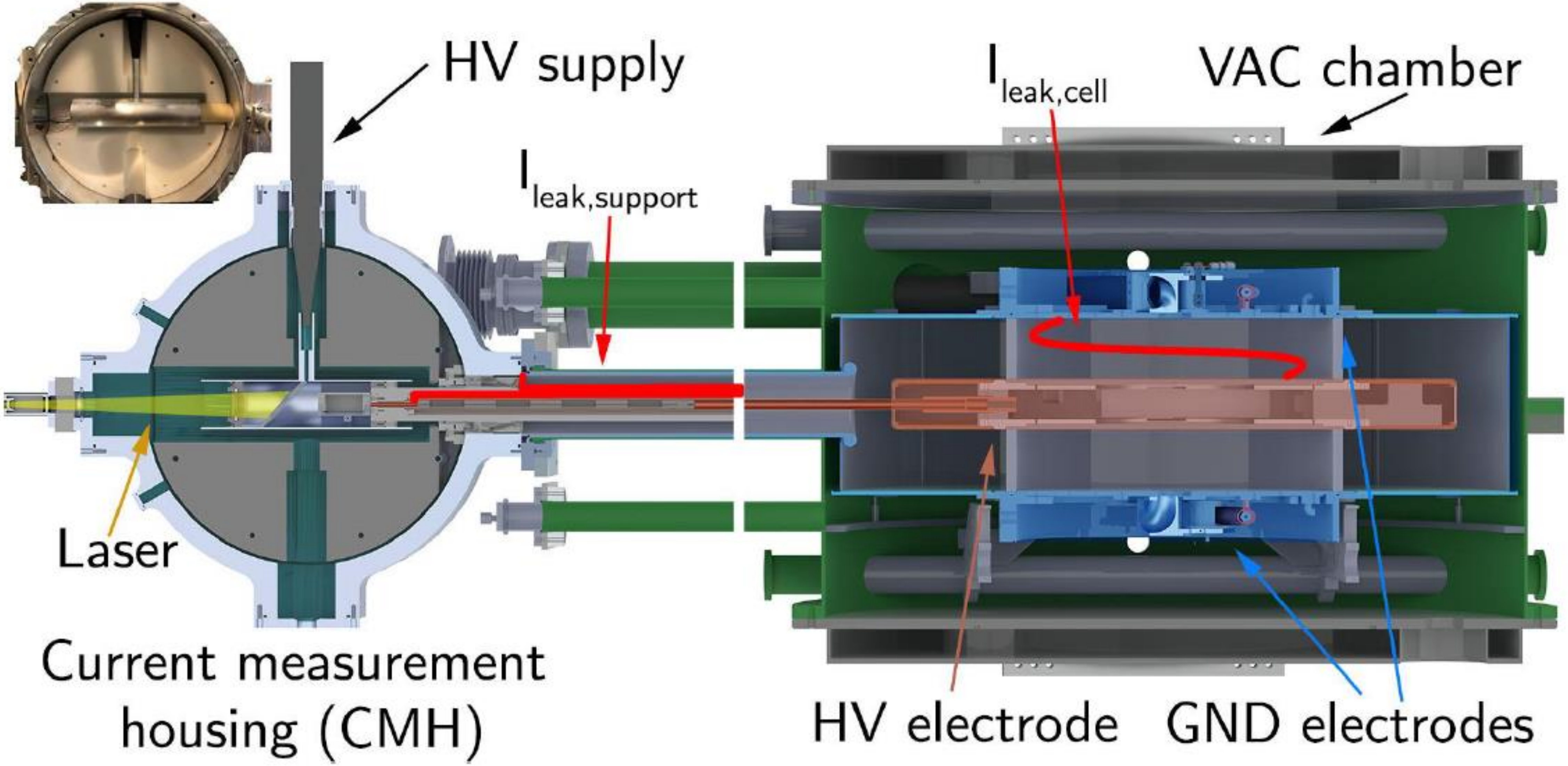
PanEDM Sensitivity [1σ, e cm]	
Per run	5.5×10^{-25}
Per day	3.8×10^{-26}
Per 100 days	3.8×10^{-27}

$|E| \approx 2$ MV/m
$T \approx 250$ s
$\alpha \approx 0.85$

Transfer loss including dilution: 97-99% for filling

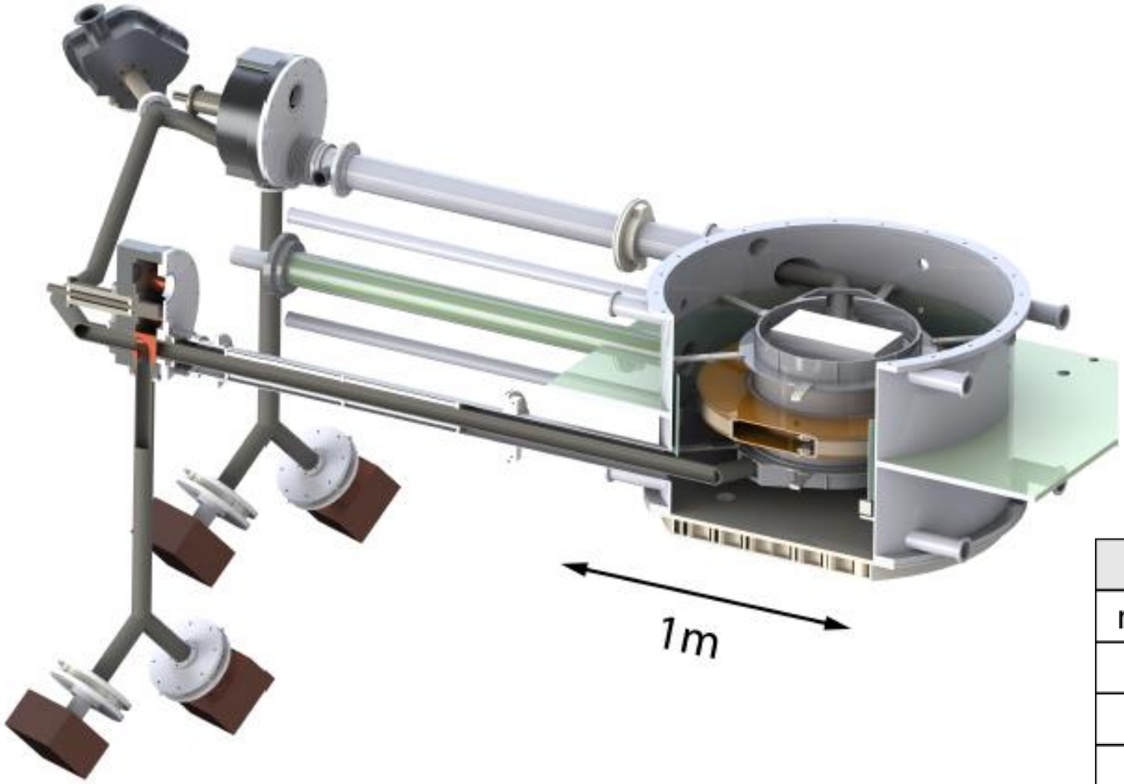
EPJ Conf. 219, 02006 (2019)

The PanEDM Experiment



D. Wurm, PhD 2021

The PanEDM Experiment

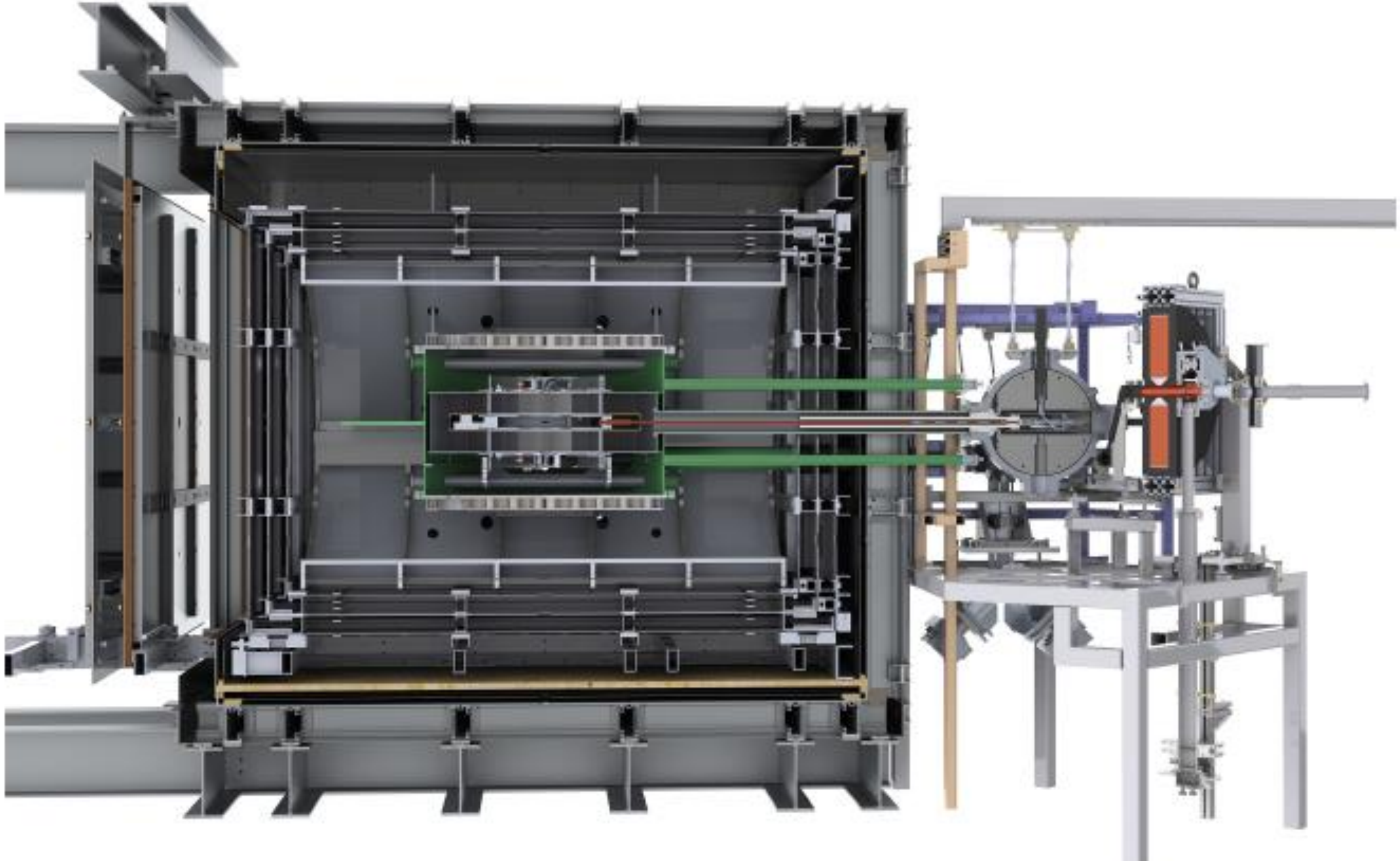


The recipe for an EDM measurement:

	preparation		Ramsey cycle			counting	
duration [s]	30	80	80	110	60	30	50
neutron beam	on	off			on		
3-way switch	vac	fill →	source ↴ detectors			detectors ↲ cells	
vac. pumping	cells		guides				
cell valves	open		closed			open	
spin flipper 1/2			various stability tests			1↑ 2↓	1↓ 2↑
Ramsey pulses			90°	180°	90°		
Hg magnet.		pumping	measure			syst. tests	
UCN detection	background, detector & souce - stability					UCN cnt	
B_0 field	set	measure					
E field	ramp	HV at setpoint					

D. Wurm, PhD 2021

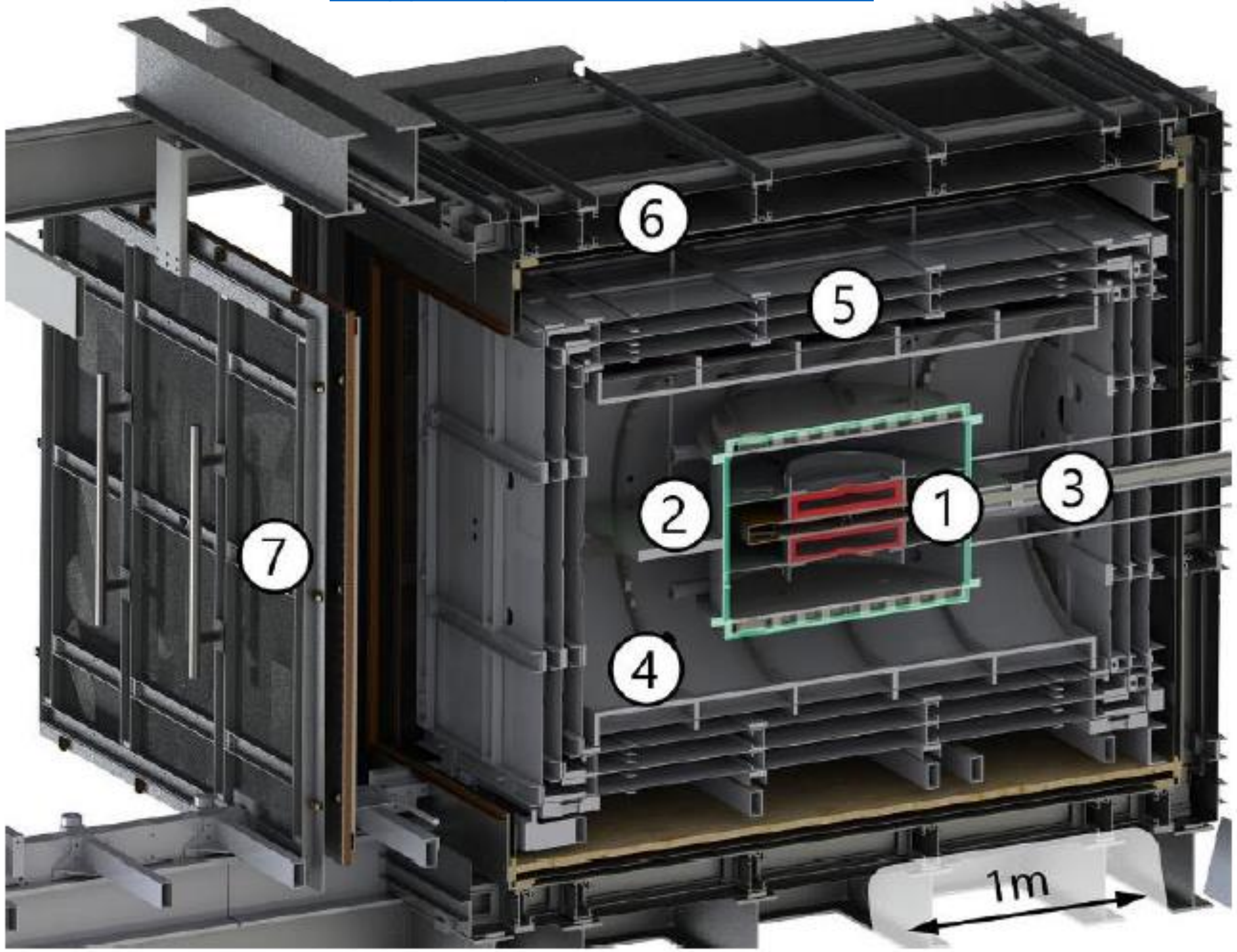
The PanEDM Experiment



D. Wurm, PhD 2021

The PanEDM Experiment

Rev. Sci. Instrum. **85**, 075106 (2014)
J. Appl. Phys. **117**, 183903 (2015)



1: EDM cells
2: Vac. Chamber
3: HV feed
4: B_0 & B_1 coil
5: Inner shield
6: Outer shield
7: Outer shield door

PanEDM @ ILL, 2021

The PanEDM Experiment

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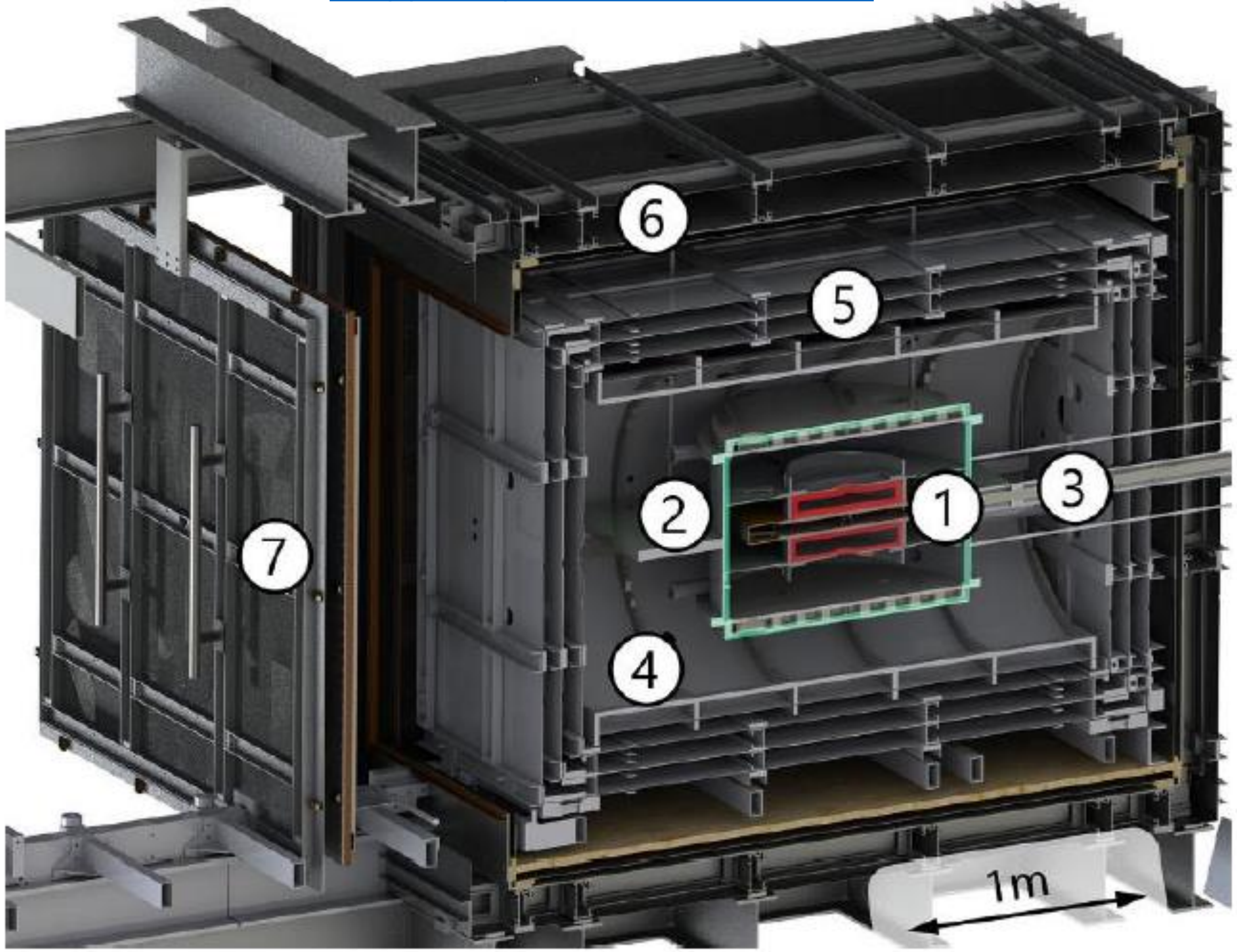

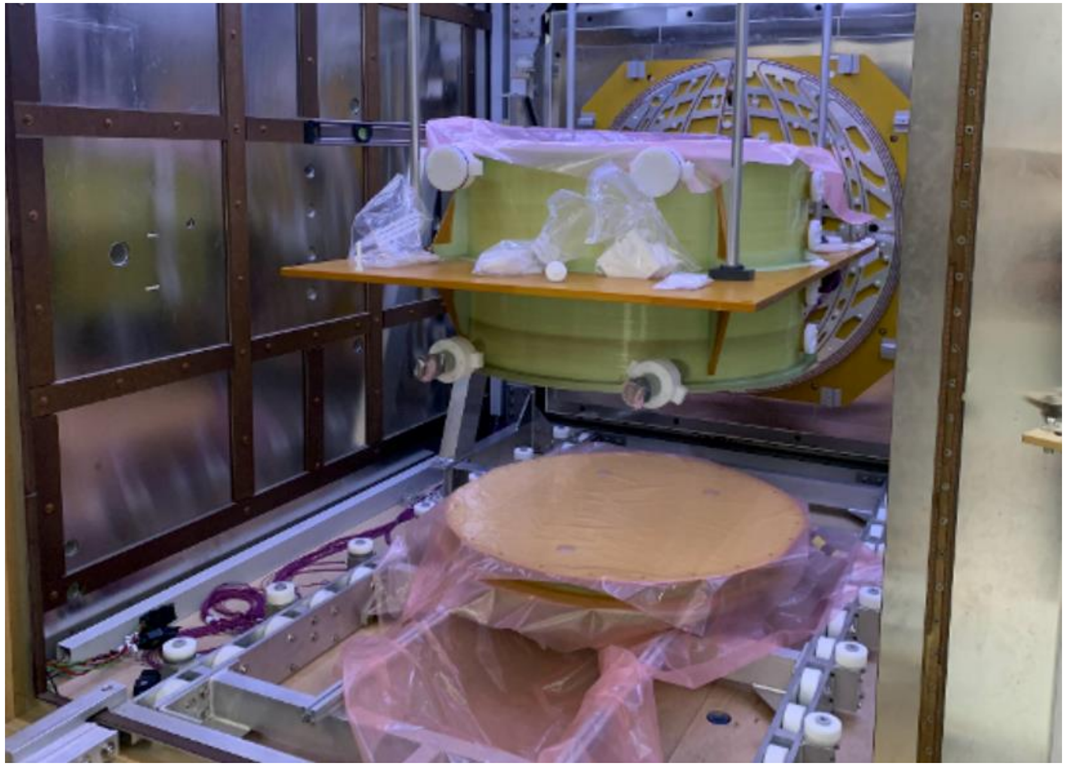

PanEDM @ ILL, 2021

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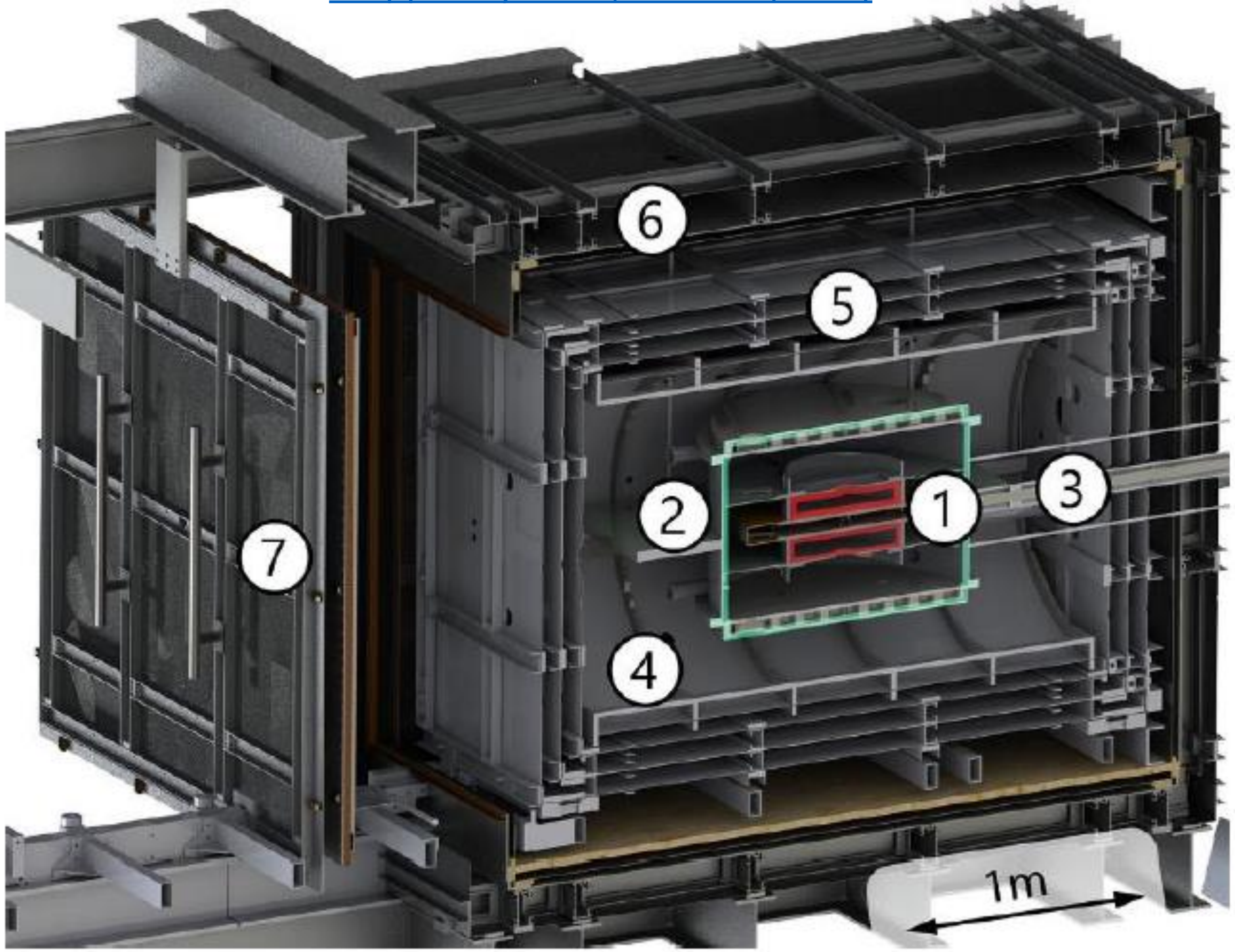
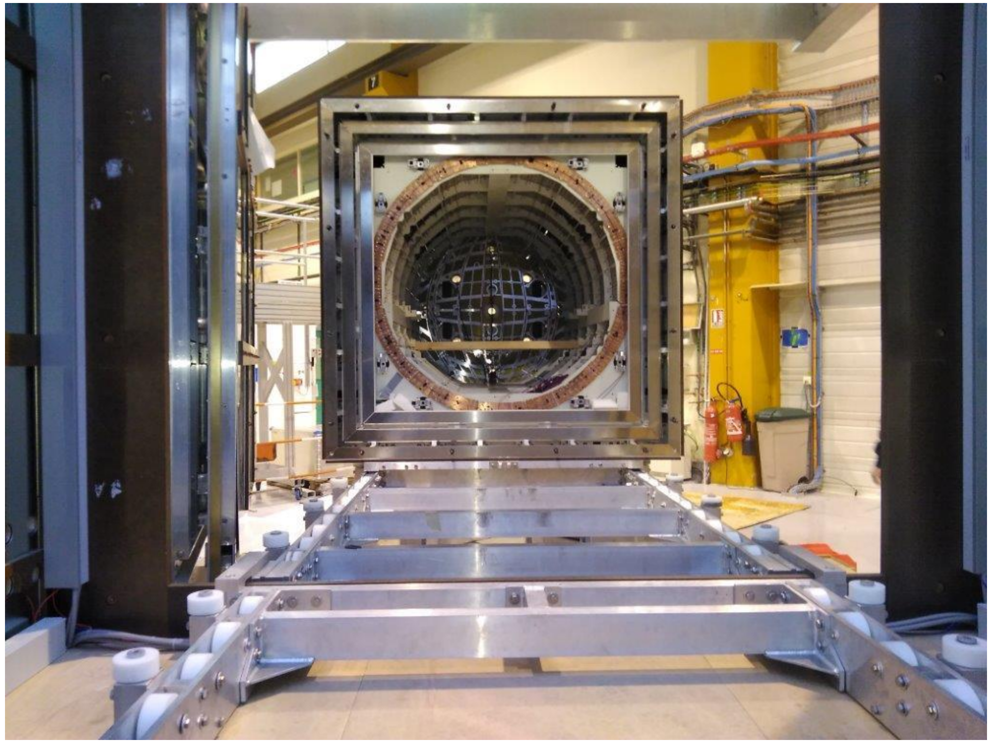


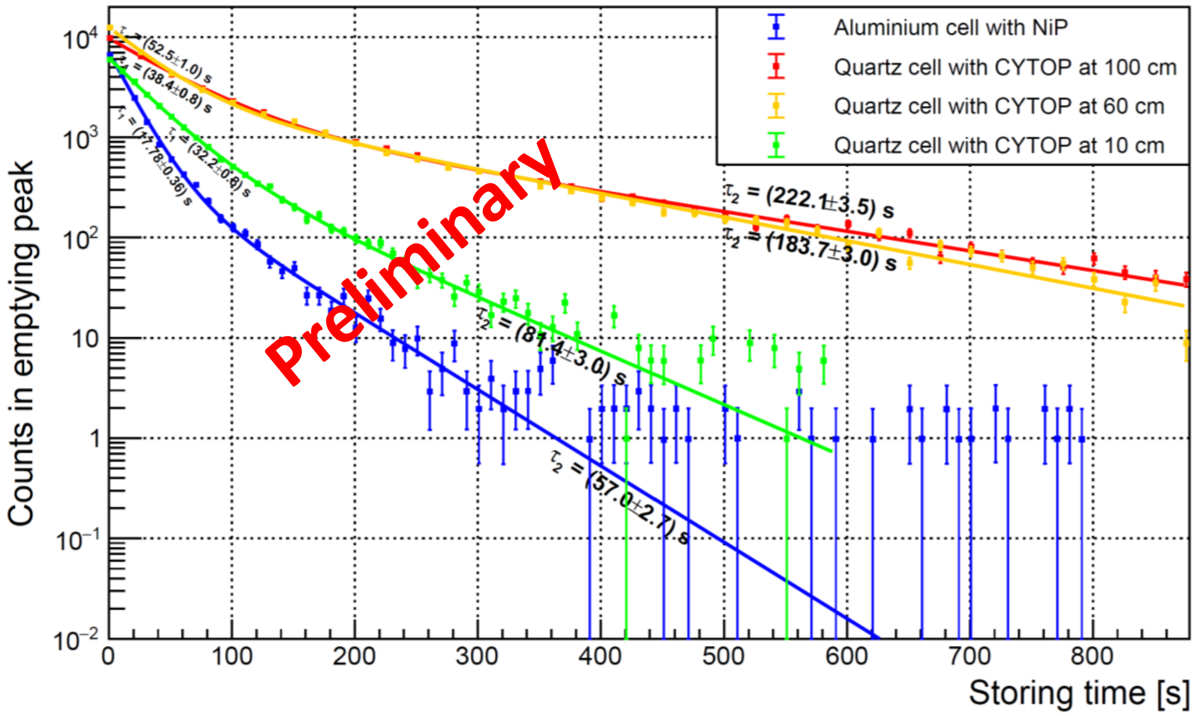


PanEDM @ ILL, 2021

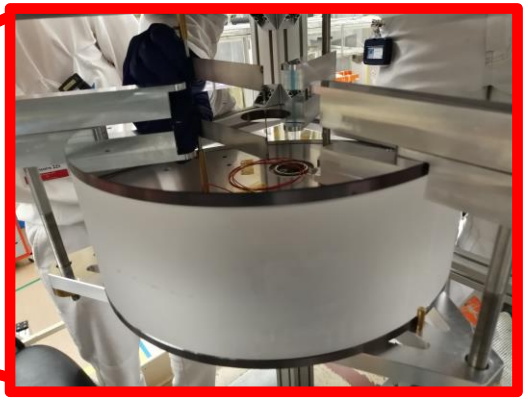
Now with biological shielding in place, and a measurement setup mounted:

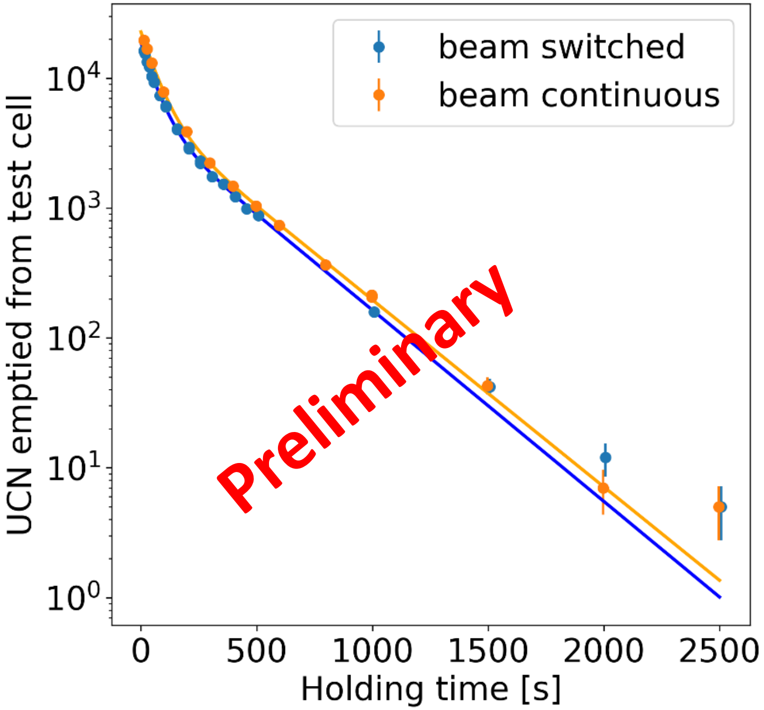
The need for UCN R&D facilities: using PF2

Storage measurements in “mock PanEDM cells”:



Transitioning to SuperSUN

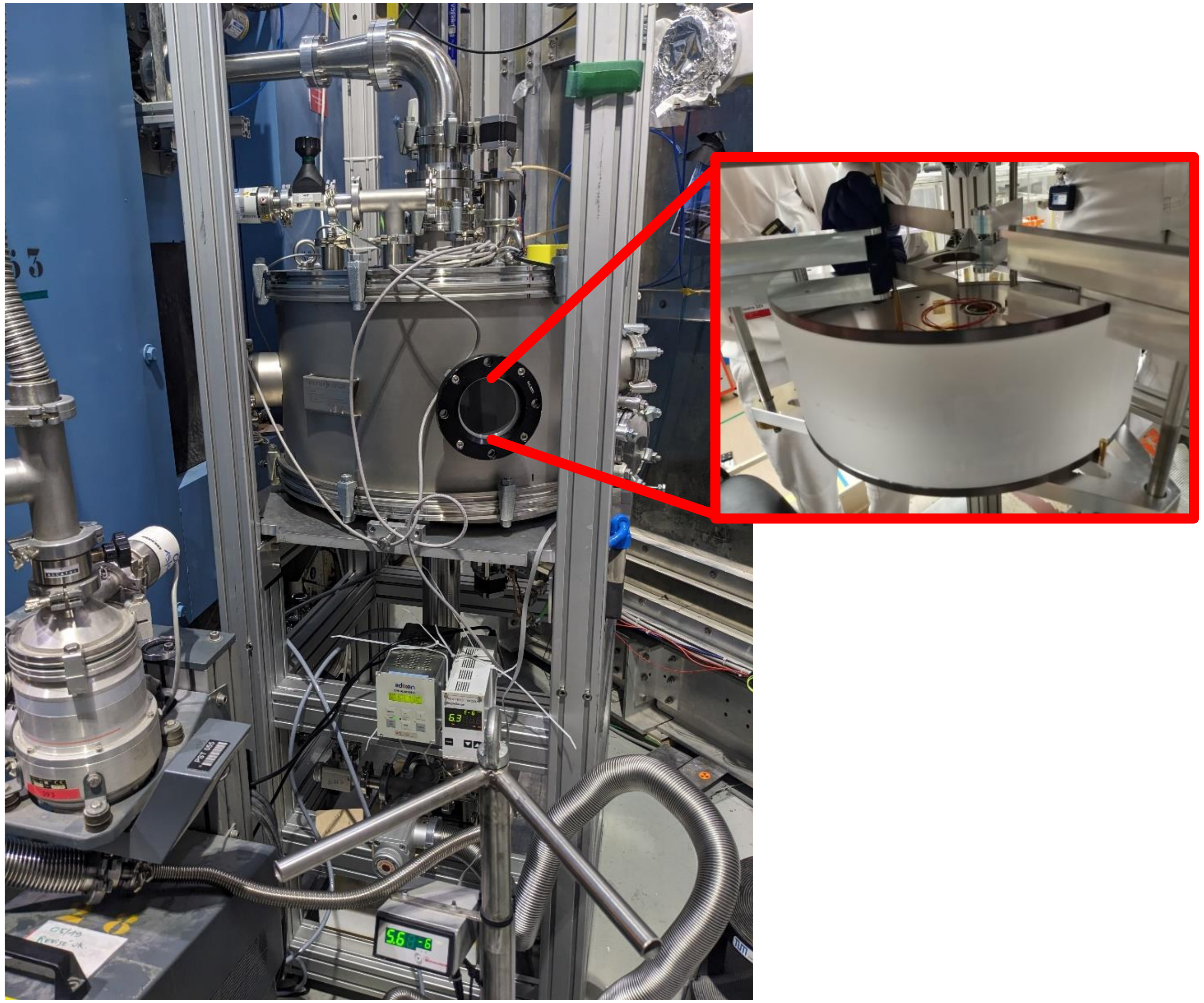




Statistics considerations

- 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
- Cold neutron losses

Transitioning to SuperSUN: lower cells



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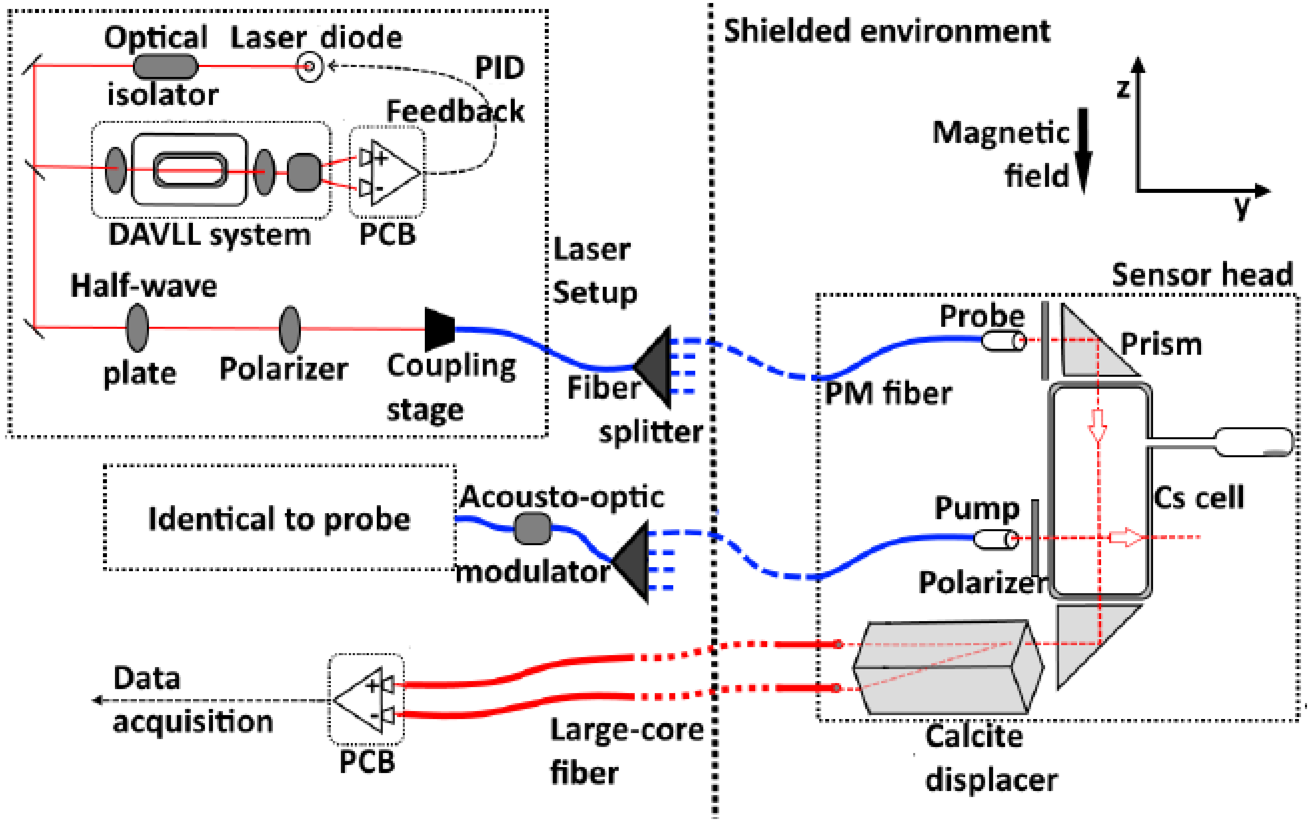
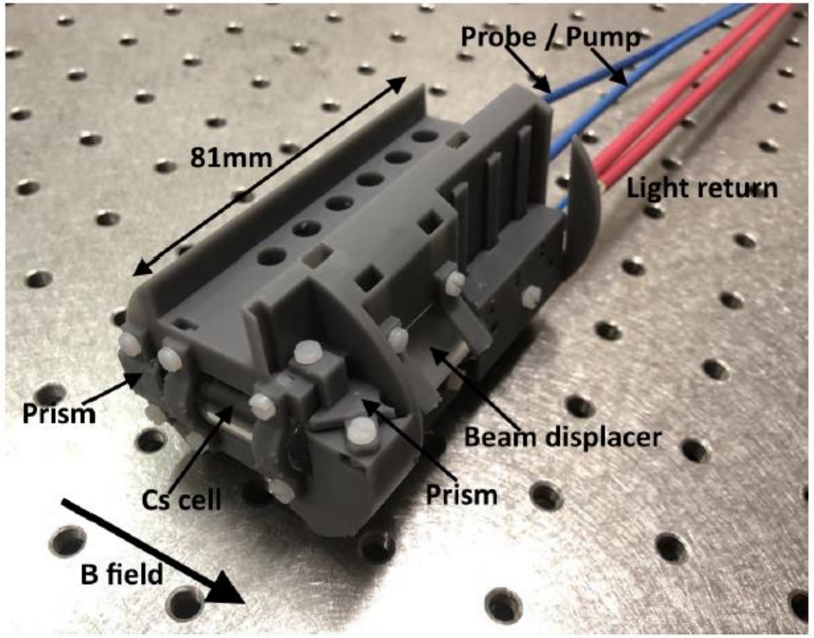
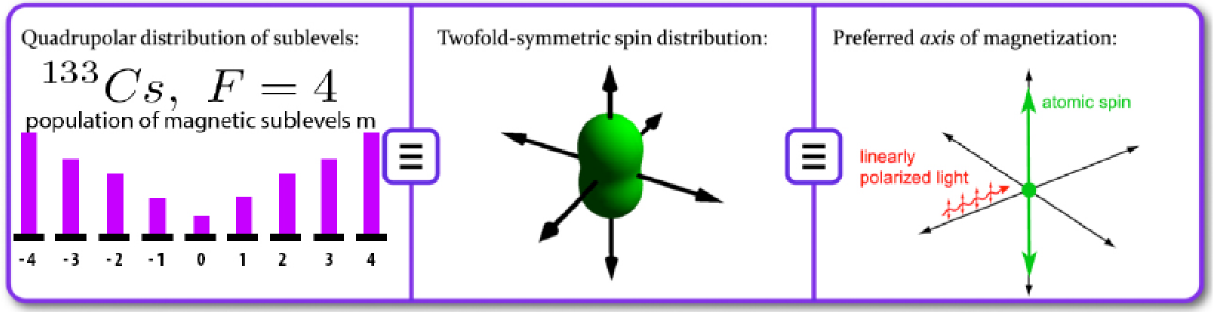
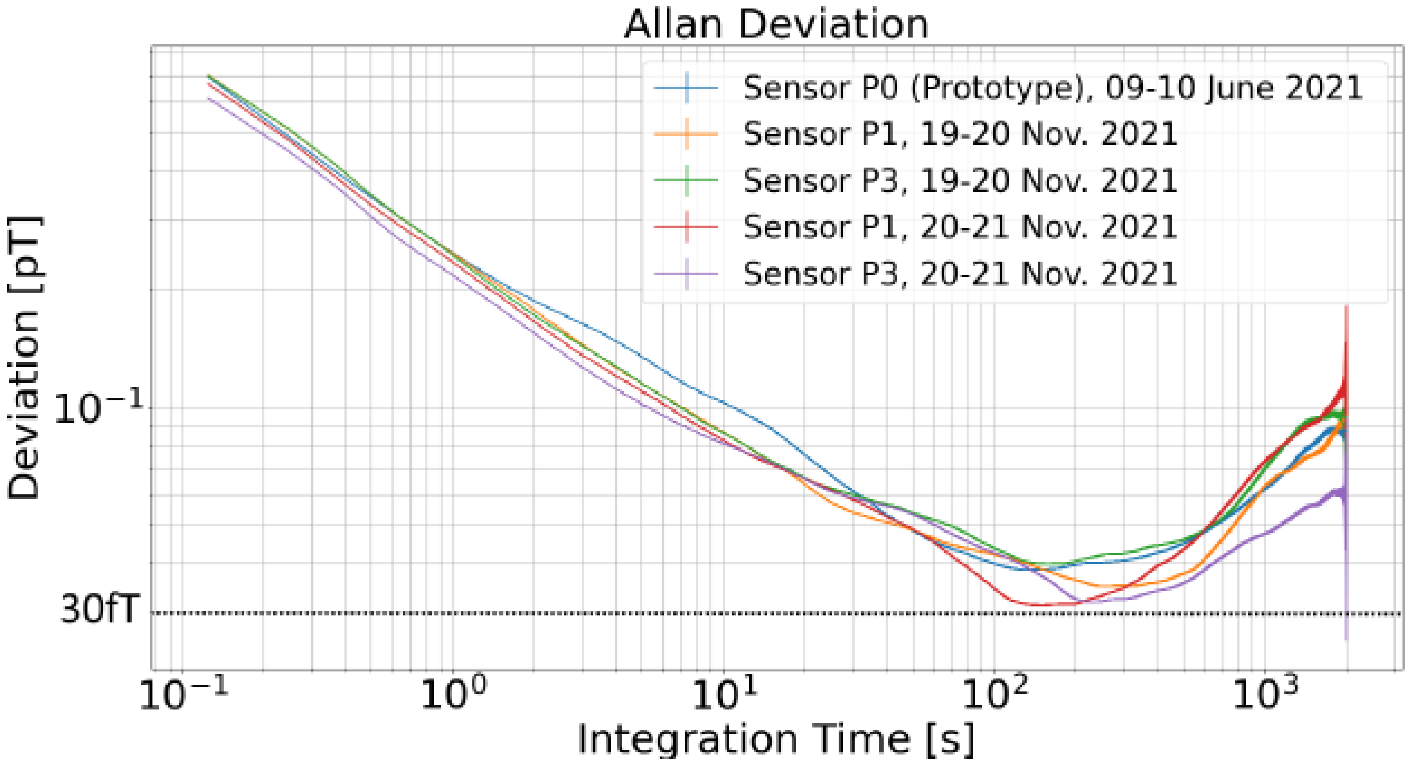
Cesium Magnetometry

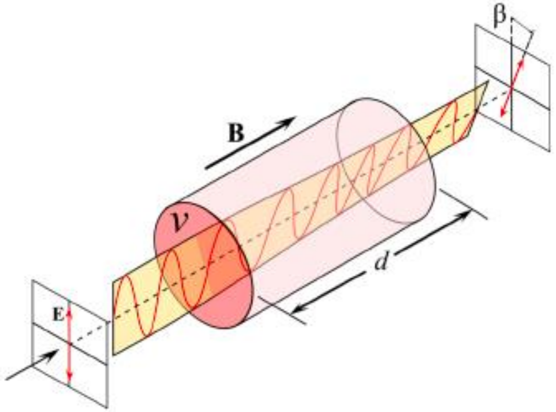




Cesium Magnetometry



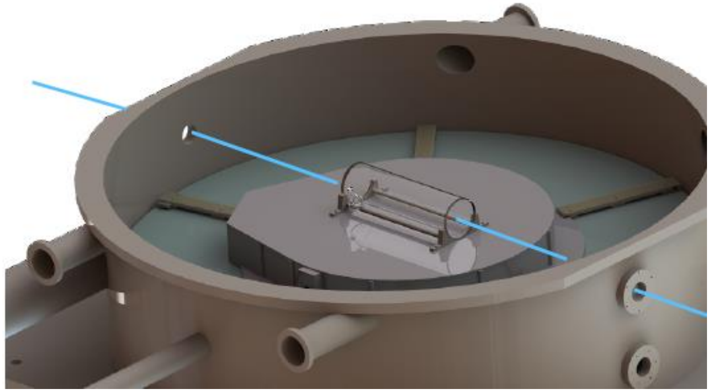




- Below 50 fT stability between 70 - 600 seconds integration
- Using a SQUID-stabilized bias field at BMSR-2, PTB Berlin
- For >100 s integration, limited by field drifts
- Compatible with longer holding times in EDM cycles

Appl. Phys. Lett. 120, 161102 (2022)

Comagnetometry: PanEDM phase I



- Cell dimensions match the ~250s holding time for UCN
- 12 fT sensitivity in 100s
- Need 4 fT differential across the stack, for phase I
- Ultimately need global gradients below ~300 pT/m
- Local dipoles below 2 pT at 3cm
- Challenging to constrain HV-correlated local dipoles without long measurements

EPJ Web of Conferences 219, 02006 (2019)

EDM Workshop in Trento: 4-8 March, 2024

FONDAZIONE BRUNO KESSLER | ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

<u>EDMs: complementary experiments and theory connections</u>

Organizers:

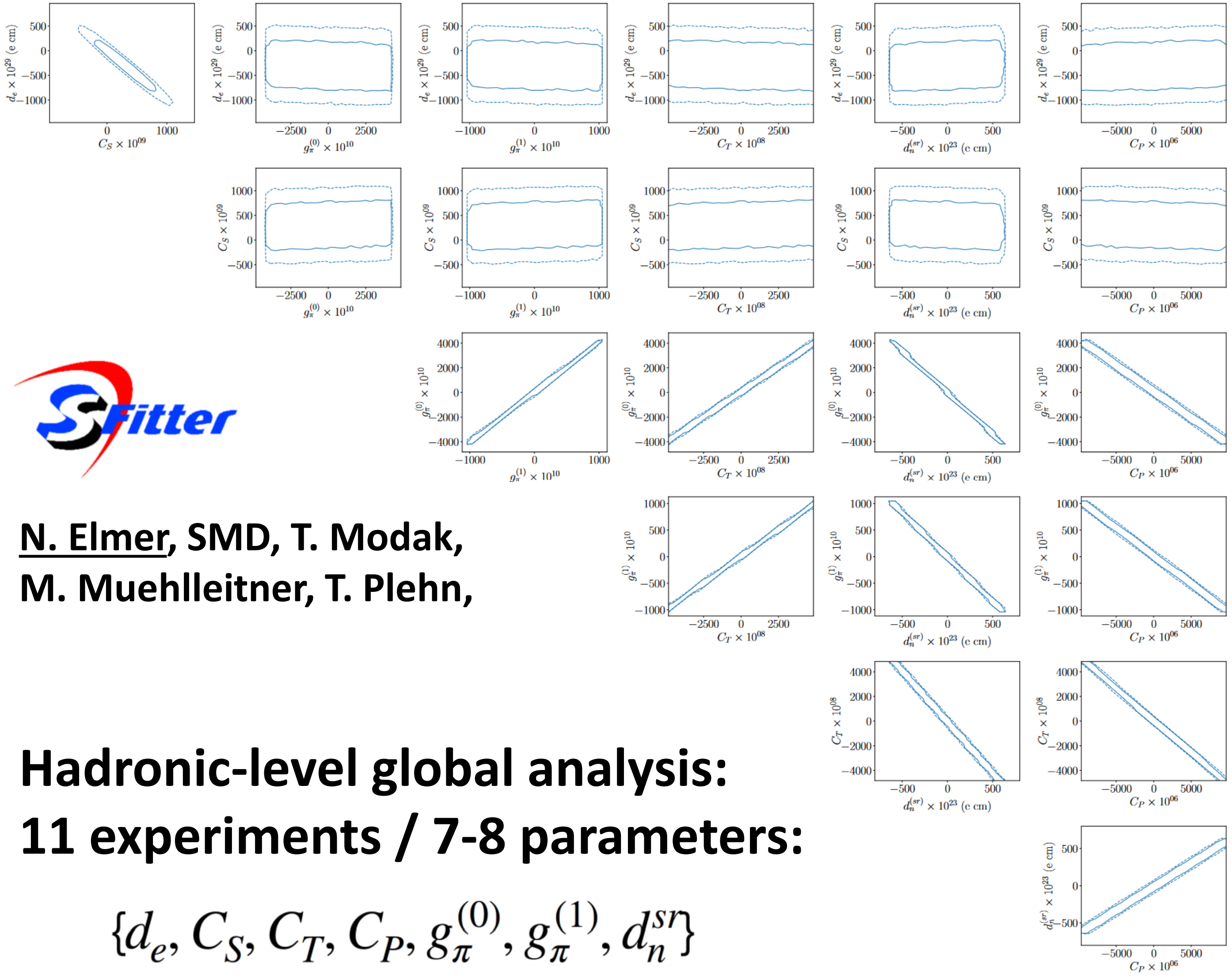
Skyler Degenkolb (U. Heidelberg)
Robert Berger (U. Marburg)
Jordy de Vries (U. Amsterdam/Nikhef)
Guillaume Pignol (LPSC Grenoble)
Philipp Schmidt-Wellenburg (PSI)
Bira van Kolck (IJCLab / U. Arizona)

Allied event: INT Program INT-24-1 at U. Washington

Permanent electric dipole moments (EDMs) provide a key experimental test of Standard Model CP-violation, and a means to search for and constrain the new physics processes needed to explain our universe's observed matter-antimatter asymmetry. This motivation and impact on high-energy physics unites EDM research, which nevertheless relies on a diverse set of experimental methods and theoretical tools to fully develop its potential. This workshop is based in a European initiative to identify and strengthen connections among the groups pursuing improved measurements and calculations, as well as conceptual bridges such as phenomenology and global analysis. The major classes of experimental systems are represented (leptons, hadrons, bare nuclei, diamagnetic and paramagnetic atoms and molecules), and key theoretical topics for the interpretation of experimental results are emphasized (nuclear DFT, lattice QCD, atomic and molecular structure, chiral EFT) in addition to dedicated calculations of observables arising from specific models.

Other Heidelberg EDM activities

^{129}Xe EDM and magnetometry



N. Elmer, SMD, T. Modak,
M. Muehlleitner, T. Plehn,

Hadronic-level global analysis:
11 experiments / 7-8 parameters:

$$\{d_e, C_S, C_T, C_P, g_\pi^{(0)}, g_\pi^{(1)}, d_n^{sr}\}$$

Seeking students and Post-Docs!

xkcd.com

Faddeev-Popov?

Questions?

what-if.xkcd.com

Special thanks to:

SuperSUN-PanEDM collaboration
Institut Laue-Langevin, NPP division
Institut Laue-Langevin, SANE division
Technical staff: ILL, HD, TUM, …

S-DH, GmbH

Reminder, for more on SuperSUN:
→ See Estelle's talk, today at 17:05

Current PanEDM Contributors

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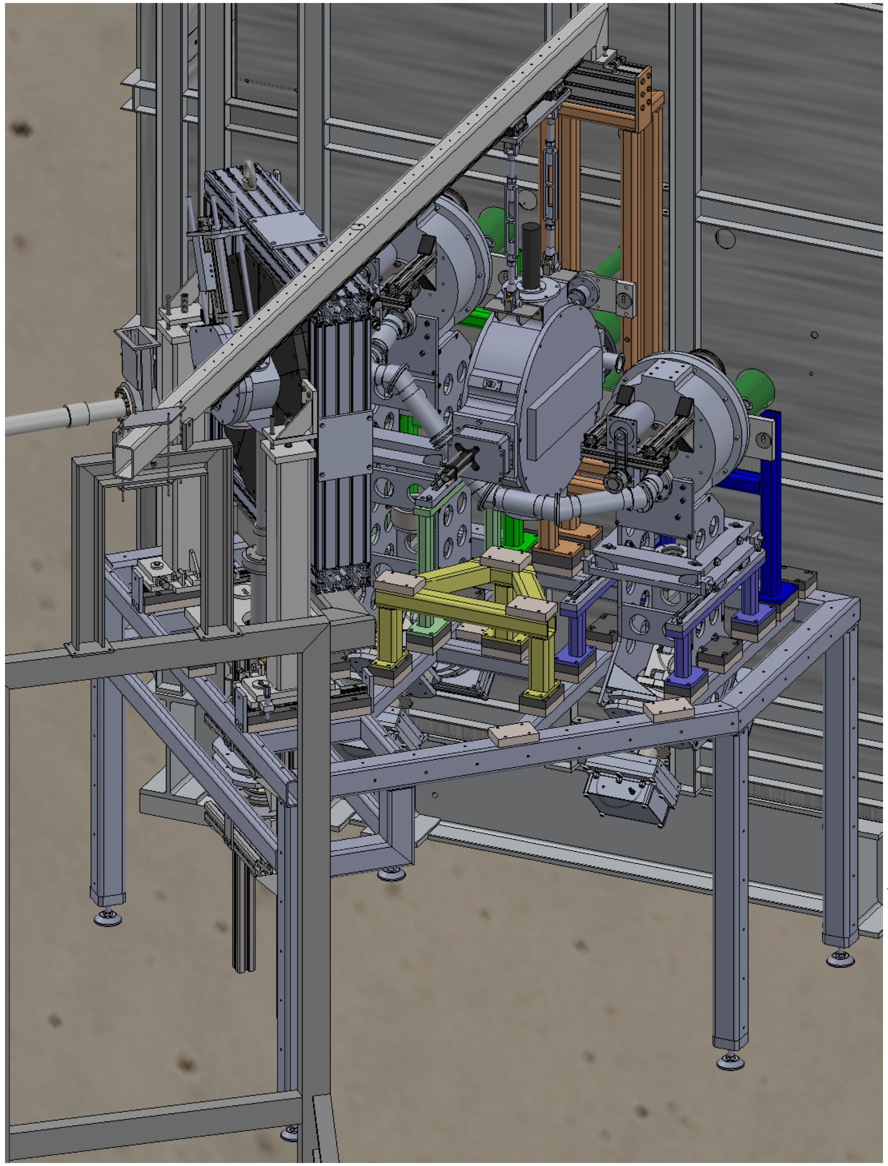
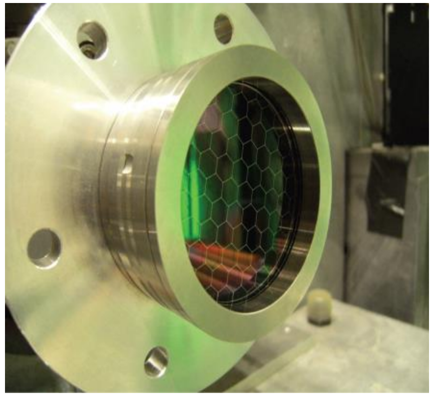
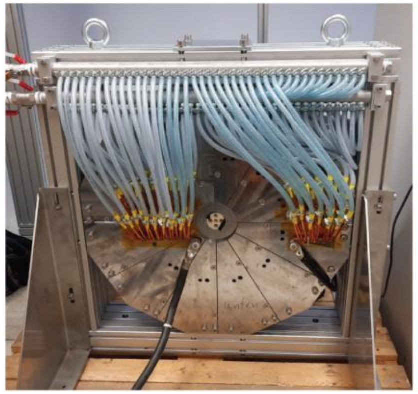
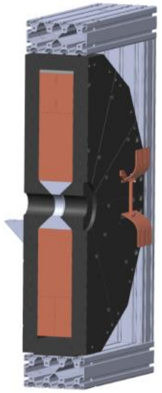
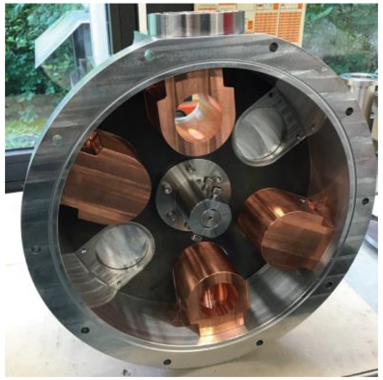
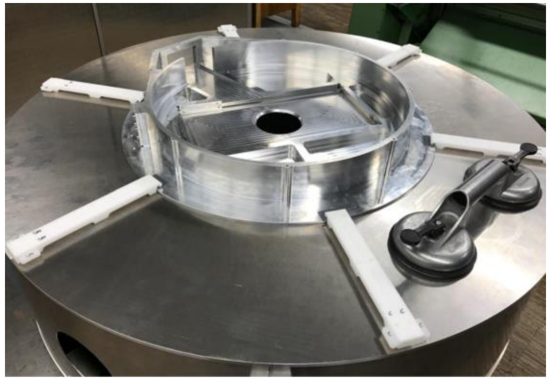
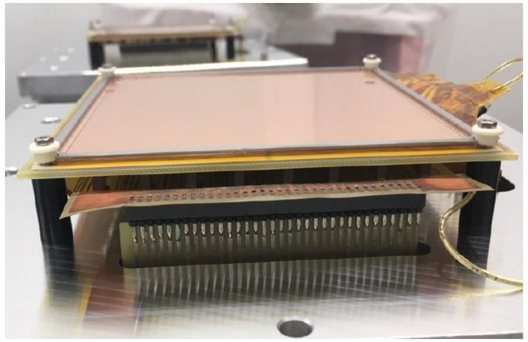
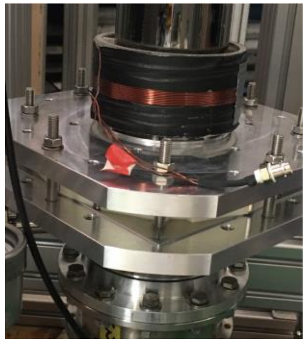
*cospokespersons

Elements of the SuperSUN-PanEDM Interface

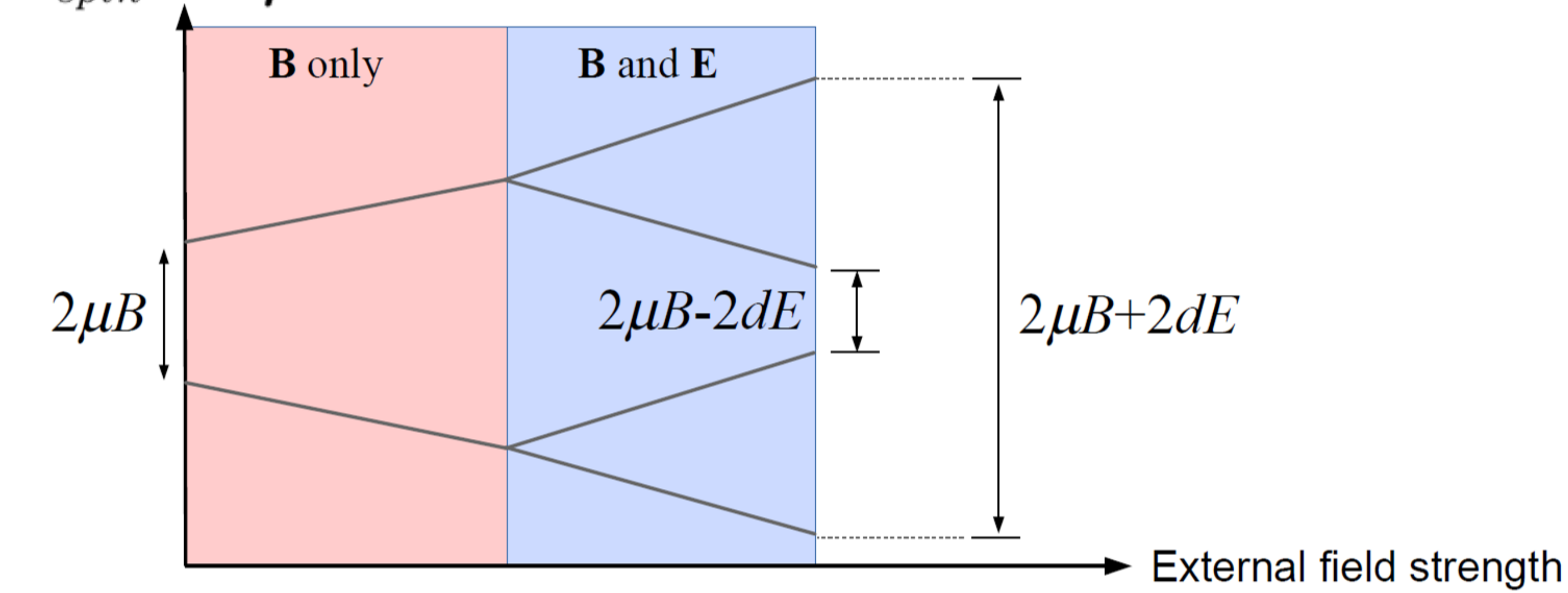


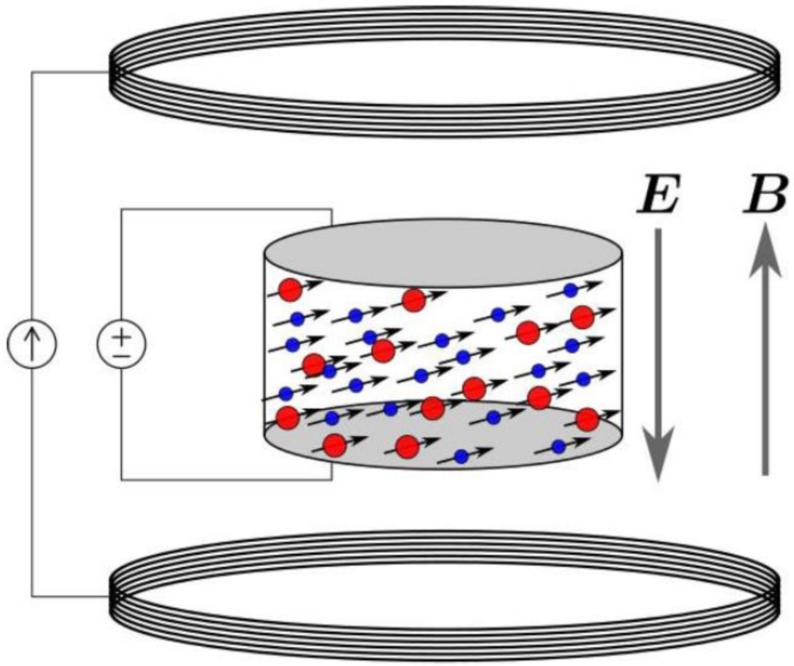


Comagnetometry

$$H_{spin} = -\boldsymbol{\mu} \cdot \mathbf{B} - \mathbf{d} \cdot \mathbf{E}$$





$$\hbar(\omega_+ - \omega_-) = 4dE$$

…up to drift, gradients, etc.

Statistics considerations

Statistics

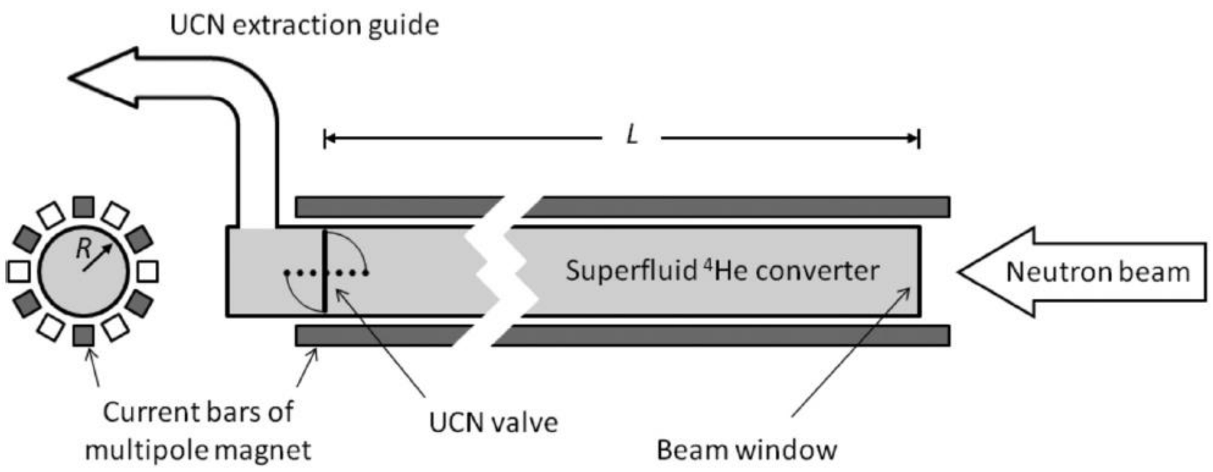
- Flux vs. *density* → $$N_{\rm cell} \sim \rho_{\rm cell} V_{\rm cell} \sim \frac{\rho_{\rm source} V_{\rm cell}}{1 + \frac{V_{\rm cell}+V_{\rm guide}}{V_{\rm source}}}$$
  - want to count many UCN, after storage
  - transport losses and dilution
- Storage time (including T_1/T_2) → $$\frac{1}{\tau} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{\rm up}} + \frac{1}{\tau_{\rm capture}} + \frac{1}{\tau_{\rm wall}} + \cdots$$
- Total measurement time/repetitions
  - duty factor vs. accumulation time
  - long-term stability becomes important
- Polarization (incl. analyzing power)
- Electric field
- Cold neutron losses

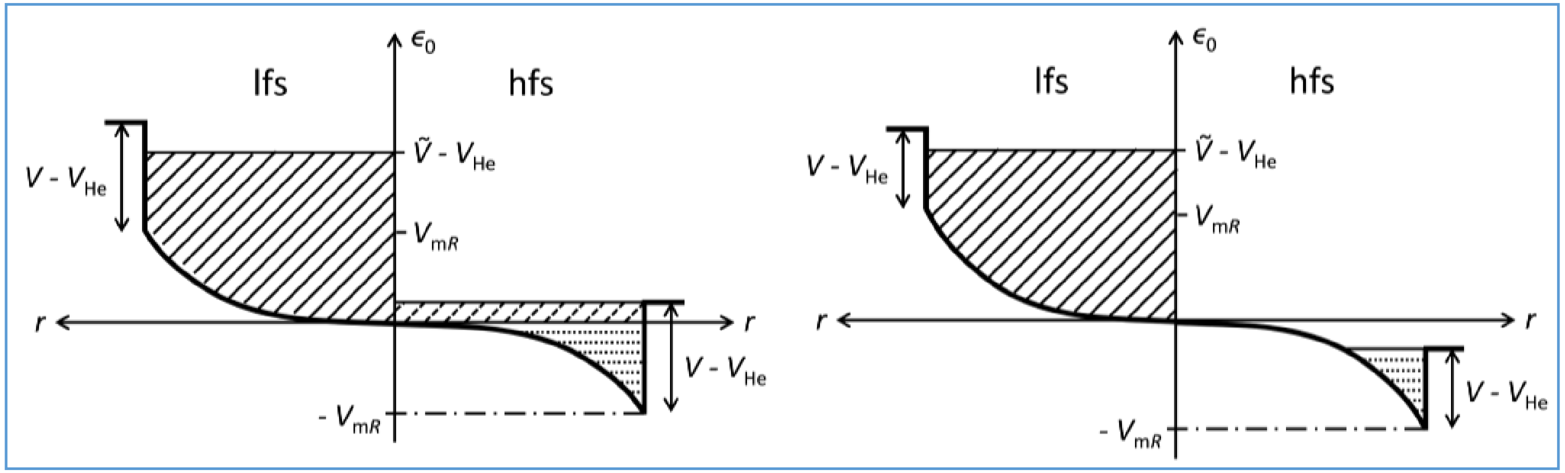
Systematics (not exhaustive)

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

Minimizing UCN Storage losses

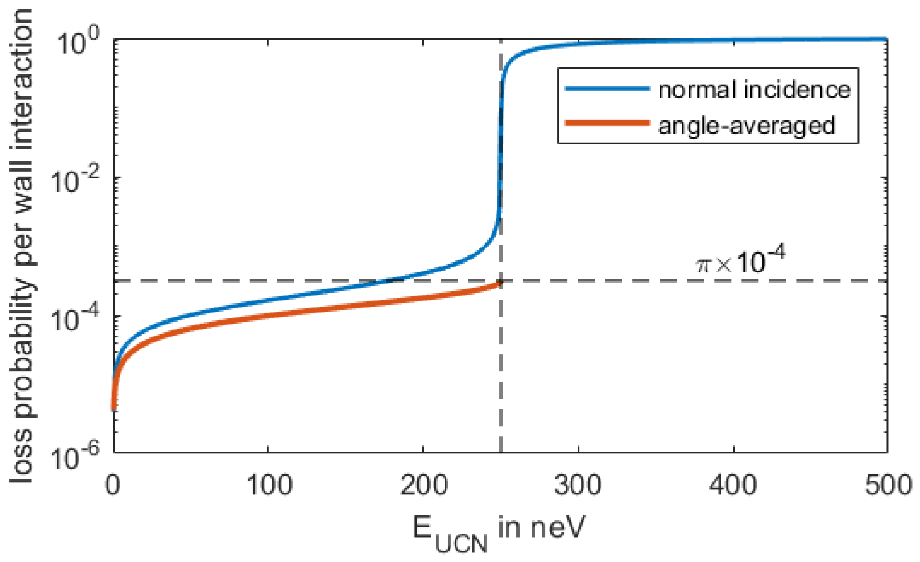
SuperSUN phase II: magnetic octupole reflector

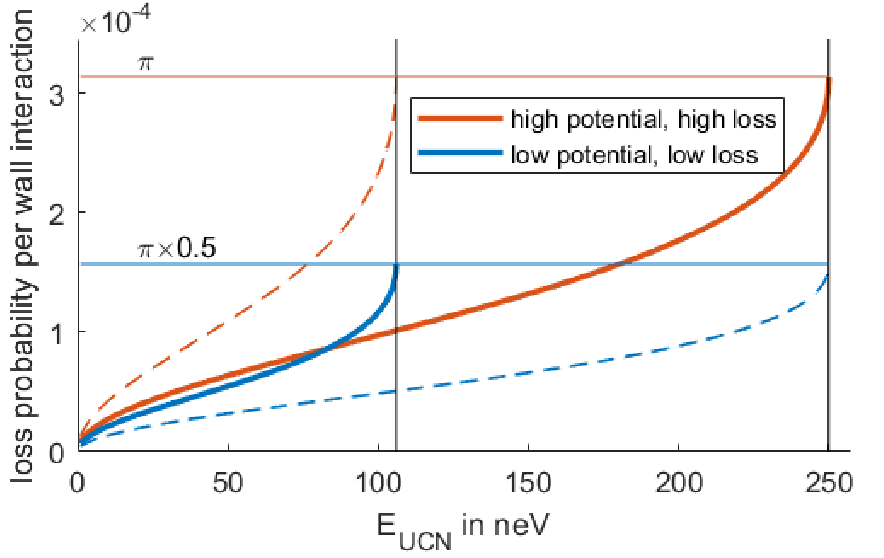




Phys. Rev. C **92**: 015501 (2015)

Material wall potentials

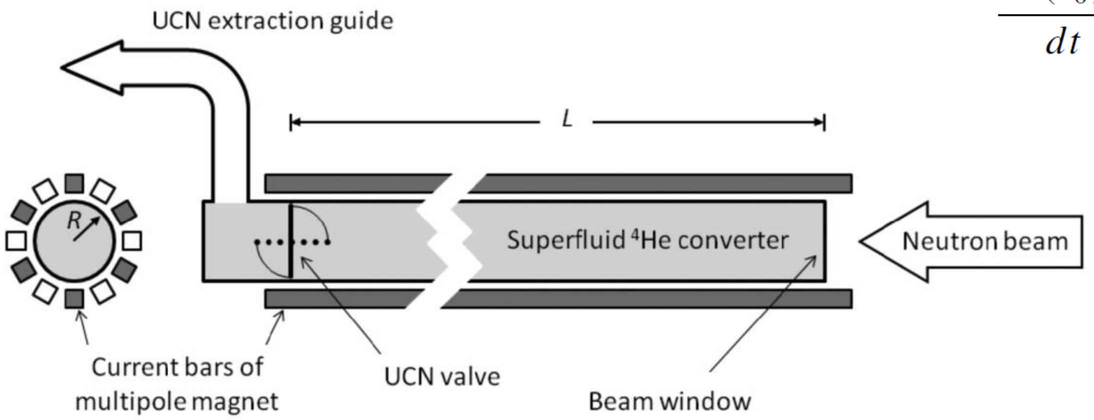


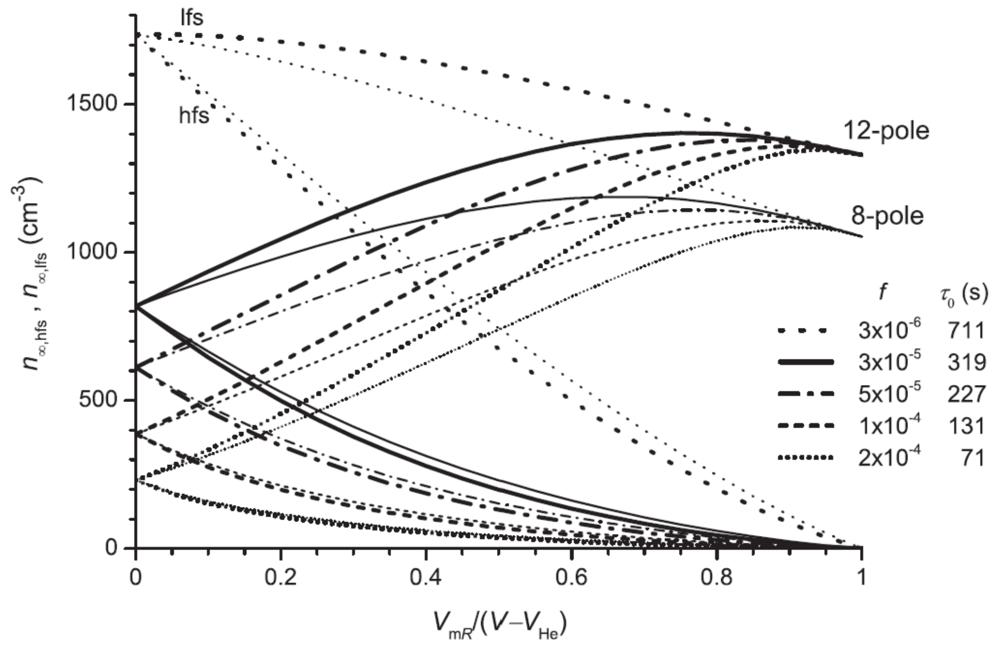


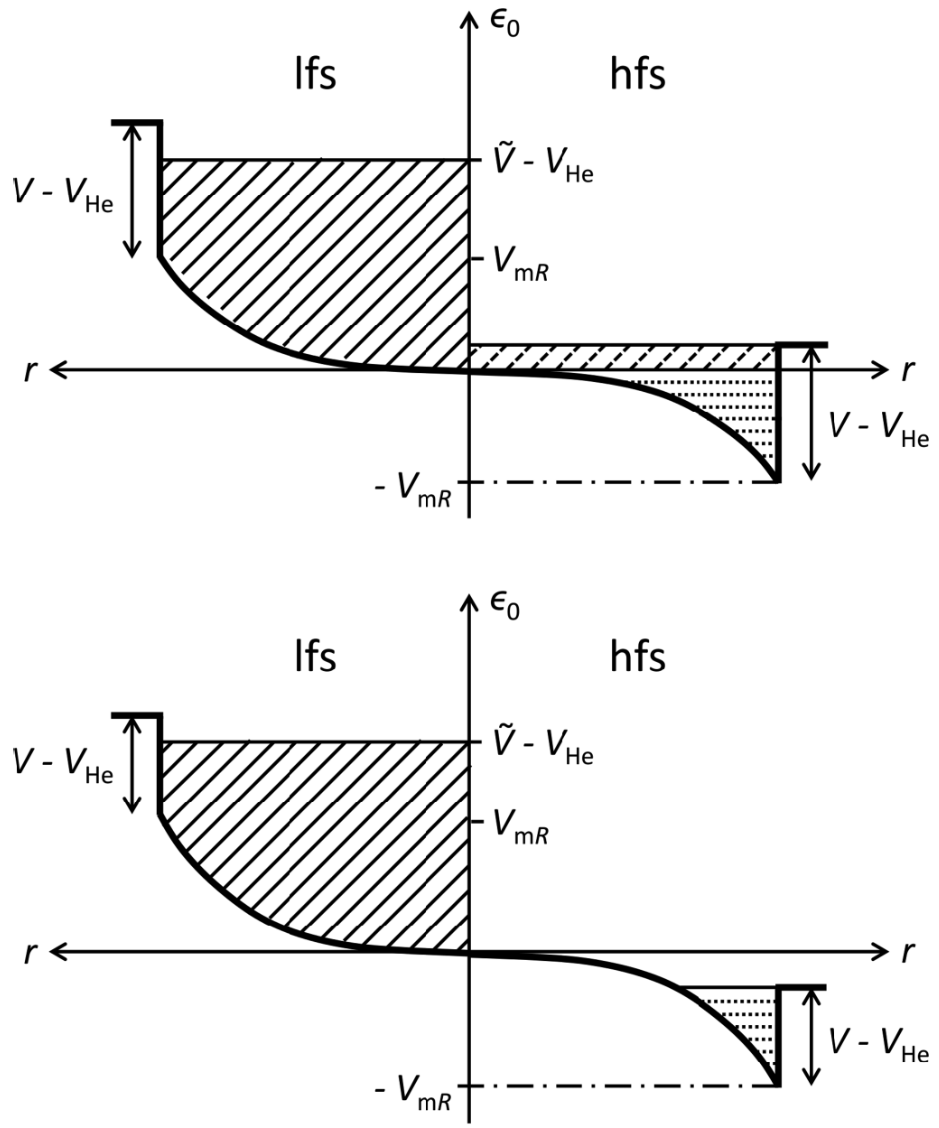
Minimizing UCN Storage losses

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

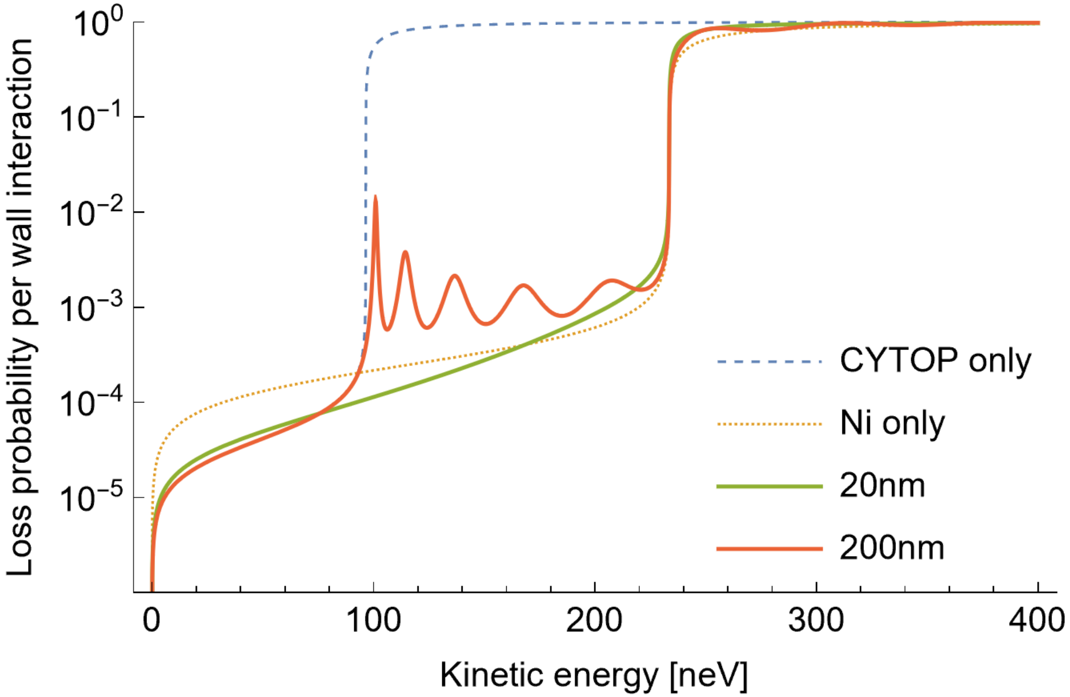
$$\frac{dn(\epsilon_0,t)}{dt} = p(\epsilon_0) - \frac{n(\epsilon_0,t)}{\tau(\epsilon_0)}$$

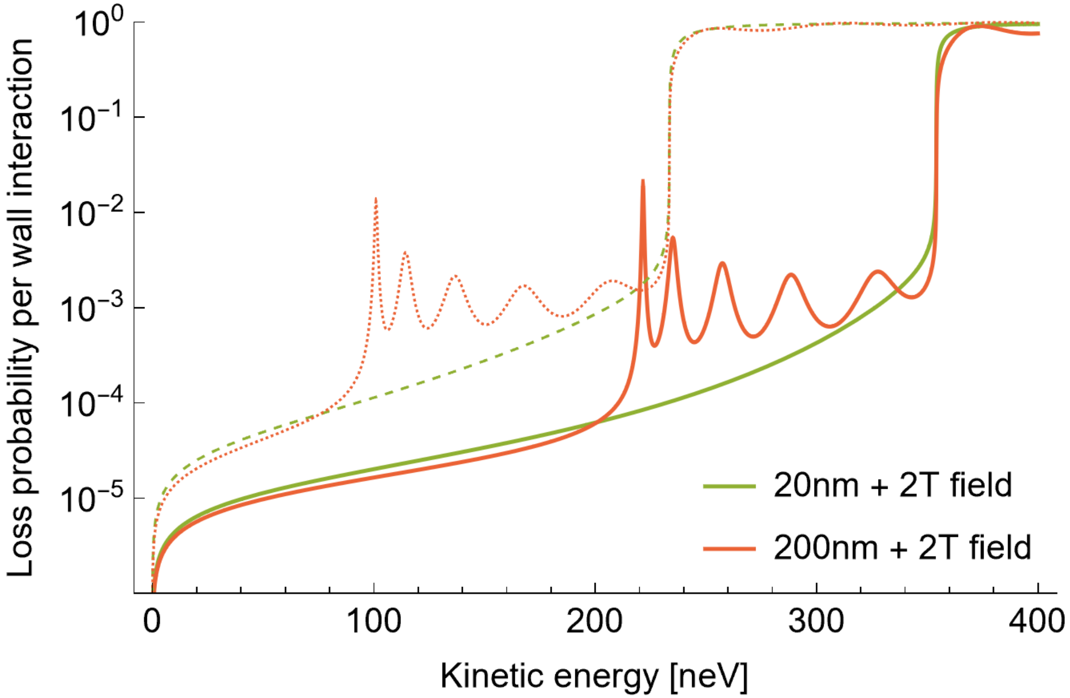




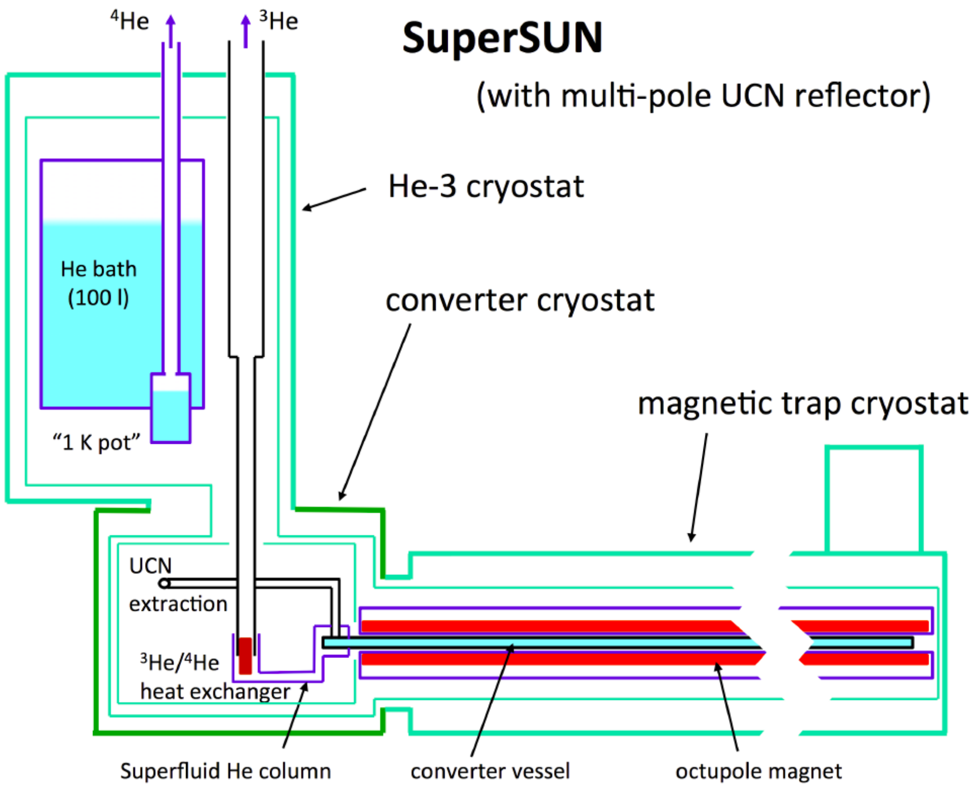


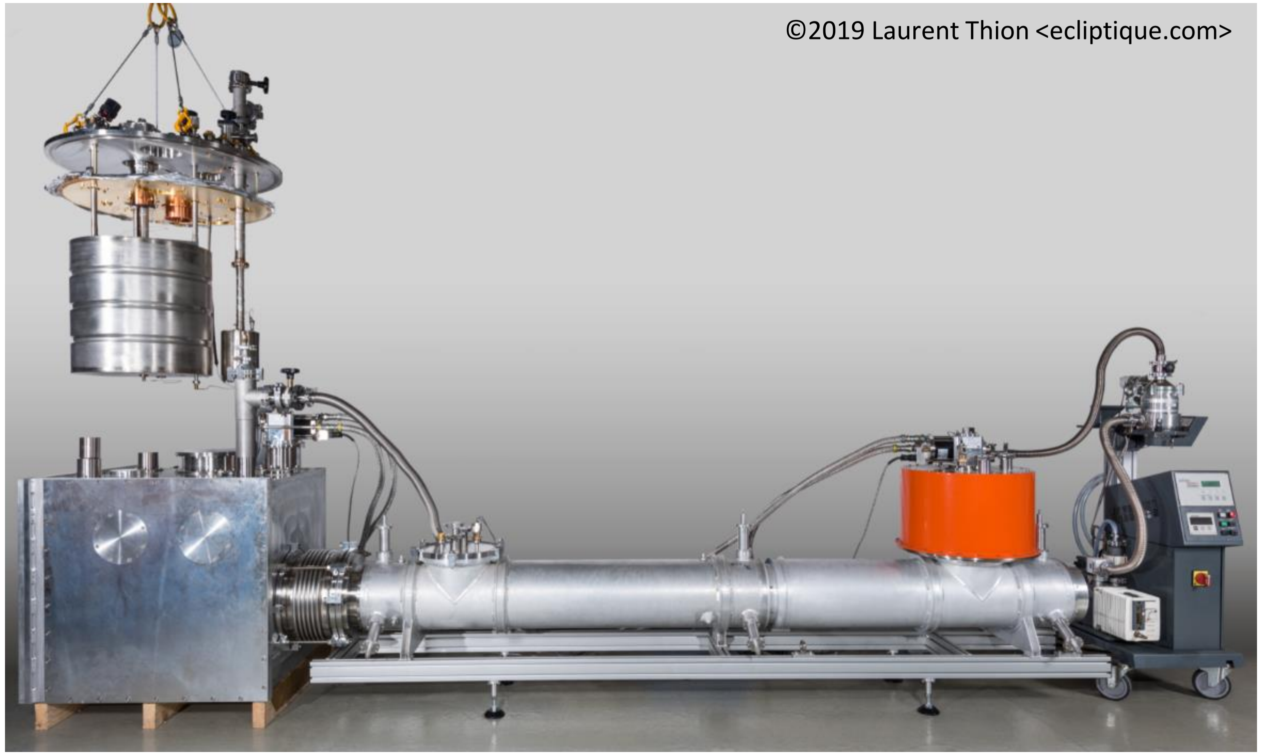
Minimizing UCN Storage losses





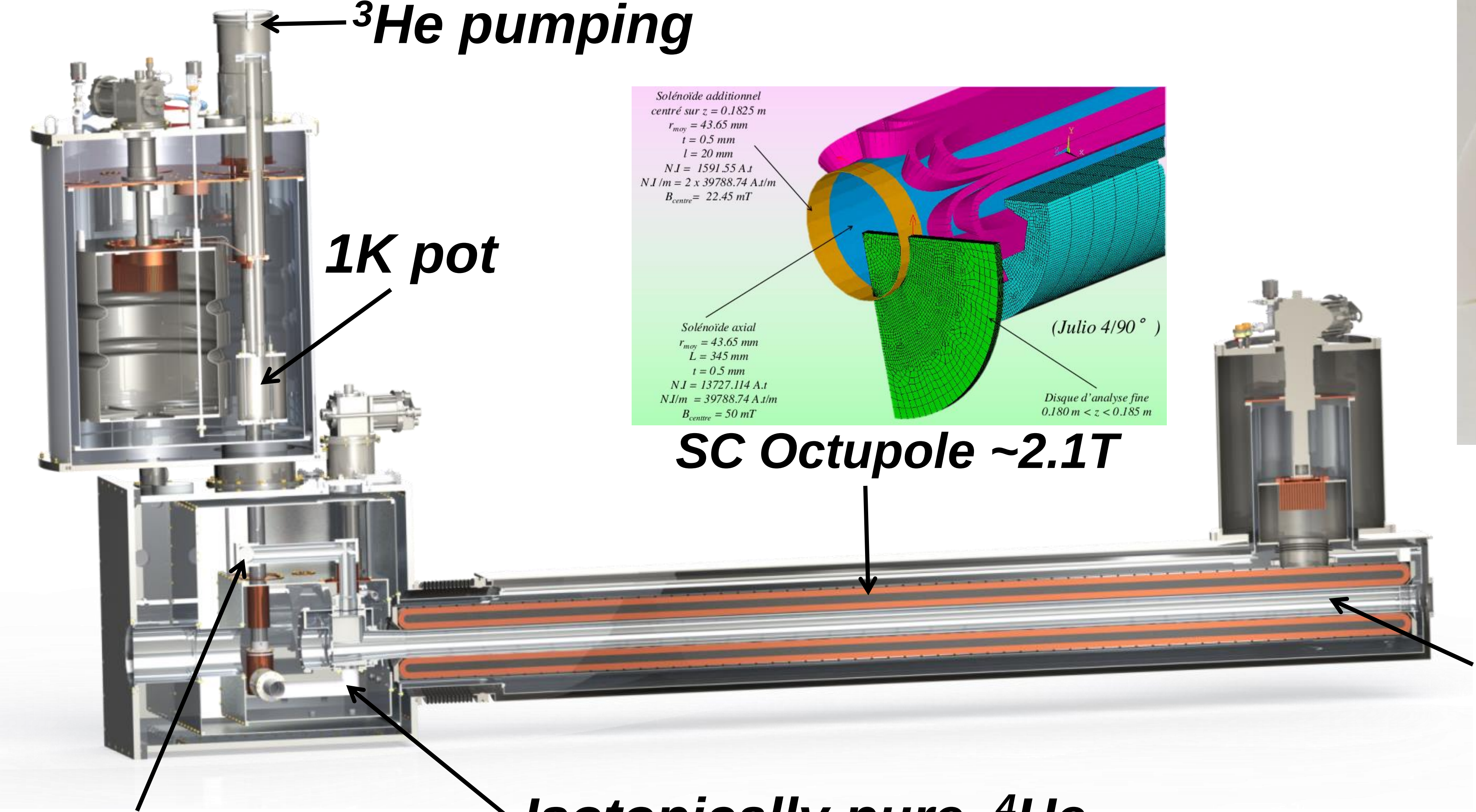
SuperSUN Neutron Source: Cutaway





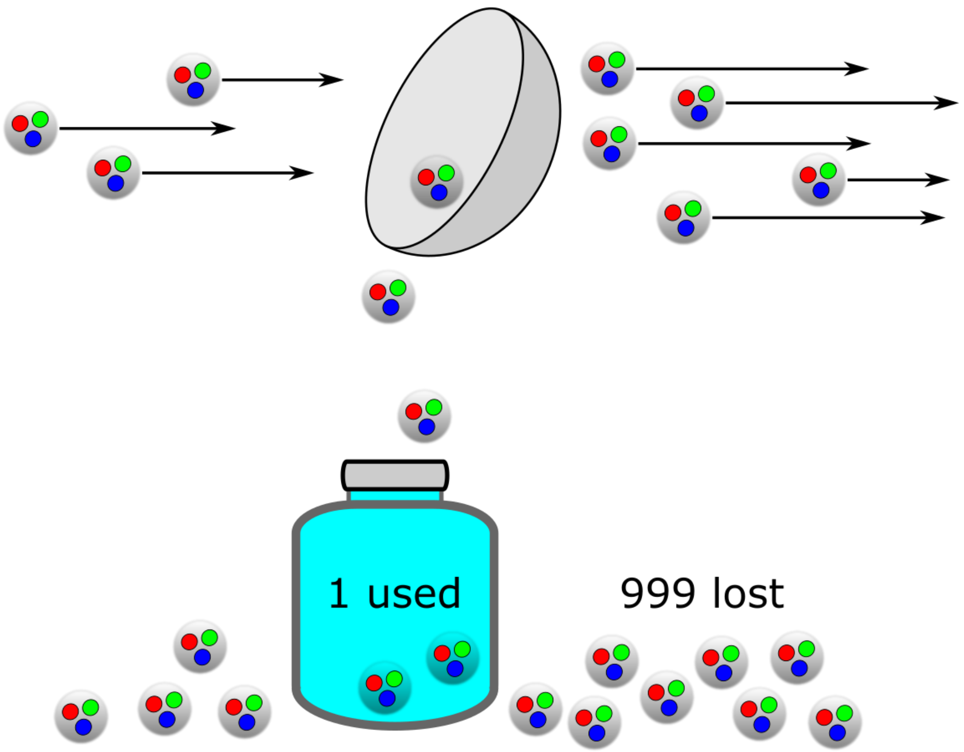
Demonstrated 100mW cooling power at 0.6 K

SuperSUN Neutron Source: Cutaway

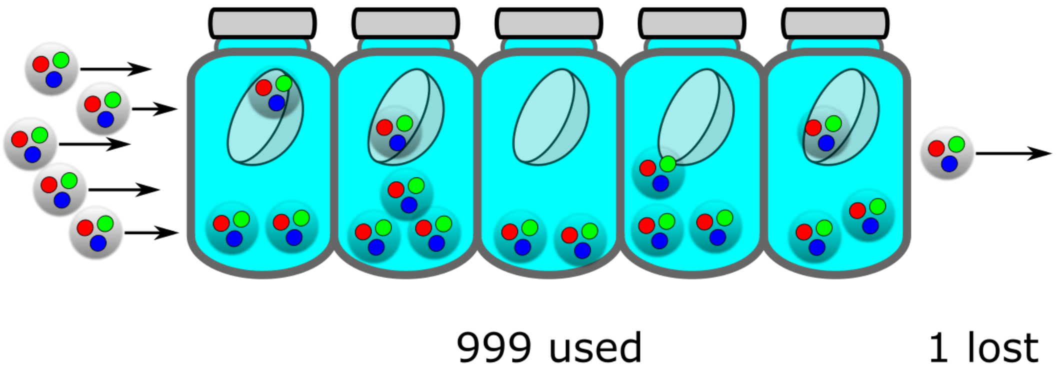


Statistics: our biggest challenge

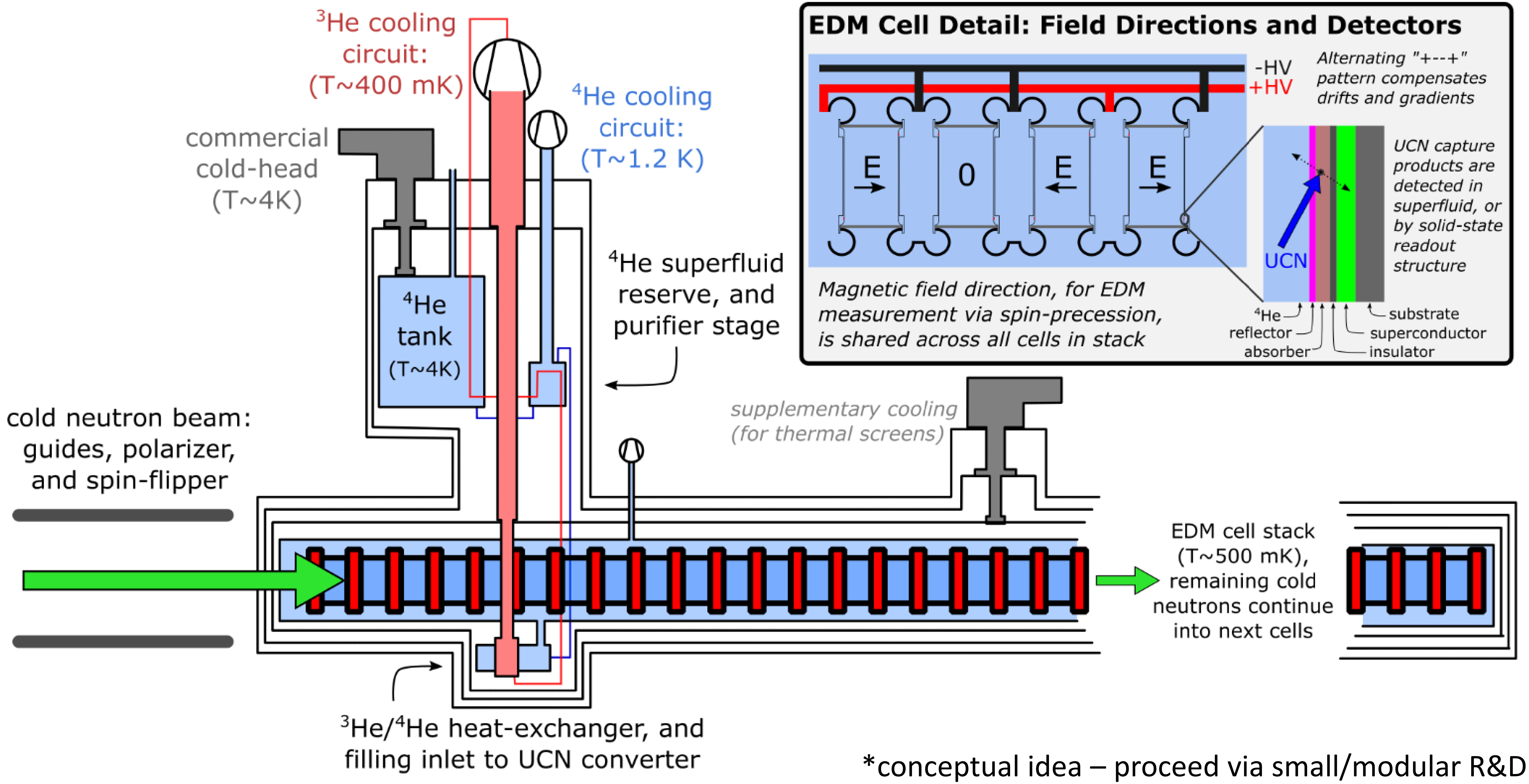
State of the art: catch/pour
...with 0.1% success



New approach: catch them **all**, directly in many bottles

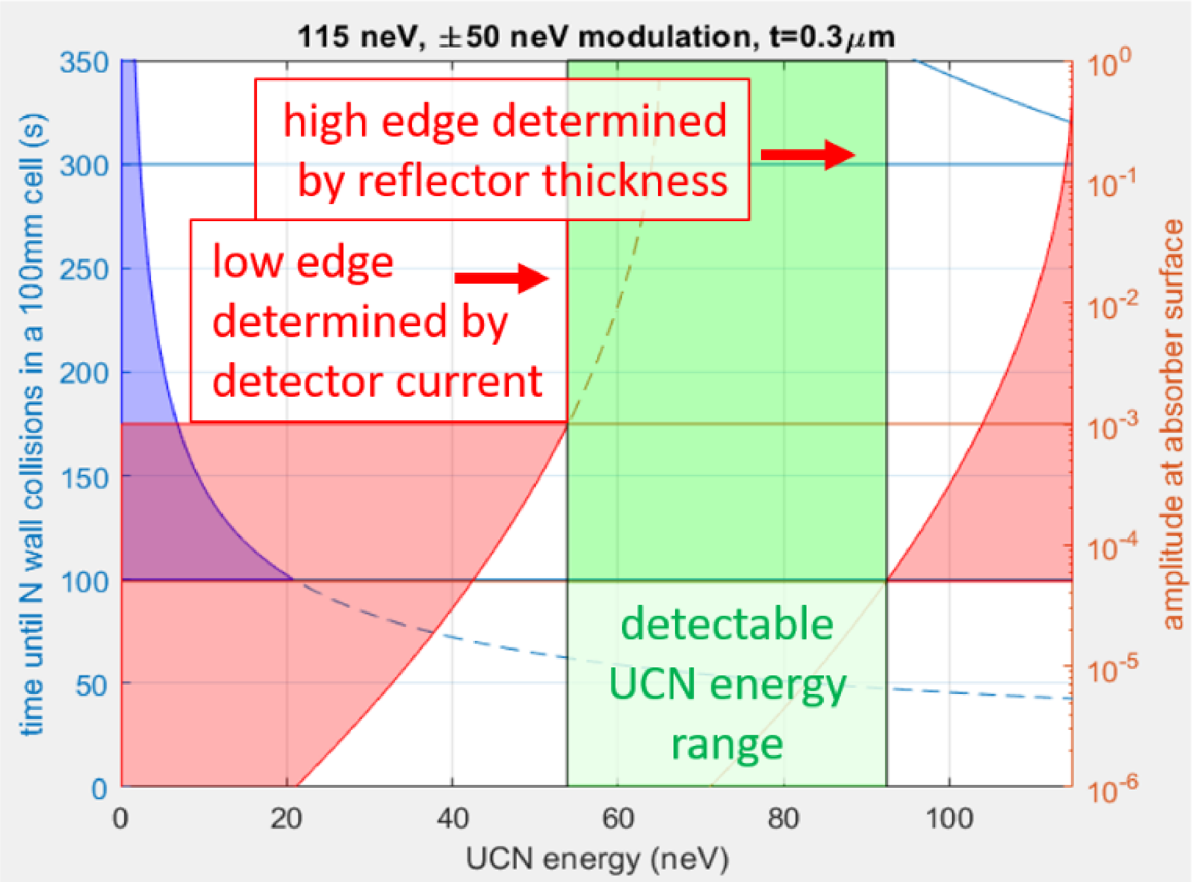


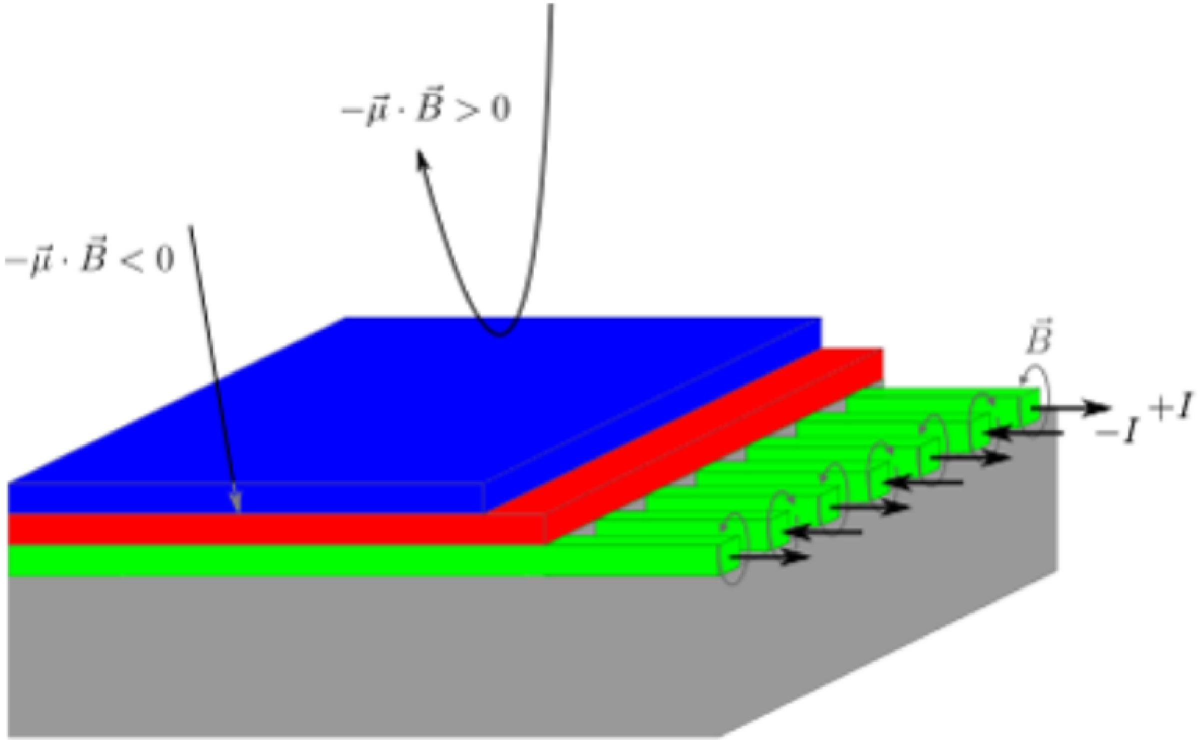
The next generation*… scaling up!



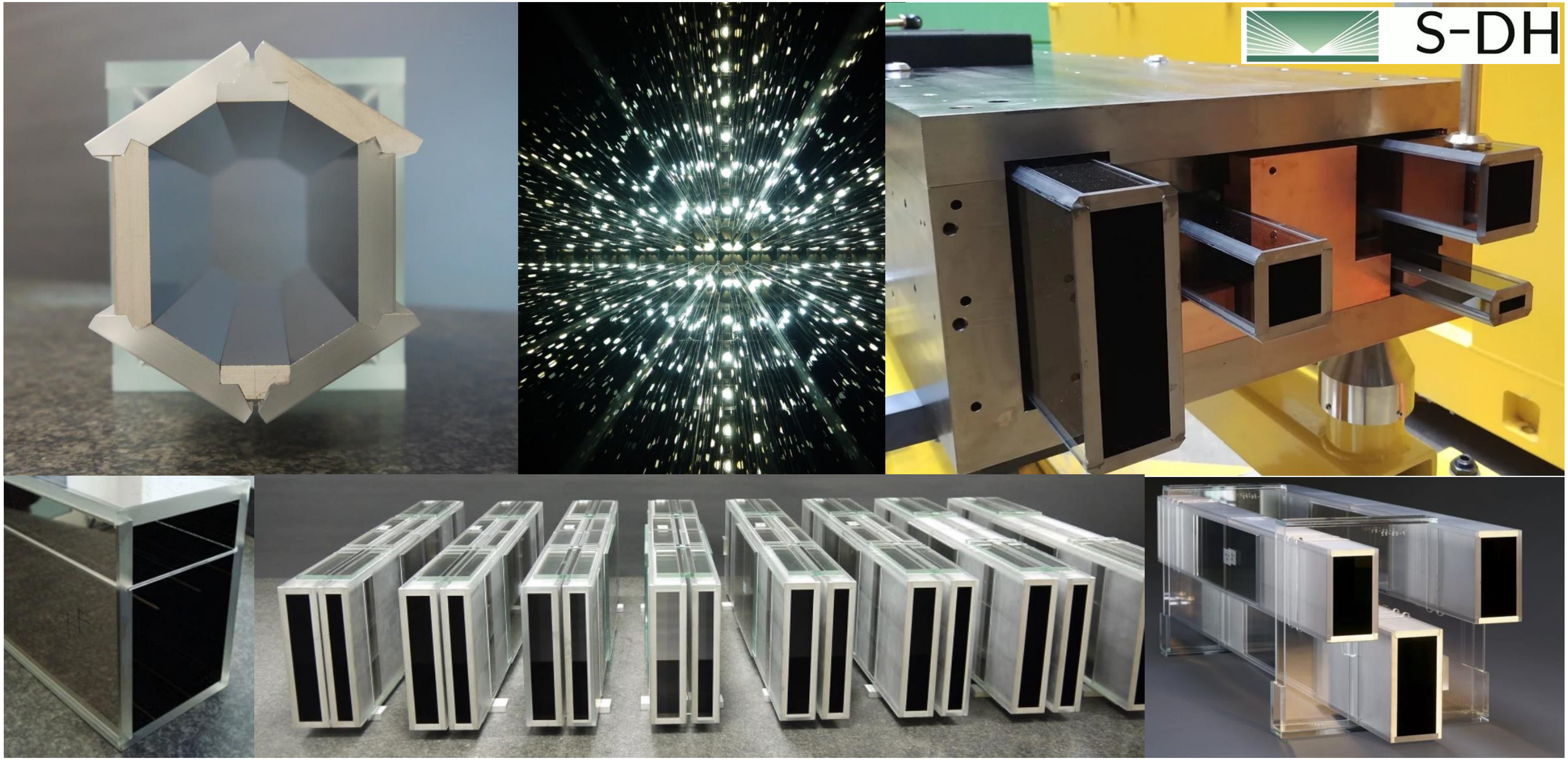
*conceptual idea – proceed via small/modular R&D steps

“Quantum Sensing”: Spin and Energy





Some Neutron Guides



Neutron Guides