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The Los Alamos Neutron Electric Dipole Moment Experiment

I. Some introductory material to put nEDMs in perspective

II. Measureing the nEDM

III. The LANL nEDM experiment

IV. Outlook

U.S. DEPARTMENT OF ENERGY
Office of Science

APS physics

GORDON AND BETTY MOORE FOUNDATION

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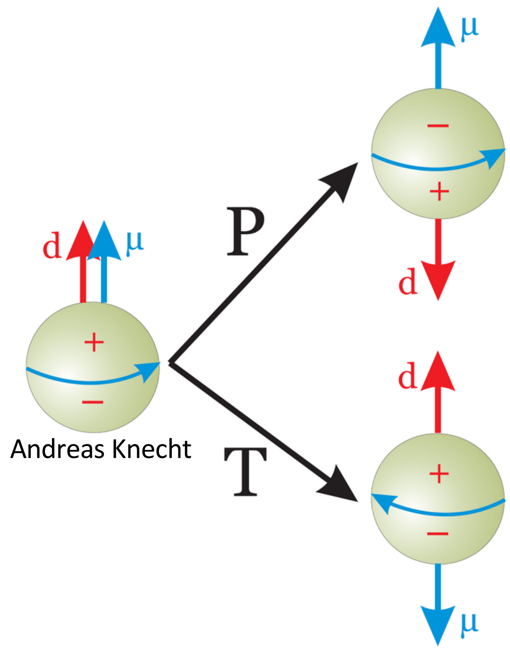
Electric Dipole Moment

$$\vec{d} = \int \vec{r}(\rho_Q(\vec{r}) - \rho_m(\vec{r}))dV = d\vec{J}$$



Put this in *E* and *B* fields

$$H = -\vec{\mu}\cdot \vec{B} - \vec{d}\cdot \vec{E} = -\mu\vec{J}\cdot \vec{B} - d\vec{J}\cdot \vec{E}$$

$P_e T_e$ $P_o T_o$ └ $\not{C}\not{P}$

$\not{C}\not{P} \longleftrightarrow$ Baryon Asymmetry $\longleftrightarrow$ NEW PHYSICS (BSMP)

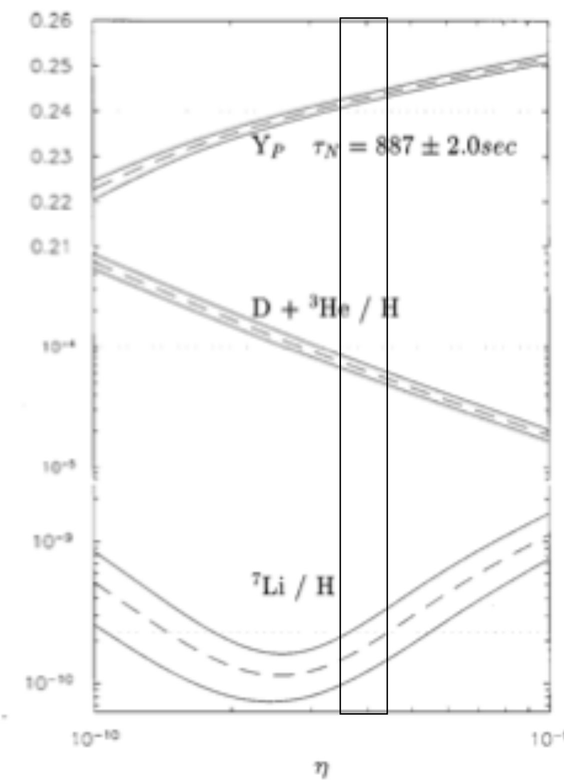
Baryon Asymmetry requires BSMP

$\not{CP} \longrightarrow$ Baryon Asymmetry $\longrightarrow$ NEW PHYSICS (BSMP)

Fact: There is more matter than antimatter

$$n_p \neq n_{\bar{p}} \quad \eta = \frac{n_p - n_{\bar{p}}}{n_p + n_{\bar{p}}} \approx few \times 10^{-10}$$

(WMAP/PLANCK, $[^4\mathrm{He}]_{,,\ldots}$)



How? A) Initial condition – NO (inflation)

B) Evolution from η=0

1) Baryon number violation

2) **CP Violation make and EDM**

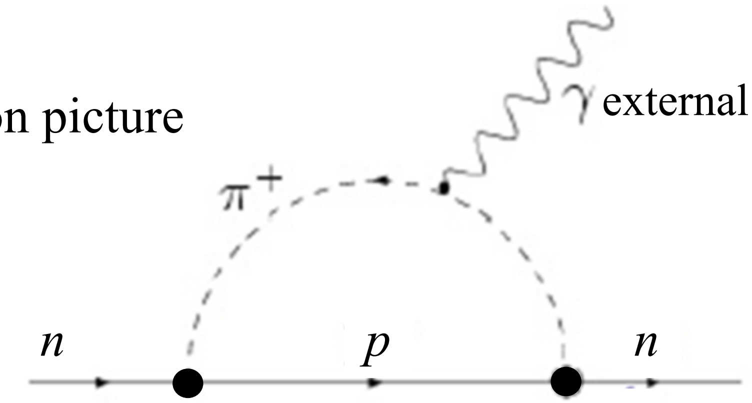
3) Rapid expansion (non-equilibrium)

A. Shakarov
Nobel Peace Prize 1975

Another possibility: CP violation in neutrinos + “seesaw”

Magnetic Dipole Moment

Pion-nucleon picture



external E-M field ($F_{\mu\nu}$)

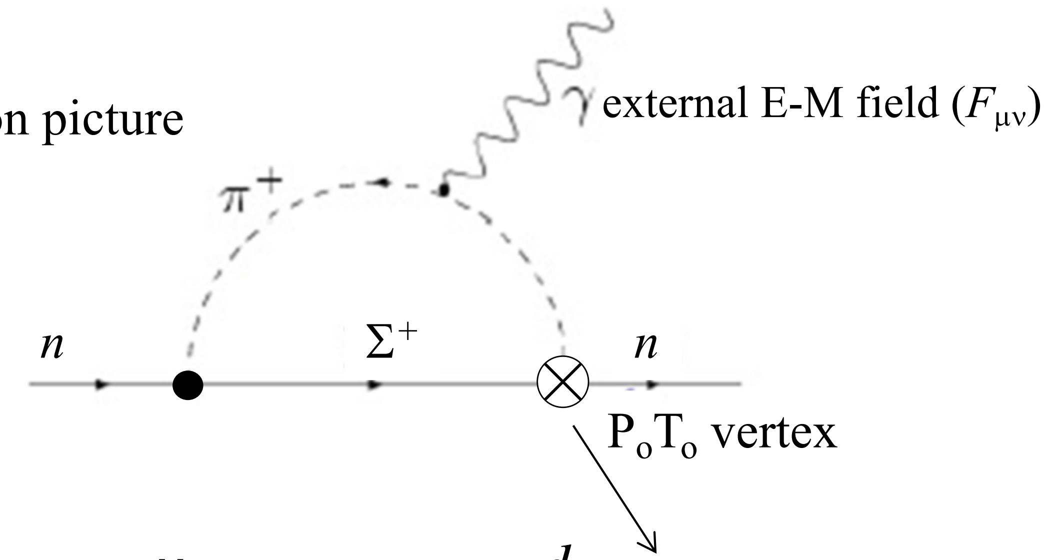
fermion

$$\mathcal{L}_{EM} = -\frac{\mu}{2}\bar{\Psi}\sigma^{\mu\nu}F_{\mu\nu}\Psi$$

$$H = -\mu\vec{\sigma}\cdot\vec{B}$$

Electric Dipole Moment

Pion-nucleon picture



$$\mathcal{L}_{EM} = -\frac{\mu}{2}\bar{\Psi}\sigma^{\mu\nu}F_{\mu\nu}\Psi - \frac{d}{2}\bar{\Psi}\sigma^{\mu\nu}i\gamma^5 F_{\mu\nu}\Psi$$

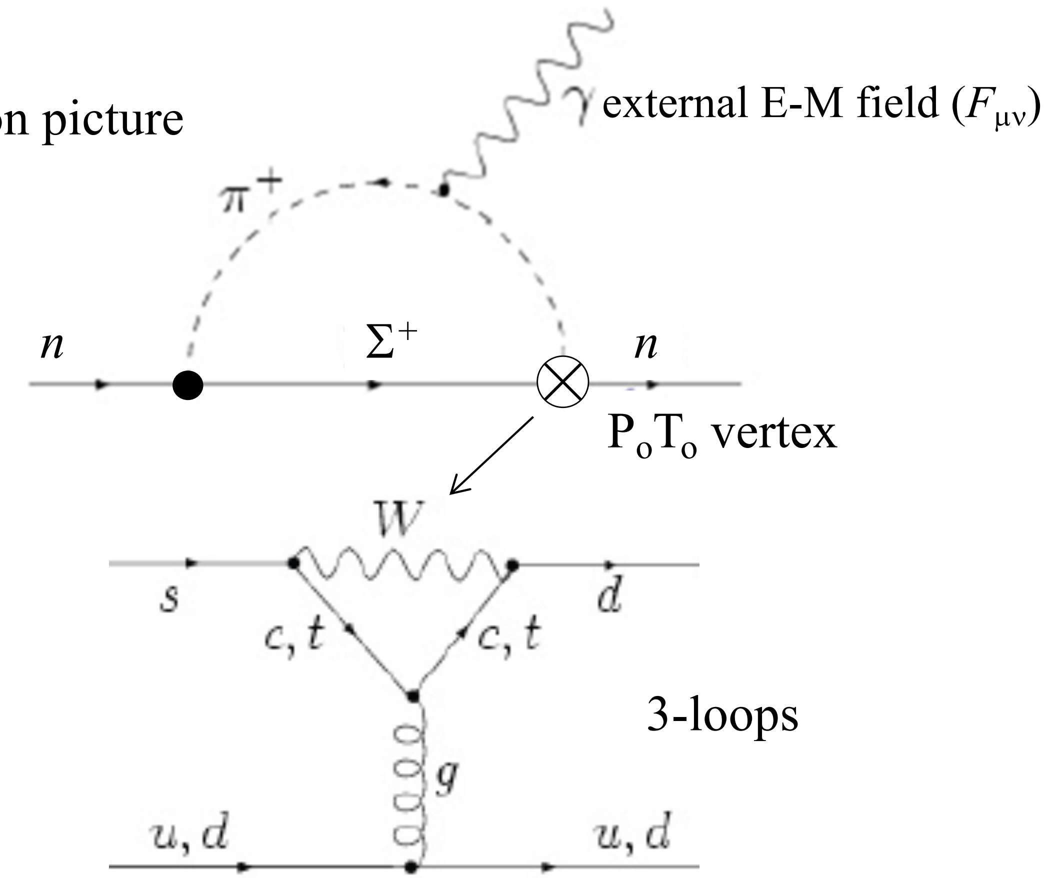
↓

$$H = -\mu\vec{\sigma}\cdot\vec{B} - d\vec{\sigma}\cdot\vec{E}$$

Standard-model/CKM EDMs small

Vanish at 2-loops for quarks and 3-loops for leptons
Khriplovich, Zhitnitsky (1982), McKellar et al., (1987)

Pion-nucleon picture



$d_n^{SM} \approx 10^{-32}$ e cm; $d_n^{exp} < 3\text{x}10^{-26}$ e cm

DISCOVERY POTENTIAL!

EDMs ALSO probe TeV-scale physics

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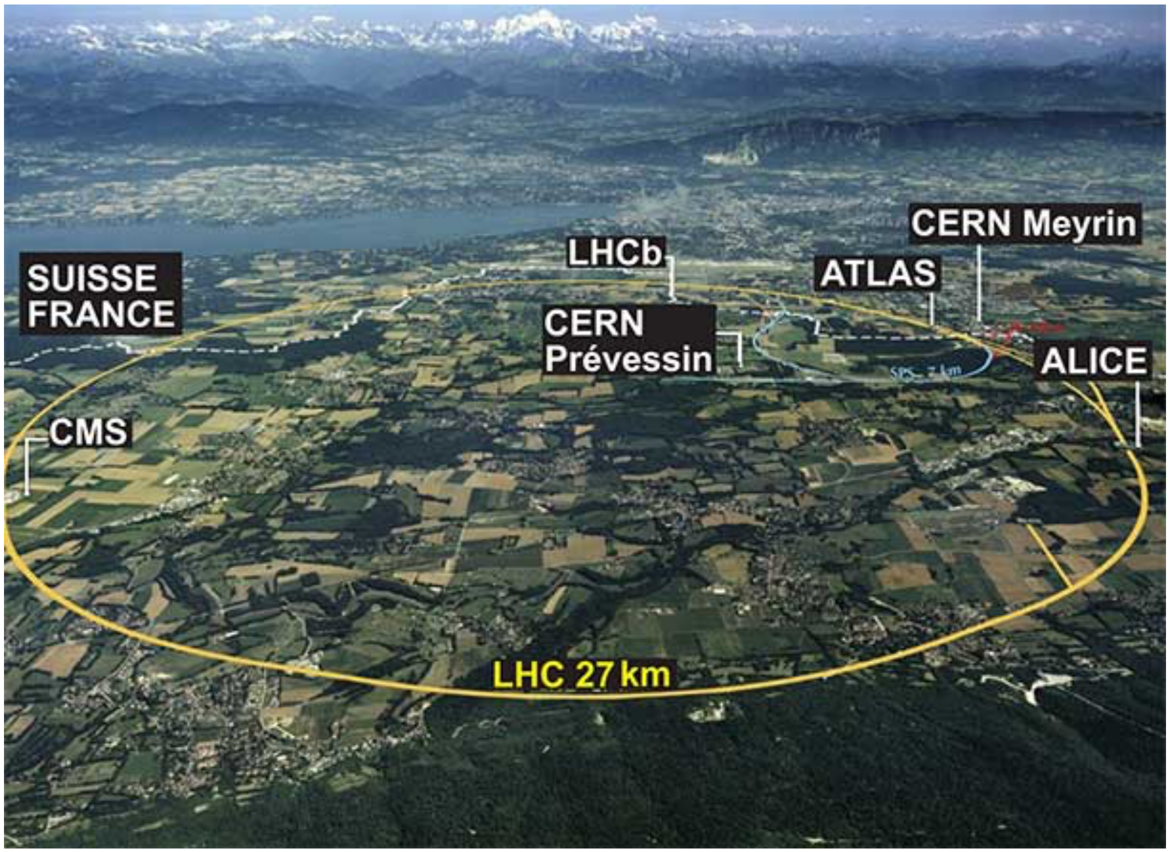


$$\mu \approx \frac{e\hbar}{2m} \qquad (\alpha = \frac{e^2}{\hbar c})$$

$$\frac{d}{\mu} \approx f^{2N}\left(\frac{m_q}{m_X}\right)^2 \sin\phi$$

$\frac{d}{\mu} \approx 10^{-14}$ $\quad f \approx \alpha \quad \sin\phi \approx 1$

$d_n \sim 10^{-26}$ e-cm

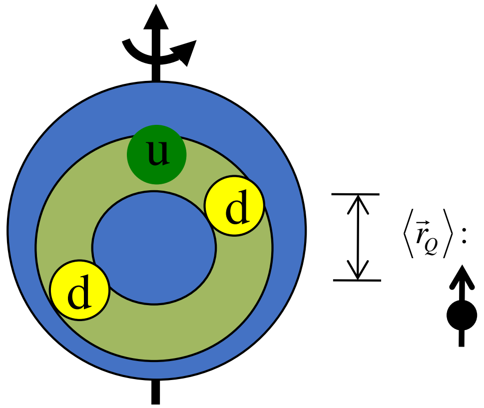
$$m_X \approx m_q\sqrt{10^{14}\alpha^N}$$

N: # loops

$\sim$ 10+ TeV LHC scale

or ϕ is small

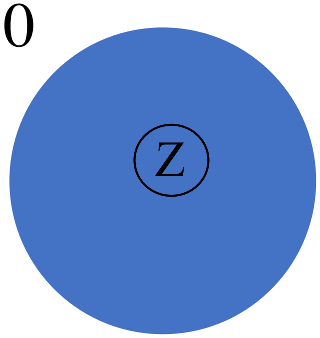
Particle Interactions Polarize Particles, Atoms, Molecules



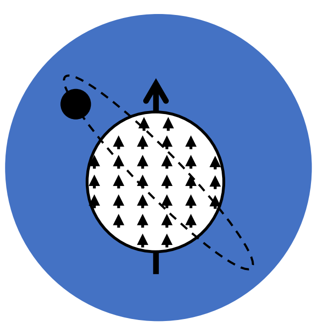
$\langle \vec{r}_Q \rangle$:

neutron (proton)

$\vec{E}(\vec{r}_e) \neq 0$



Paramagnetic ($\vec{L} \cdot \vec{S}$ coupling) $\propto Z^{\approx 3}$



$\vec{E} \propto \vec{J}$

Diamagnetic: Schiff moment, MQM $\propto Z^2$

$$\vec{S} = S\vec{J} = \frac{1}{10}\langle r^2 \vec{r}_p \rangle - \frac{1}{6} Z \langle r^2 \rangle \langle \vec{r}_p \rangle$$

EDMs arise from many sources

Rev. Mod. Phys., Vol. 91, No. 1 (Jan 2019)

Fundamental theory

Wilson coefficients (13)

$$\mathcal{L}^{\rm eff}_{\rm CPV} = \sum_{k,d} \alpha_k^{(d)} \left(\frac{1}{\Lambda}\right)^{d-4} \mathcal{O}_k^{(d)}$$

Low energy parameters

$$\bar{g}^0_{CP} \approx 0.027\, \theta_{QCD}$$

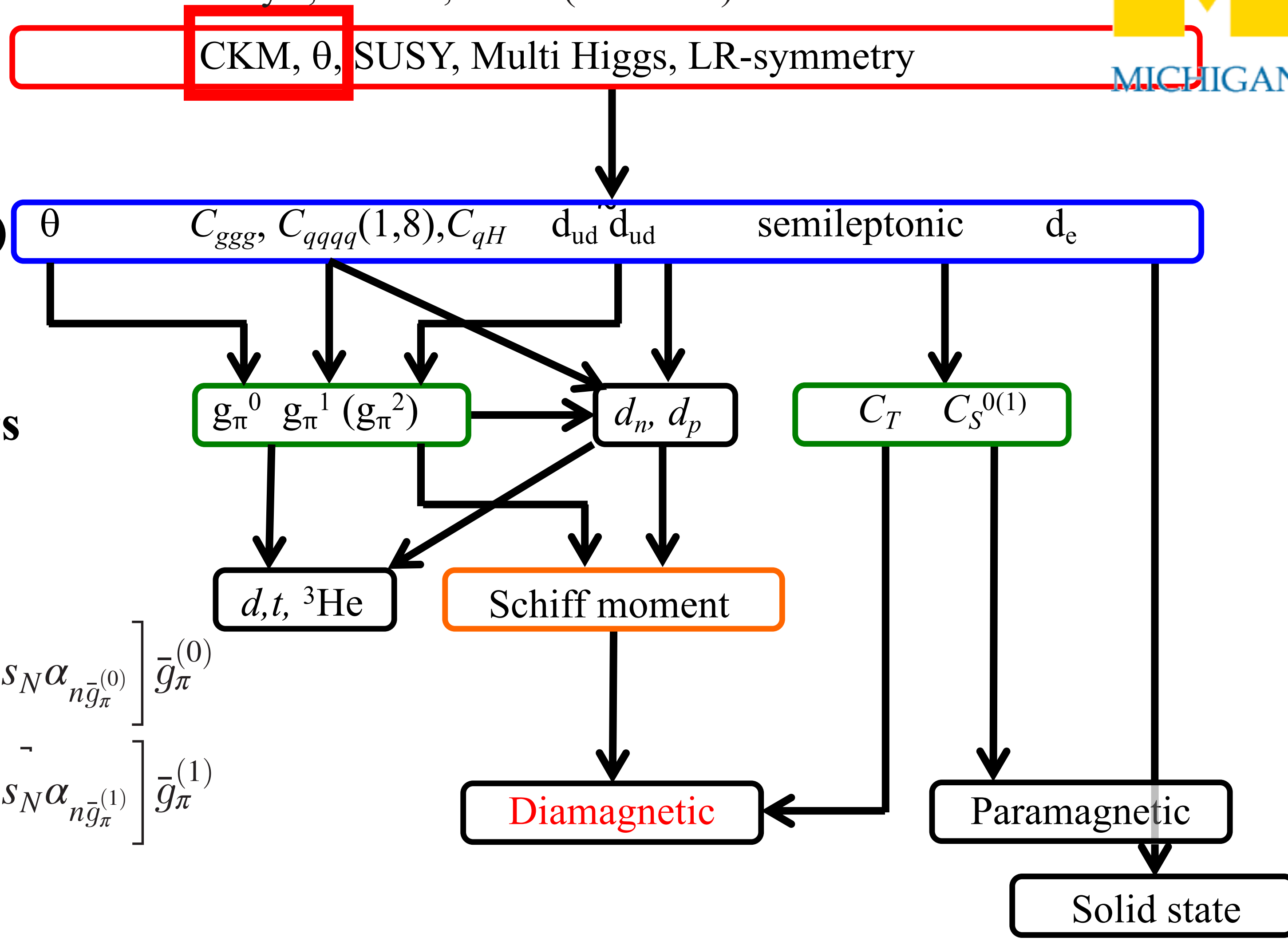
Nucleus level

$$S = s_N \bar{d}_N^{sr} + \left[\frac{m_N g_A}{F_\pi} a_0 + s_N \alpha_{n\bar{g}_\pi^{(0)}}\right] \bar{g}_\pi^{(0)} + \left[\frac{m_N g_A}{F_\pi} a_1 + s_N \alpha_{n\bar{g}_\pi^{(1)}}\right] \bar{g}_\pi^{(1)}$$

Atom/molecule level

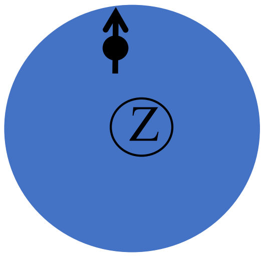
$$d_A = \eta_e d_e + \kappa_S S(\theta_{QCD}, g_\pi) + (k_T C_T + k_S C_S) + \boldsymbol{h.o.}$$

$\sim Z^3$ $\sim Z^2$

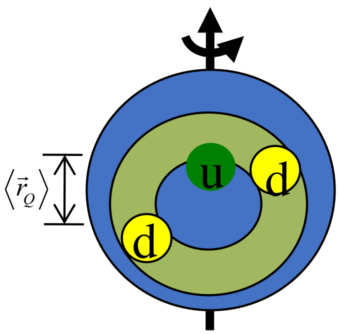


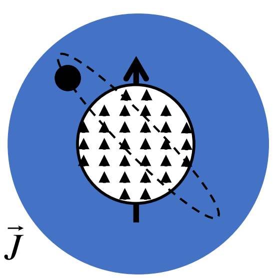
Rev. Mod. Phys. v. 91 015001 (2019)

EDM results



$\vec{E}(\vec{r}_e) \neq 0$





$\vec{E} \propto \vec{J}$

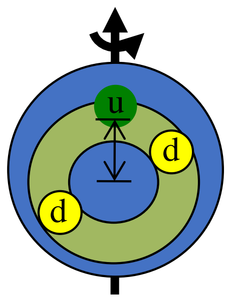
Rev. Mod. Phys., Vol. 91, No. 1 (Jan 2019)

System	Result	95% u.l.	ref.	
Paramagnetic systems				
Xe^m	$d_A = (\ 0.7 \pm 1.4) \times 10^{-22}$	3.1×10^{-22} e-cm	a	
Cs	$d_A = (-1.8 \pm 6.9) \times 10^{-24}$	1.4×10^{-23} e-cm	b	
	$d_e = (-1.5 \pm 5.7) \times 10^{-26}$	1.2×10^{-25} e-cm		
Tl	$d_A = (-4.0 \pm 4.3) \times 10^{-25}$	1.1×10^{-24} e-cm	c	
	$d_e = (\ 6.9 \pm 7.4) \times 10^{-28}$	1.9×10^{-27} e-cm		
YbF	$d_e = (-2.4 \pm 5.9) \times 10^{-28}$	1.2×10^{-27} e-cm	d	2017
ThO	$\omega^{NE} = -510 \pm 485\ \mu$rad/s		e	2018 (8x)
	$d_e = (4.3 \pm 4.0) \times 10^{-30}$	1.1×10^{-29} e-cm		
	$C_S = (2.9 \pm 2.7) \times 10^{-10}$	7.3×10^{-10}		
HfF^+	$2\pi f^{BD} = 0.6 \pm 5.6$ mrad/s		f	
	$d_e = (0.9 \pm 7.9) \times 10^{-29}$	16×10^{-29} e-cm		
Diamagnetic systems				
n	$d_n = (-0.0 \pm 1.1) \times 10^{-26}$	2.2×10^{-26} e-cm	g	2020 (1.6x)
^{199}Hg	$d_A = (2.2 \pm 3.1) \times 10^{-30}$	7.4×10^{-30} e-cm	h	2017 (4x)
^{129}Xe	$d_A = (1.4 \pm 6.9) \times 10^{-28}$	1.4×10^{-27} e-cm	i	2019 (5x)
^{225}Ra	$d_A = (4 \pm 6) \times 10^{-24}$	1.4×10^{-23} e-cm	j	2016
TlF	$d\ = (-1.7 \pm 2.9) \times 10^{-23}$	6.5×10^{-23} e-cm	k	
Particle systems				
μ	$d_\mu = (0.0 \pm 0.9) \times 10^{-19}$	1.8×10^{-19} e-cm	l	
Λ	$d_\Lambda = (-3.0 \pm 7.4) \times 10^{-17}$	7.9×10^{-17} e-cm	m	

Diagmagetic atoms and nucleons

T.C. & M. Ramsey-Musolf – Phys. Rev. C **91** 035502 (2015)

	C_T	$g_\pi{}^0$	$g_\pi{}^1$	$d_0{}^{sr}$	$d_1{}^{sr}$
n, *p*				1	-1
Xe, Hg, TlF, Ra	x	x	x		
95% upper limit	$3\text{x}10^{-7}$	$1.2\text{x}10^{-9}$	$2.9\text{x}10^{-10}$	$1.8\text{x}10^{-23}$	



$$d_n = \bar{d}_n^{\rm sr} - \frac{e g_A \bar{g}_\pi^{(0)}}{8\pi^2 F_\pi}\left\{\ln\frac{m_\pi^2}{m_N^2} - \frac{\pi m_\pi}{2m_N} + \frac{\bar{g}_\pi^{(1)}}{4\bar{g}_\pi^{(0)}}(\kappa_1 - \kappa_0)\frac{m_\pi^2}{m_N^2}\ln\frac{m_\pi^2}{m_N^2}\right\}$$

$$\approx \bar{d}_n^{sr} - (1.44\times10^{-14} g_\pi^{(0)} - 8.3\times10^{-16} g_\pi^{(1)})\; e - cm$$

$$\bar{g}_\pi^{(0)} \approx 0.27\,\bar{\theta}$$

$$\bar{\theta} < (2\times10^{-10} - 4\times10^{-9})$$

$d_n^{\bar{\theta}} \approx -(0.9\text{–}1.2) \times 10^{-16}\bar{\theta} e\,\text{cm}.$ $\qquad$ $\bar{g}_\pi^{(0)} < 3\times10^{-7}$

MOTIVATES AXION SEARCHES

Neutron electric dipole moment

From Wikipedia, the free encyclopedia

"NEDM" redirects here. For the Sussex experiment, see Sussex/RAL/ILL neutron EDM experiment.

The **neutron electric dipole moment** (**nEDM**) is a measure for the distribution of positive and negative charge inside the neutron. A finite electric dipole moment can only exist if the centers of the negative and positive charge distribution inside the particle do not coincide. So far, no neutron EDM has been found. The current best upper limit amounts to $|d_n| < 2.9 \times 10^{-26}\, e{\cdot}\text{cm}$.[1]

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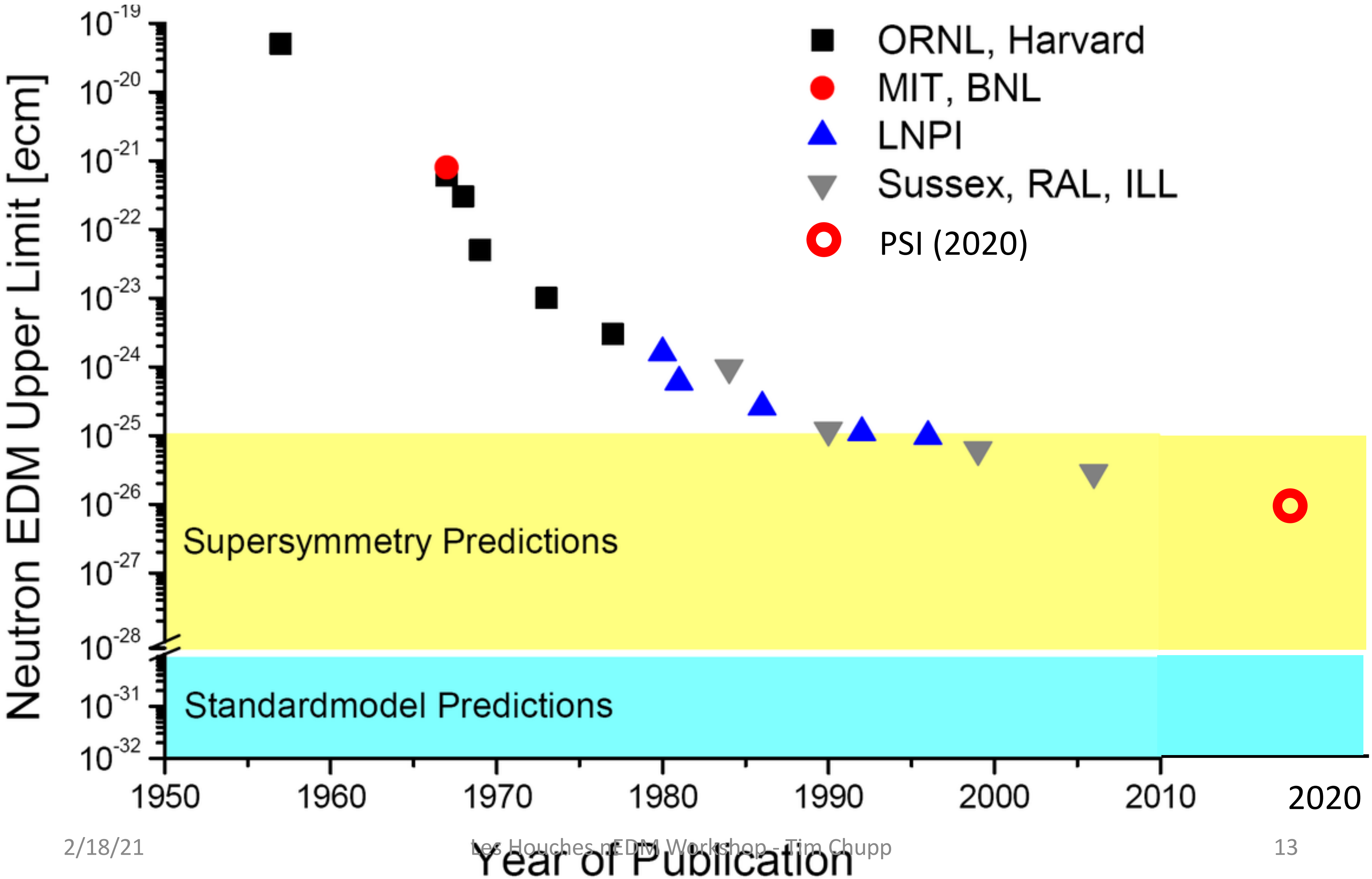

Storage Ring EDMs will challenge neutrons

Particle	J	a	$\|\vec{p}\|$ (GeV/c)	γ	$\|\vec{B}\|$ (T)	$\|\vec{E}\|$ (kV/cm)	$\|\vec{E}'\|/\gamma$ (kV/cm)	R (m)	σ_d^{goal} (e cm)	Ref.
$\mu^{\pm}$	1/2	+0.001 17	3.094	29.3	1.45	0.0	4300	7.11	10^{-21}	E989
			0.3	3.0	3.0	0.0	8500	0.333	10^{-21}	E34
			0.5	5.0	0.25	22.0	760	7.0	10^{-24}	srEDM
			0.125	1.57	1.0	6.7	2300	0.42	10^{-24}	PSI
p^+	1/2	+1.792 85	0.7007	1.248	0.0	80.0	80	52.3	10^{-29}	srEDM
			0.7007	1.248	0.0	140.0	140	30.0	10^{-29}	JEDI
d^+	1	−0.142 99	1.0	1.13	0.5	120.0	580	8.4	10^{-29}	srEDM
			1.000	1.13	0.135	33.0	160	30.0	10^{-29}	JEDI
$^3He^{++}$	1/2	−4.184 15	1.211	1.09	0.042	140.0	89	30.0	10^{-29}	JEDI

Stable

Fermilab, Jparc, BNL, COSY

~10 years

EDM Measurement

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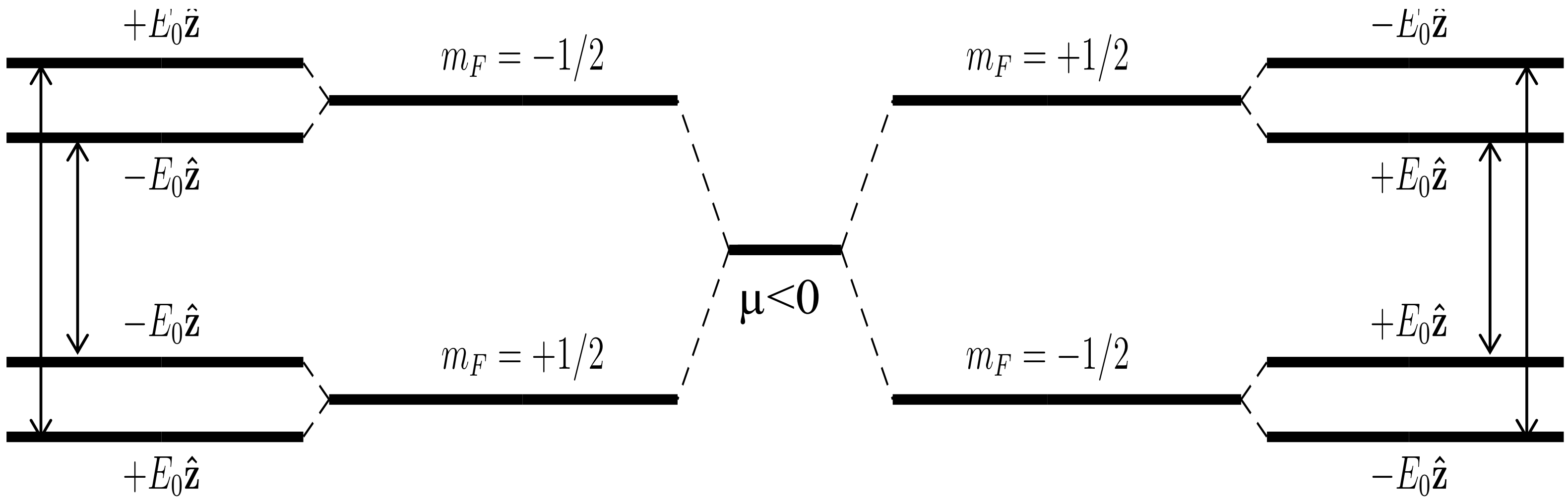
$$H = \boxed{-\vec{\mu}\cdot \vec{B}} - \vec{d}\cdot \vec{E}$$

- Strong electric field (static): need neutral particles (or confined ion)
- Large signal needs POLARIZATION (usually optical pumping)



- MEASURE FREQUENCIES:

$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{T_2}\frac{1}{S/N}$$

$$\rightarrow \frac{1}{2E}\frac{\hbar}{T_2}\frac{1}{\sqrt{\varphi_n T_2}}$$ Phase-noise limit

$$\rightarrow \frac{1}{2E}\frac{\hbar}{T_2}\frac{1}{\sqrt{N_\gamma}}$$ Count-rate limit

- **AND MAGNETIC FIELDS**

Experiments

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$$H = \boxed{-\vec{\mu}\cdot\vec{B}} - \vec{d}\cdot\vec{E}$$

- Strong electric field
- Large signal needs POLARIZATION (usually optical pumping)
- MEASURE FREQUENCIES (N. Ramsey…)
- **AND MAGNETIC FIELDS - (Co)magnetometry**

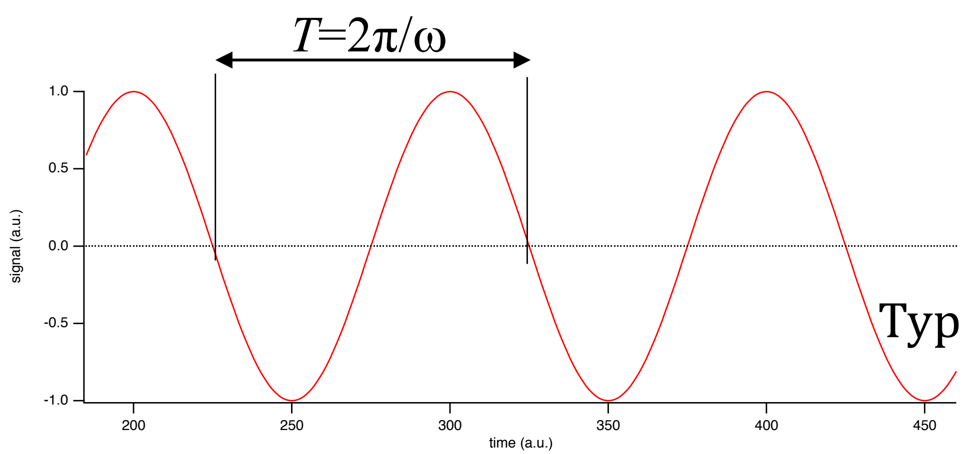
$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N}$$

Measurement time (HV dwell)

Measuring Frequencies

ω convention: always write $\frac{\omega}{2\pi}$ (Hz)

- Inverse of the period of an oscillator



Measure many cycles

Type equation here.

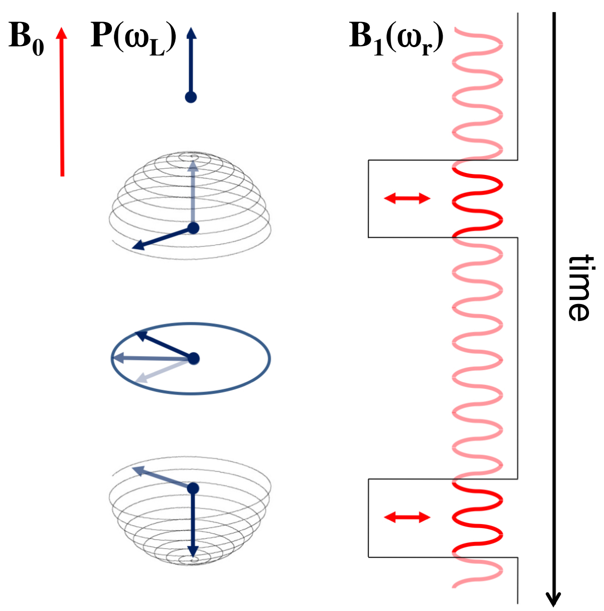
- Rate of change of phase (need a phase detector)

$$\omega = \frac{\Delta\varphi}{\tau}$$

$$\sigma_\omega = \frac{\sigma_\varphi}{\tau}$$

Measuring Phase – Ramsey SOF

Separated Oscillatory Fields



Mea

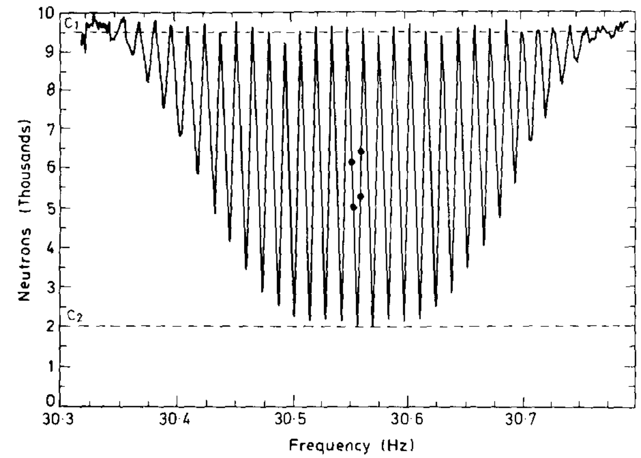


Fig. 2. A neutron magnetic resonance curve obtained using the time-separated oscillatory fields technique. Polarized ultra-cold neutrons were stored for 68 s in a magnetic field of 1 μT, giving a linewidth of 7 mHz for the central fringe. Data are taken at the four points shown, which are approximately halfway up each side of the central fringe, and separated by one tenth of a linewidth.

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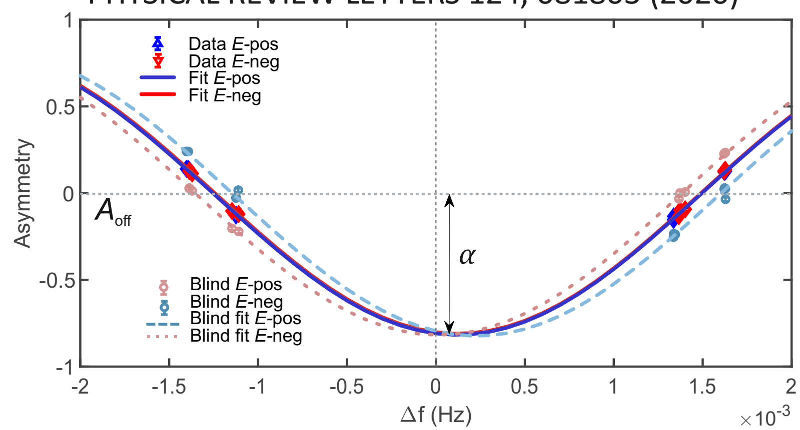


Experiments

$$H = \boxed{-\vec{\mu}\cdot\vec{B}} - \vec{d}\cdot\vec{E}$$

- Strong electric field

- Large signal needs POLARIZATION (usually optical pumping)

- MEASURE FREQUENCIES $\propto \frac{1}{\tau^{3/2}}$ Per HV dwell

- **AND MAGNETIC FIELDS - (Co)magnetometry**

$$\sigma_d \approx \frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{S/N}$$

Measurement time (HV dwell)

$$\frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{\sqrt{\varphi_n \tau}}$$ Phase-noise limit

$$\frac{1}{2E}\frac{\hbar}{\tau}\frac{1}{\sqrt{N}}$$ Count-rate limit (P=A=1)

What we want

What we want	How we get it	σ_d Dependence
Long observation times	UCN Storage	1/T
High electric fields	Limited by ”bottle”	1/E
Precise phase measurement	Lots of UCNs	$1/\sqrt{N_{UCN}}$
Stable magnetic fields	MSR, magnetometry	σ_B
Uniform magnetic fields	Magnet design	$\nabla\vec{B}$

Ultra-Cold Neutrons (UCN)

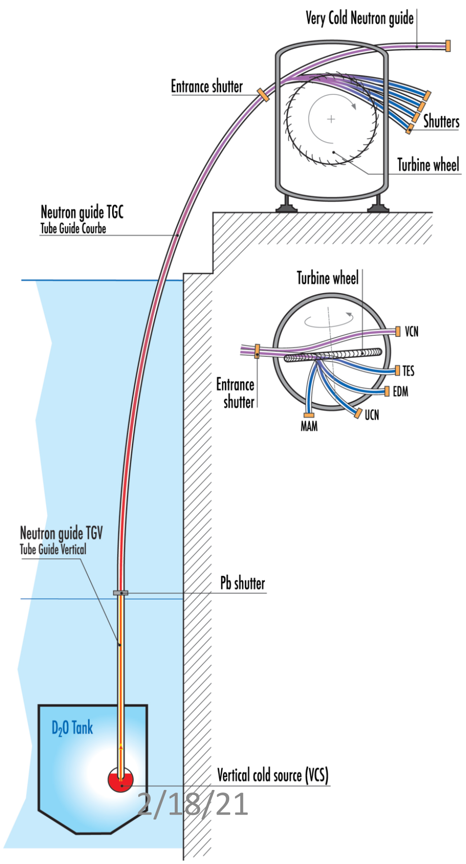
SLOW (<8 m/s), “long” wavelength (50 nm) with OPTICAL PROPERTIES - Storage

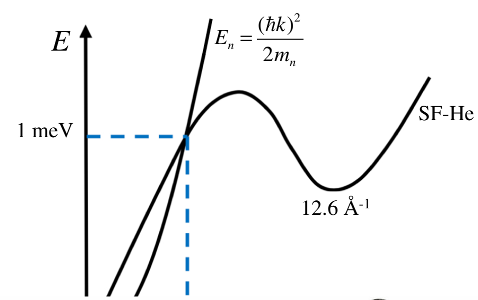
Property	Value	Feature
Charge	0	“Inert”
Magnetic moment	$2\mu/m_n$=(3.4 m/s)^2/T	Polarize/spin transport
Mass	mg=(3.1 m/s)^2/m	Manipulate with gravity
Strong Interactions		Reflect/absorb/Store
Weak interactions	τ_n=781 s	Limits observation time

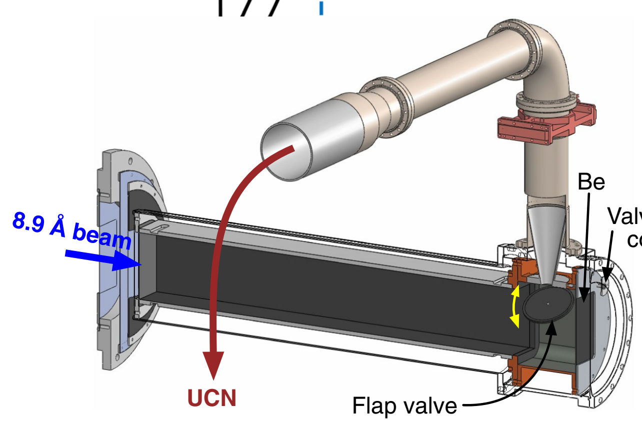
Ultra-Cold Neutrons (UCN)

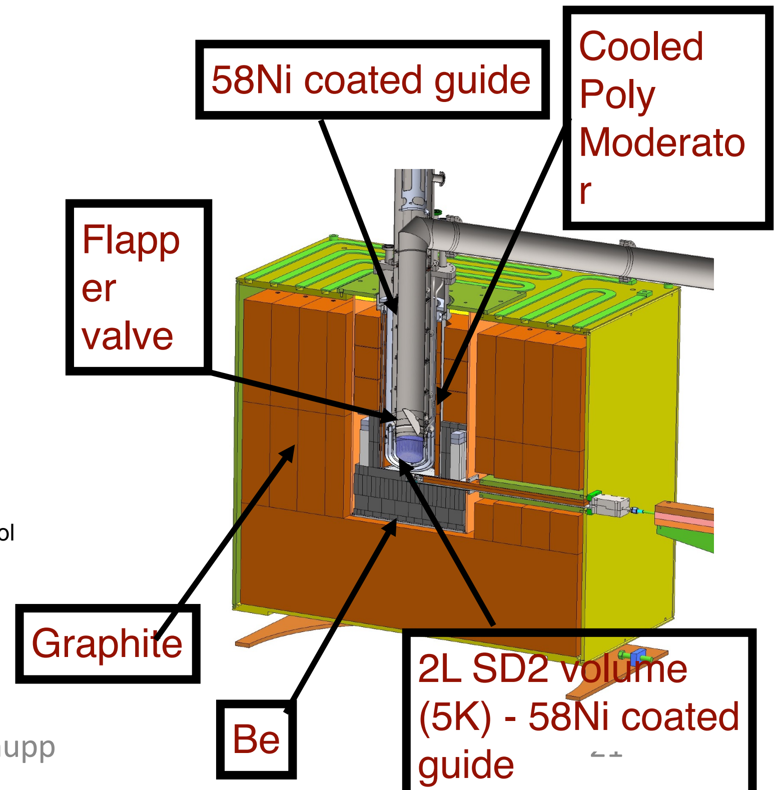
SLOW (<8 m/s), "long" wavelength (50 nm)
OPTICAL PROPERTIES

Source	Type	Converter	UCN/cm^3	Ref.
ILL PF2	Reactor cold source	(Turbine)	Two polarized; based on detected UCN	(a)
LANL	Spallation	sD_2	40 polarized; observed in a test chamber	(b)
PSI	Spallation	sD_2	22 unpolarized; in standard storage bottle	(c)
TRIGA Mainz	Pulsed reactor	sD_2	Ten unpolarized	(d)
ILL SUN-II	Reactor cold-neutron beam	SF-He	Ten polarized; from production, dilution, and polarization	(e)
JPARC	Spallation VCN	Rotating mirror	1.4 unpolarized; measured at source	(f)





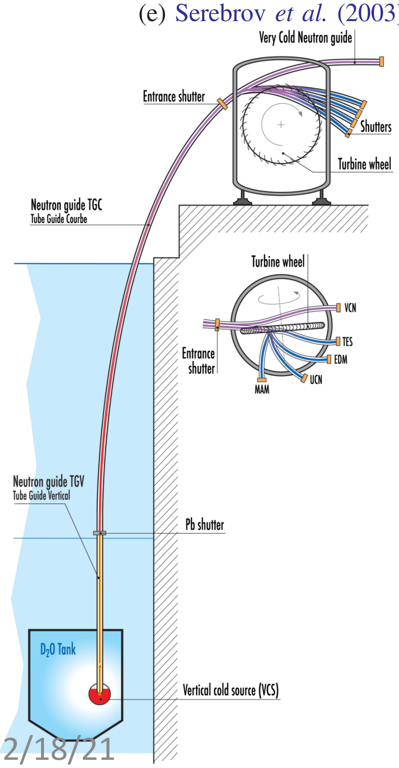


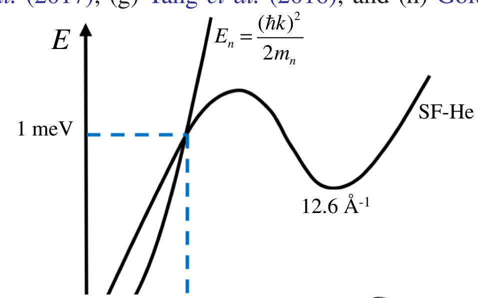


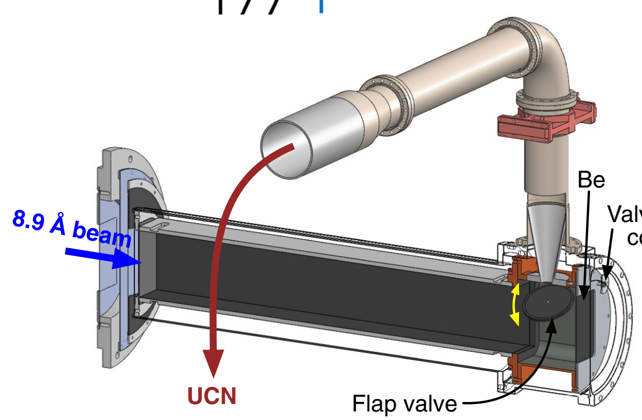
Ultra-Cold Neutrons (UCN)

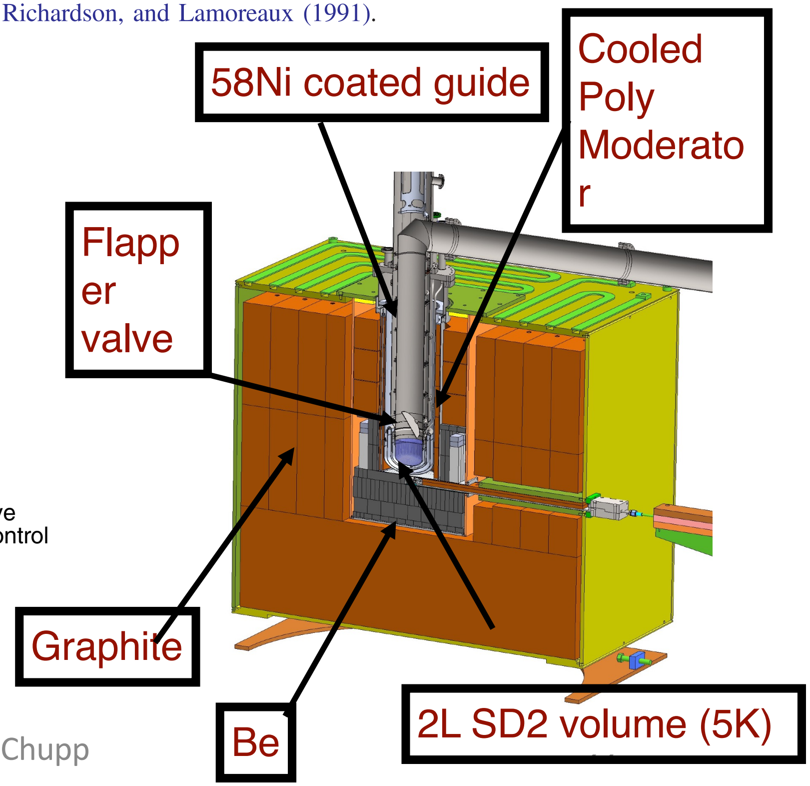
Material	V (neV)	Loss per bounce	Ref.	Depolarization	Ref.
DPe (300 K)	214	1.3×10^{-4}	(a)	4×10^{-6}	(b)
DLC on Al substrate (70 K)	270	1.7×10^{-4}	(c)	0.7×10^{-6}	(c)
DLC on Al substrate (300 K)	270	3.5×10^{-4}	(c)	3×10^{-6}	(c)
DLC on PET substrate (70 K)	242	1.6×10^{-4}	(c)	$15 \pm \times 10^{-6}$	(c)
DLC on PET substrate (300 K)	242	5.8×10^{-4}	(c)	$(14 \pm 1) \times 10^{-6}$	(c)
Fomblin 300 K	106.5	2.2×10^{-5}	(d)	1×10^{-5}	(e)
Be (10 K)	252	3×10^{-5}	(d)	1.1×10^{-5}	(e)
Be (300 K)	252	$(4 - 10) \times 10^{-5}$	(d)	1.1×10^{-5}	(e)
NiP	213	1.3×10^{-4}	(f)	$< 7 \times 10^{-6}$	(g)
^{58}Ni	335		(h)	Strong	
Fe/steel/stainless	180–190		(h)	Strong	

References: (a) Brenner *et al.* (2015); (b) T. Ito *et al.* (2018); (c) Atchison *et al.* (2007); (d) Serebrov *et al.* (2005); (e) Serebrov *et al.* (2003); (f) Pattie *et al.* (2017); (g) Tang *et al.* (2016); and (h) Golub, Richardson, and Lamoreaux (1991).

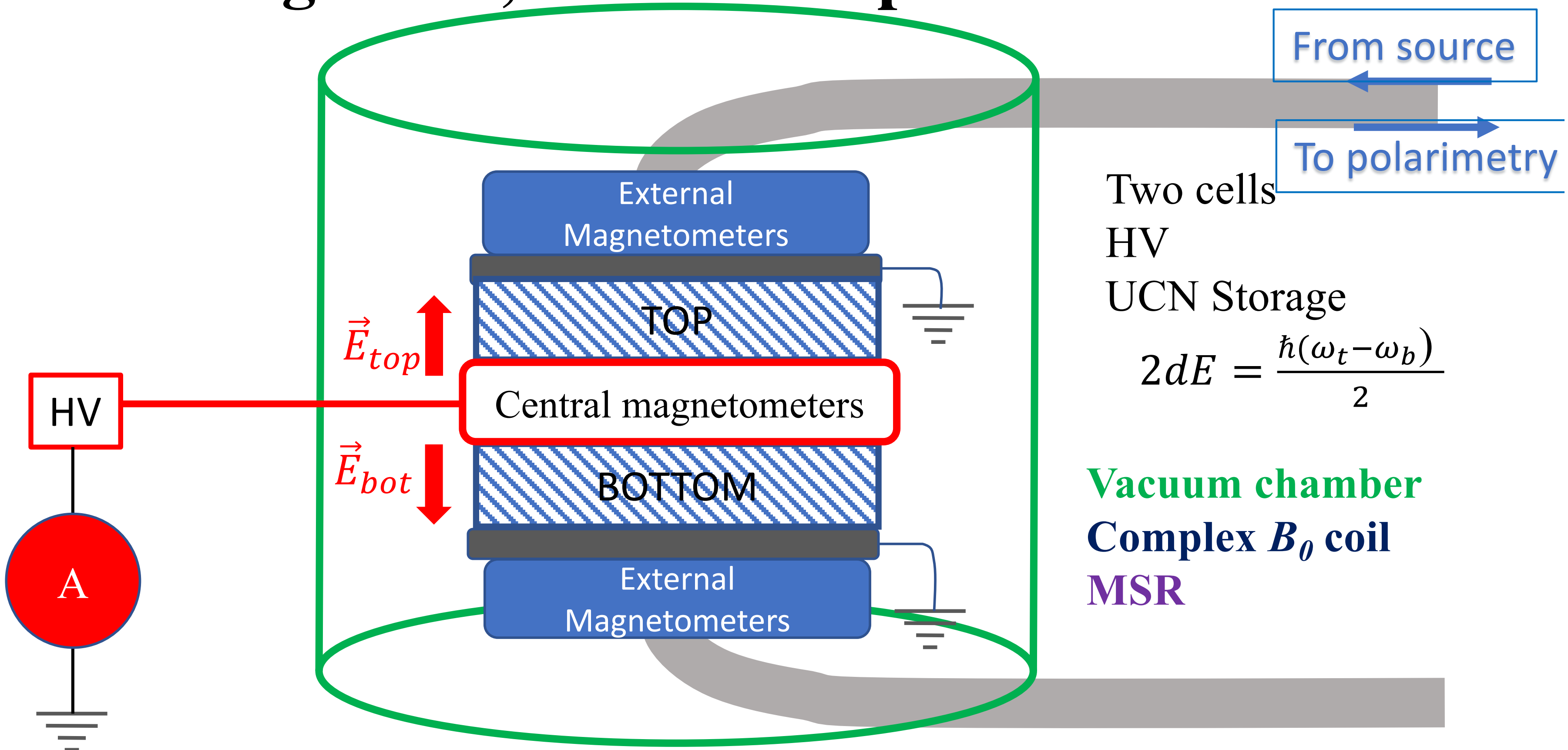








The generic, non-SNS experiment



Two cells
HV
UCN Storage

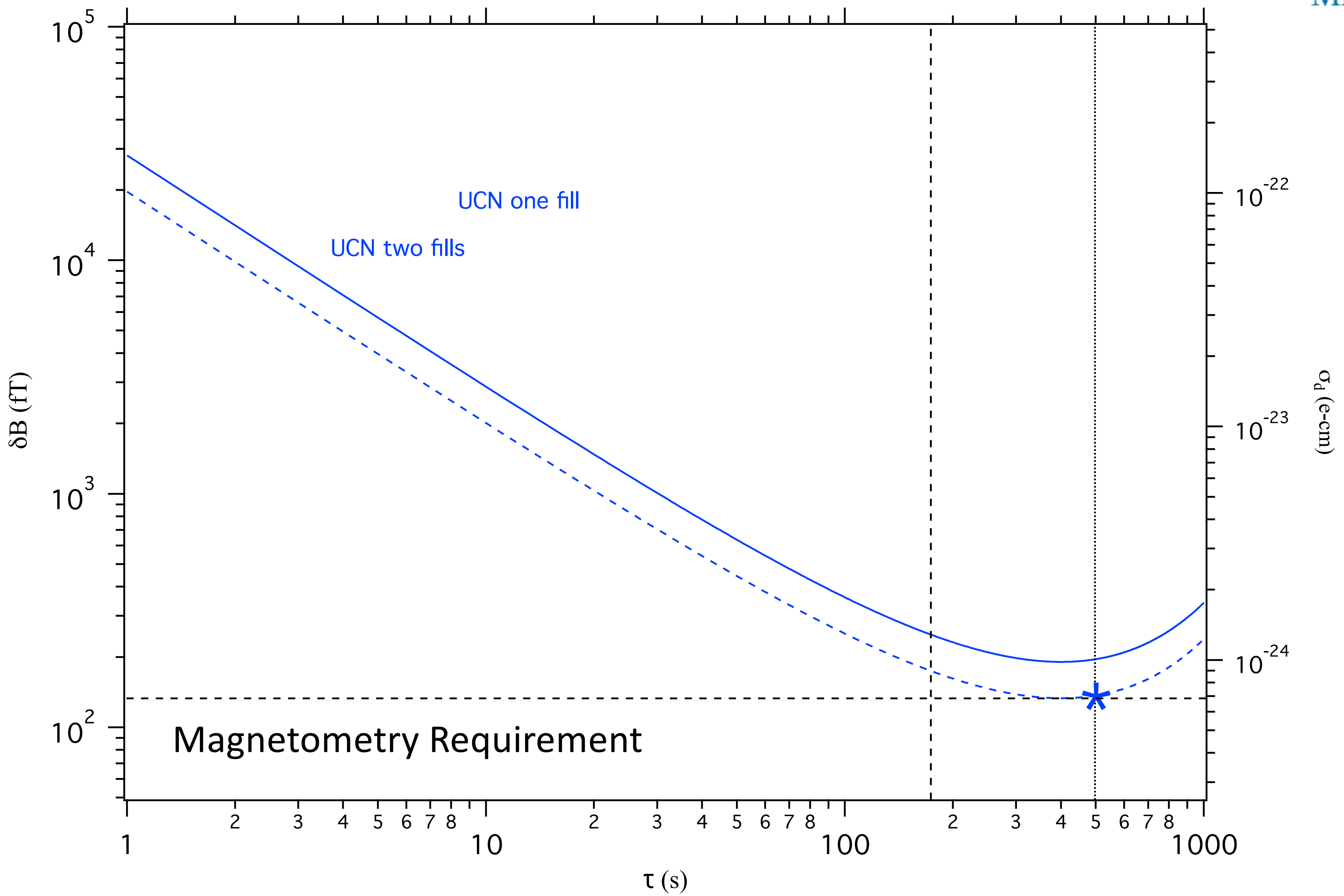
$$2dE = \frac{\hbar(\omega_t - \omega_b)}{2}$$

Vacuum chamber
Complex B_0 coil
MSR

Major systematic effects

Effect	Mitigation
B-field variations	MSR, Two cells, magnetometry
Leakage currents	Monitor, Construction (comagnetometry)
vxE effects	Uniform fields
Lots of higher order stuff	

EDM sensitivity (LANL nEDM)



LANL nEDM Collaboration

T. Chupp*, S. Clayton, C. Cude-Woods, S. Currie, T. Hassan, T. Ito, M. Makela, C. Morris, C. O'Shaughnessy, Z.Tang, W. Uhrich, A. Urbaitis,

Los Alamos National Laboratory

** 2020 LANL Rosen scholar*

T. Chupp, A. Tewsley-Booth, F.B. Hills

University of Michigan

N. Sachdeva

Northwestern University

J. Chen, F. Gonzales, C. Hughes, C.-Y. Liu, J. Long, A. Reid, W. Snow, D. Wong

Indiana University

A. Aleksandrova, J. Brewington, W. Korsch, M. McCrea, P. Palamure, B. Plaster

University of Kentucky

R. Pattie Jr. — *East Tennessee State University*

A. Holley — *Tennessee Tech University*

S. Stanislaus

Valparaiso University

T. J. Bowles, B. Heckel

University of Washington

S.K. Lamoreaux — *Yale University*

E. Sharapov — *Joint Institute of Nuclear Research*

Collaboration Talks

MICHIGAN

Wed

14:00

Overview of the new UCN facility at TRIUMF — *Florian Kuchler*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 14:00 - 14:20

Time-dependent thermal modeling for the TUCAN source — *Jeffery Martin*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 14:20 - 14:40

Optimizing the performance of a spallation-driven ultracold-neutron source with deuterium and superfluid-helium mode...
Wolfgang Schreyer

15:00

Nickel-Phosphorus Coating Challenges of the TUCAN UCN source — *Russell Mammei*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 15:00 - 1

Scre

Development of a Helium-3 Cryostat for the TRIUMF Ultra-Cold Advanced Neutron Source — *Shinsuke Kawasaki*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 15:20 - 15:40

Performance measurement of ultracold neutron guides at J-PARC for a neutron EDM experiment in TRIUMF — *Sohei Imajo*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 15:40 - 16:00

16:00

Ultra cold neutron transport for the Neutron Electric Dipole Moment Search at Los Alamos National Laboratory
Douglas Wong

Measurement of Neutron Polarization and Transmission for the nEDM@SNS Experiment. — *Kavish Imam*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 16:50 - 17:10

17:00

PSI UCN source — *Ingo Rienäcker*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 17:10 - 17:30

Thurs

14:00

The magnetometer system planned for the neutron electric dipole moment (nEDM) experiment at LANL — *Yi (Jennie) Chen*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 14:00 - 14:20

Laser-based comagnetometry for the TUCAN nEDM measurement — *Eric Miller*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 14:20 - 14:40

Optical magnetometry for the TUCAN nEDM experiment — *Wolfgang Klassen*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 14:40 - 15:00

15:00

Magnetometry for the Los Alamos National Laboratory's nEDM experiment — *Felicity Hills*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 15:00 - 15:20

Mercury comagnetometer: the light shift — *Selim Touati*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 15:20 - 15:40

The caesium magnetometer array for the n2EDM experiment — *Duarte Pais*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 15:40 - 16:00

Screen

16:00

Fri 19/02

Imprimer | PDF | Plein écran | Vue détaillée | Filtre

16:00

Scree

Magnetic Field System in the nEDM experiment at the SNS — *Alina Aleksandrova*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 16:40 - 17:00

17:00

Creation of a superconducting switch to close the B0 coil in the nEDM@SNS experiment — *Clark Hickman*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 17:00 - 17:20

Magnetic Shim Coils for the TUCAN nEDM Experiment — *Mark McCrea*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 17:20 - 17:40

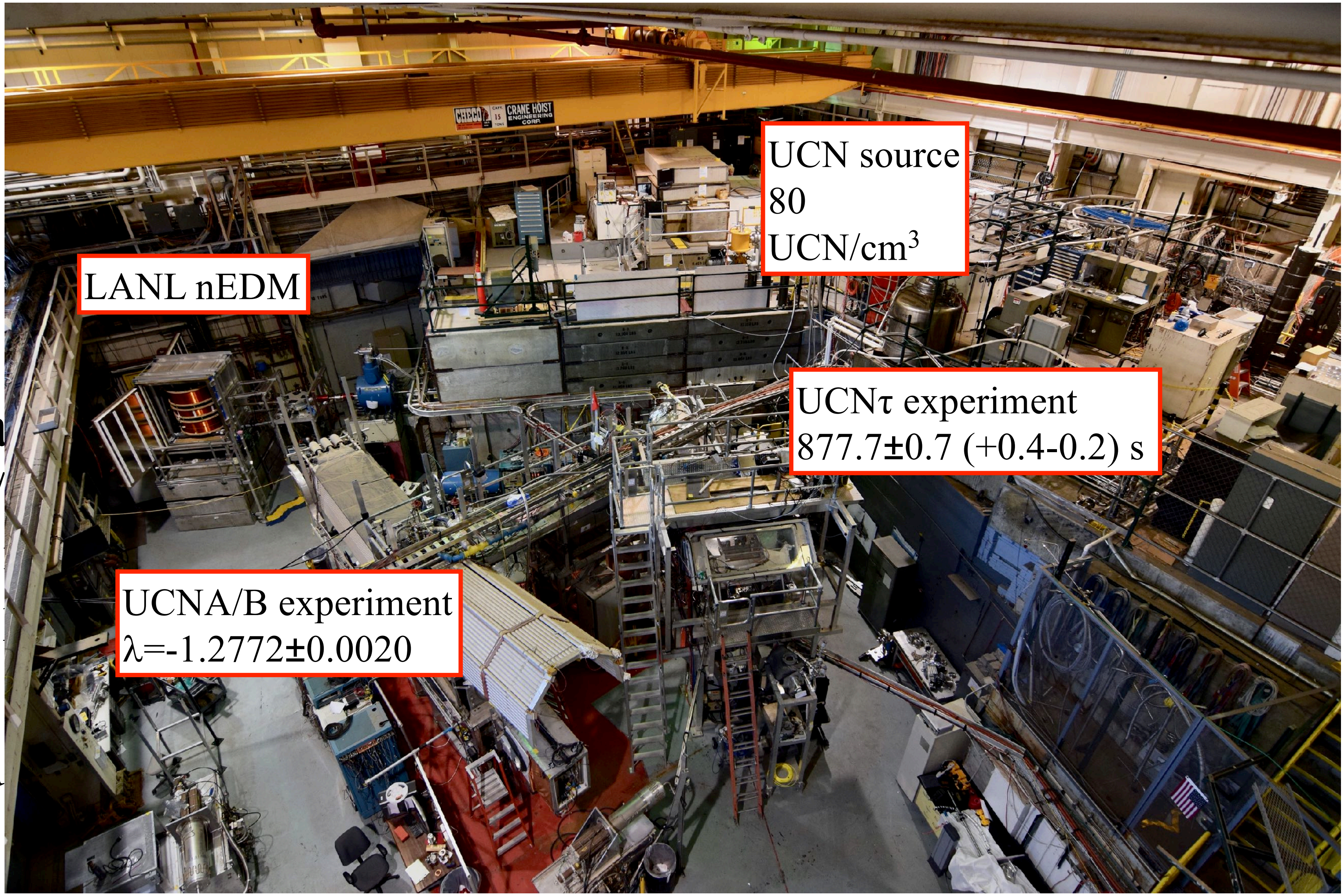
B0 Magnetic Field Coil Design and Fabrication for the LANL nEDM Experiment — *Jared Brewington*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 17:40 - 18:00

18:00

Magnetic Gradient Amelioration for nEDM@LANL — *Austin Reid*
FRANCE - 74 310 LES HOUCHES, Les Houches School of Physics — 18:00 - 18:20

Use the "world's best best UCN source" to reach σ_d~$2x10^{-27}$ e-cm in five years

rma
CN/
CN
CN
A;
tau

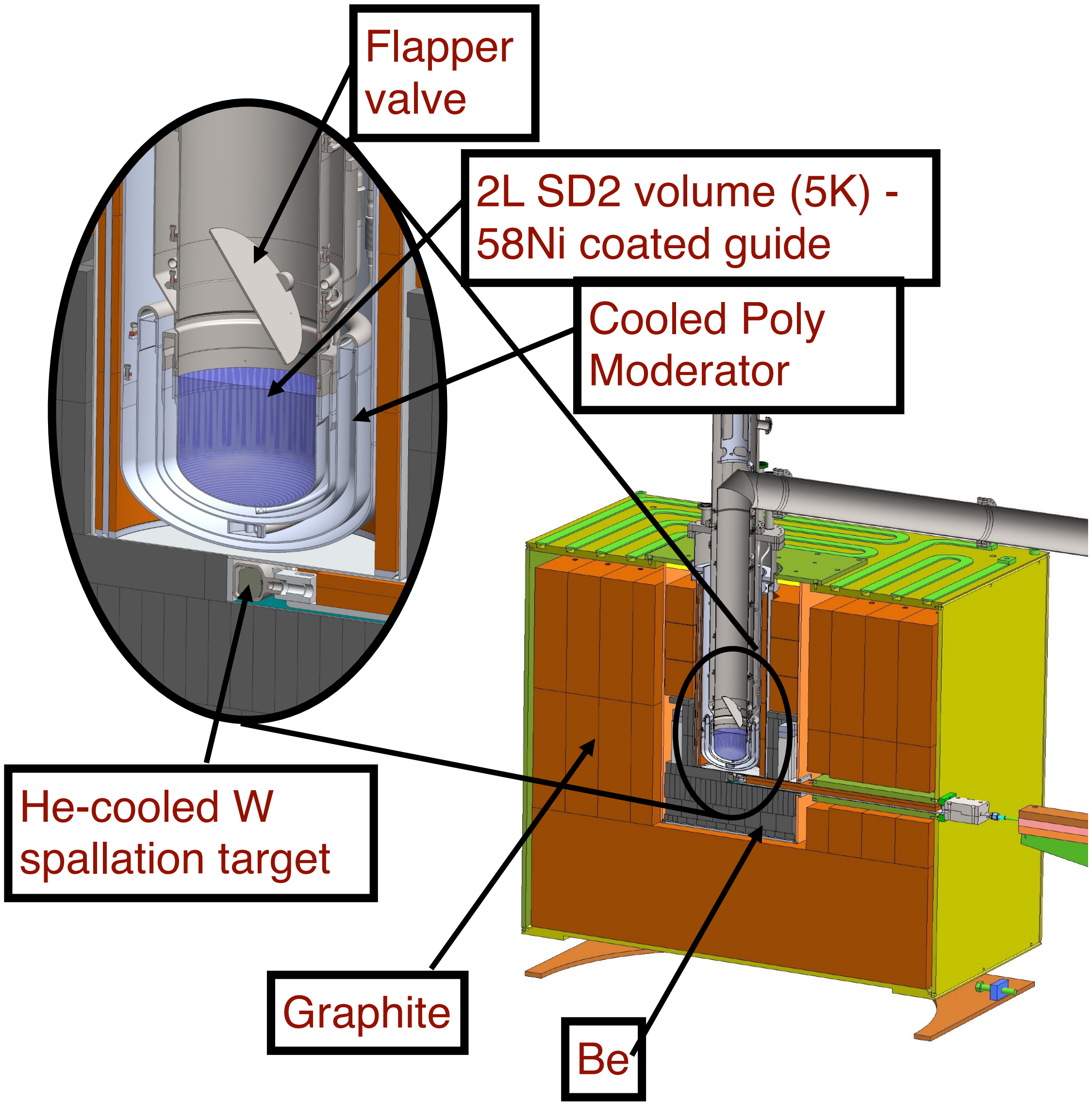


Use the "world's best" UCN source to reach $\sigma_d \sim 2\times10^{-27}$ e-cm in five years

MICHIGAN

Parameters	Values
E(kV/cm)	12.0
N(per cell)	39,100
T_{free} (s)	180
T_{duty} (s)	300
α	0.8
σ/day/cell (10^{-26} e-cm)	5.7
σ/day (10^{-26} e-cm) (for double cell)	4.0
σ/year (10^{-27} e-cm) (for double cell)	2.1
90% C.L./year (10^{-27} e-cm) (for double cell)	3.4

UCN source



Spallation neutrons from W target ~ 2 MeV

↓

Thermal neutrons in Be and graphite moderator ~ 25 meV

↓

Cold neutrons in polyethylene cold moderator ~ 6 meV

↓

Ultracold neutrons in SD2 converter ~ 100 neV

UCN source upgrade

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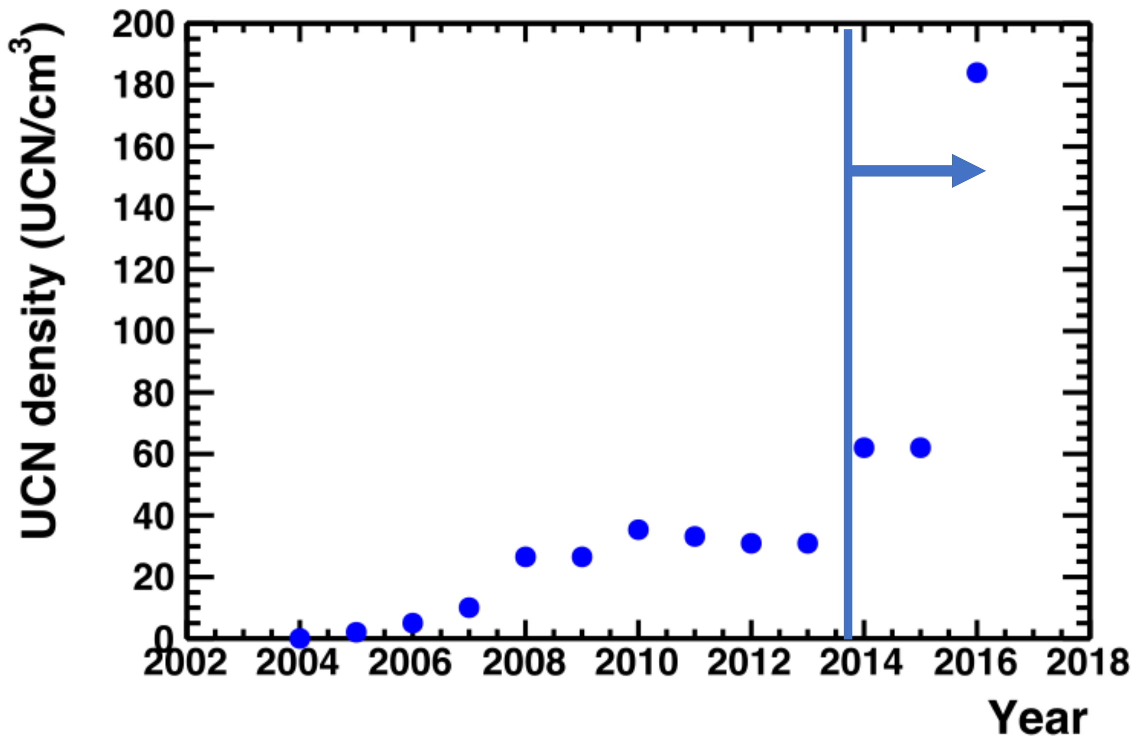
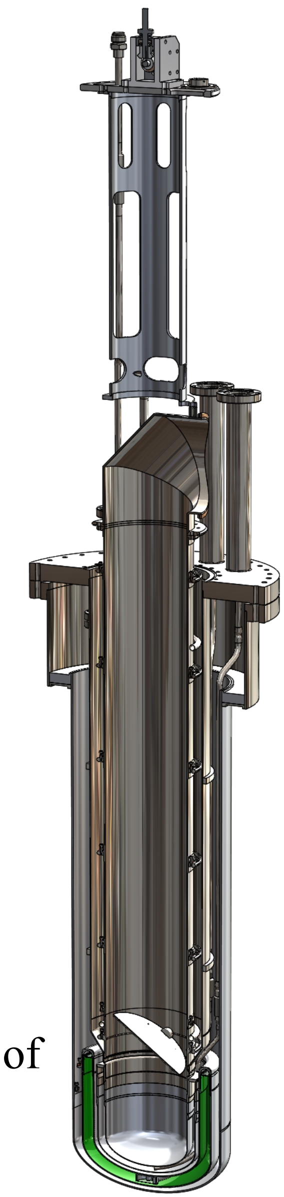
- Simulation based optimization of cryostat and moderator geometry
- Replaceable moderator; New flapper valve design; Modify UCN tee

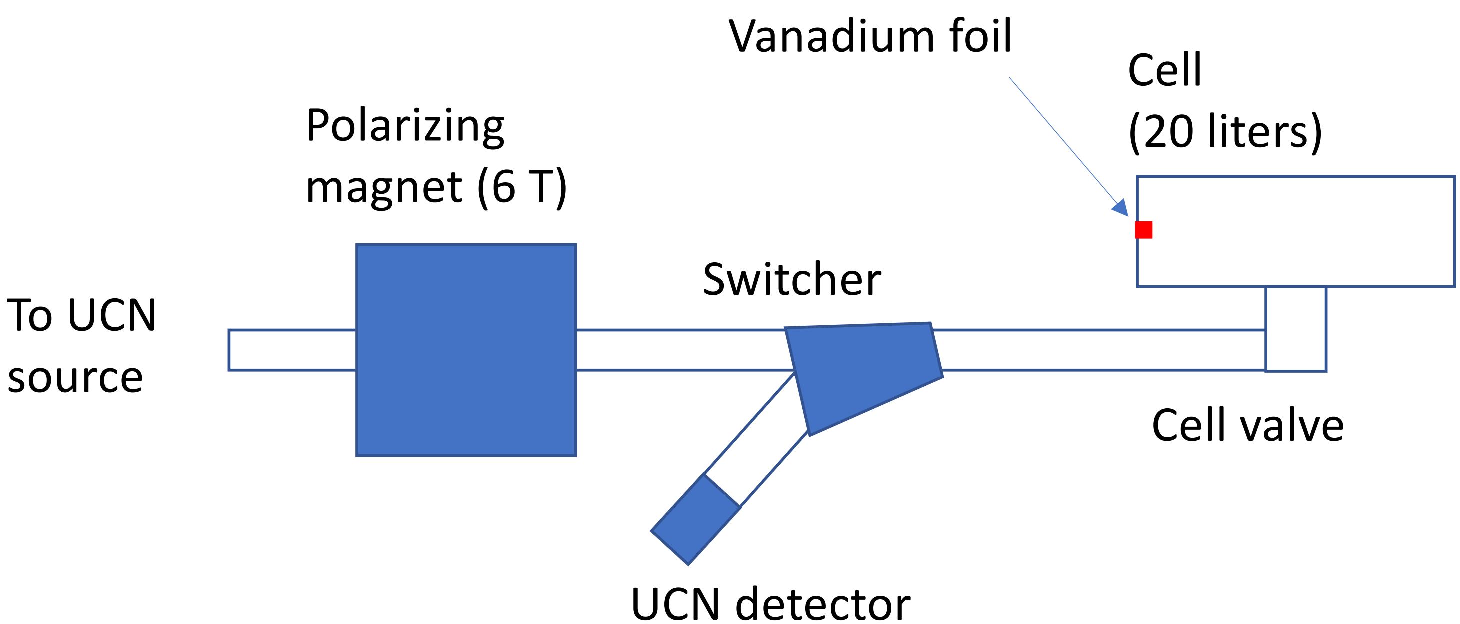




The source is shown to perform as modeled. The UCN density measured at the exit of the biological shield was **184(32) UCN/cm³**, a fourfold increase from the highest previously reported

Storage cell Measurement

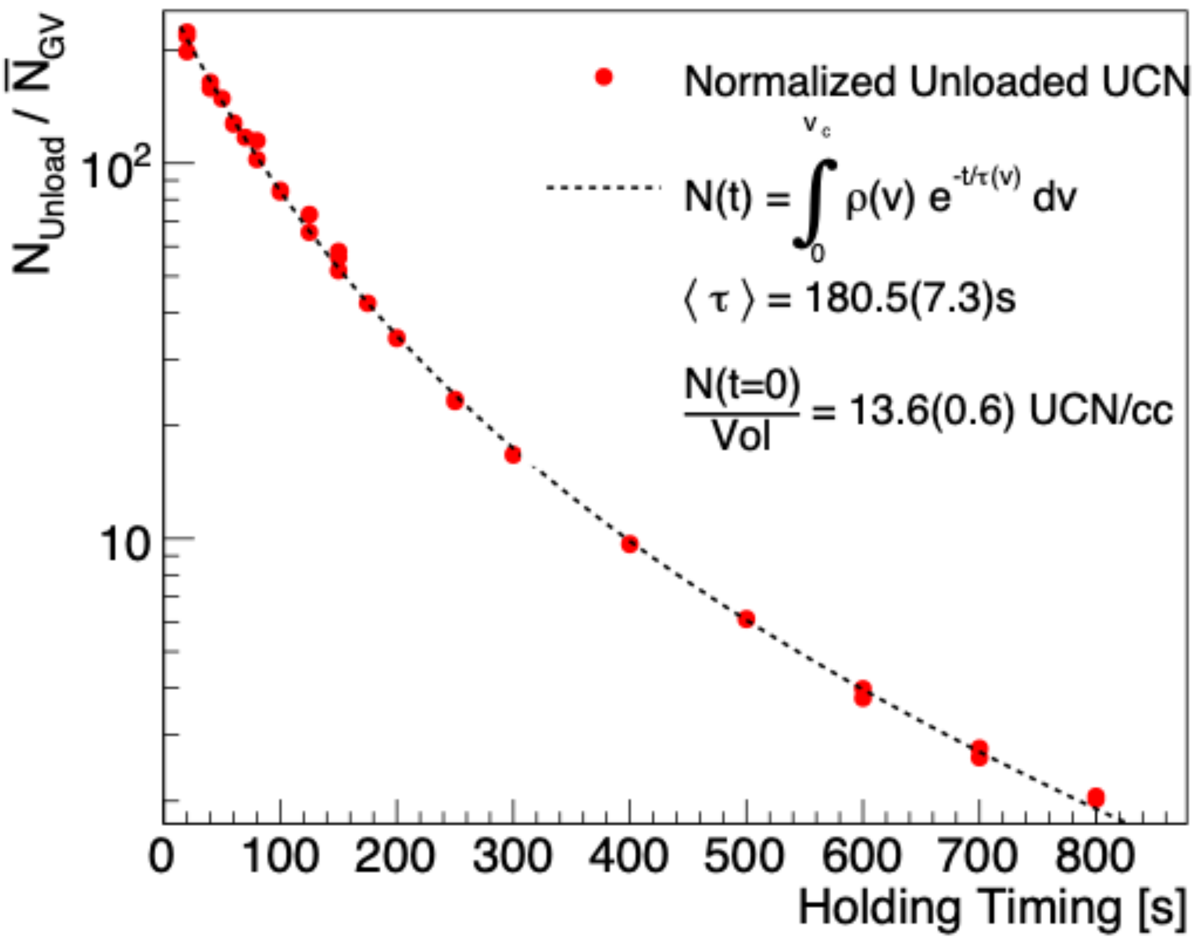
$$^{51}V + n \rightarrow {}^{52}V \rightarrow {}^{52}Cr + \beta + \gamma\ (1.4\ MeV)$$



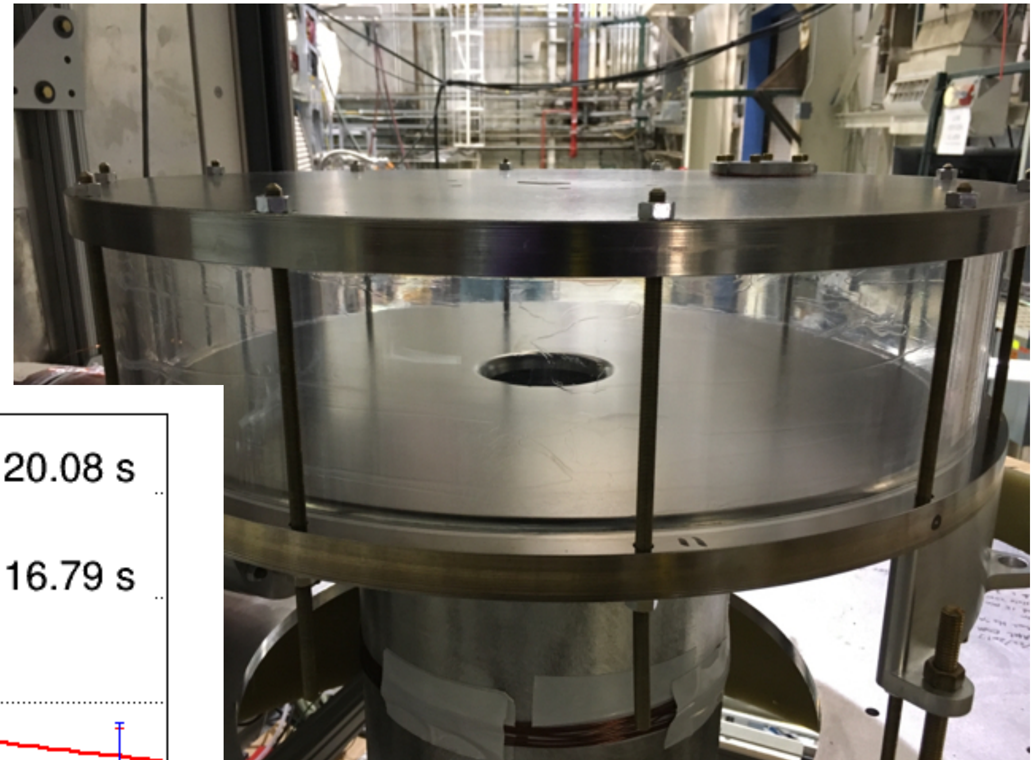
PHYSICAL REVIEW C **97**, 012501(R) (2018)

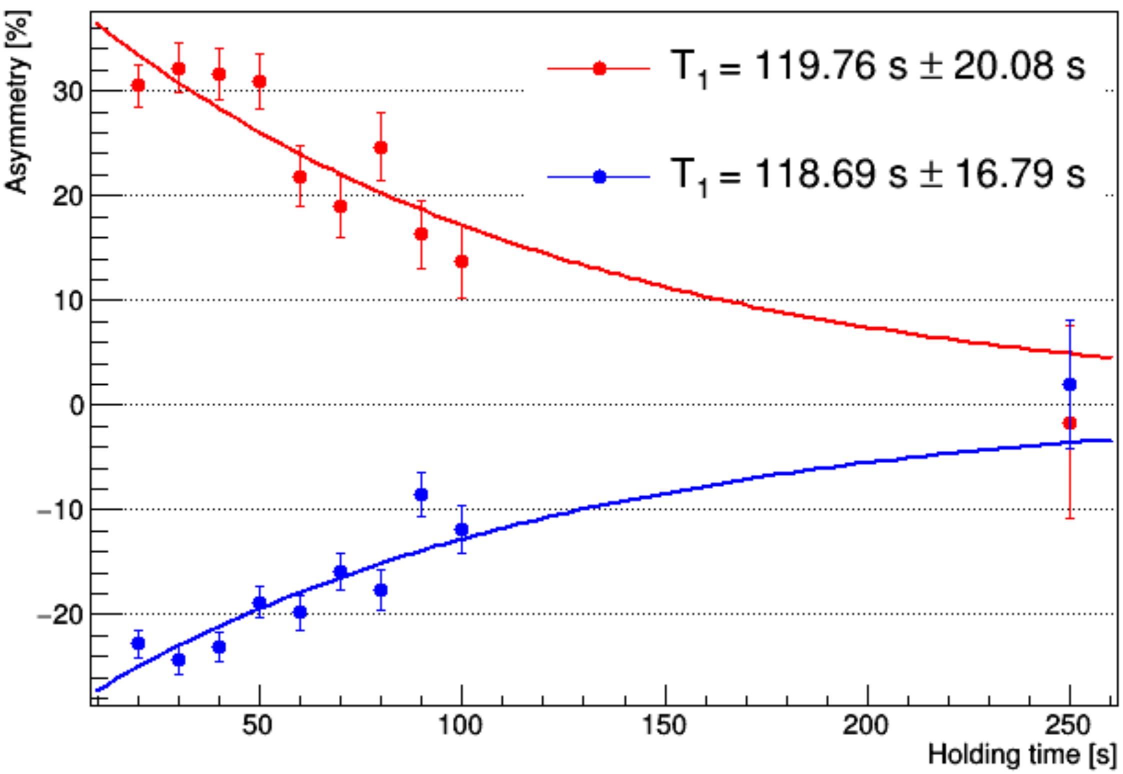
The polarized UCN density stored in an external chamber was measured to be **39(7) UCN/cm3**

Storage time measurement



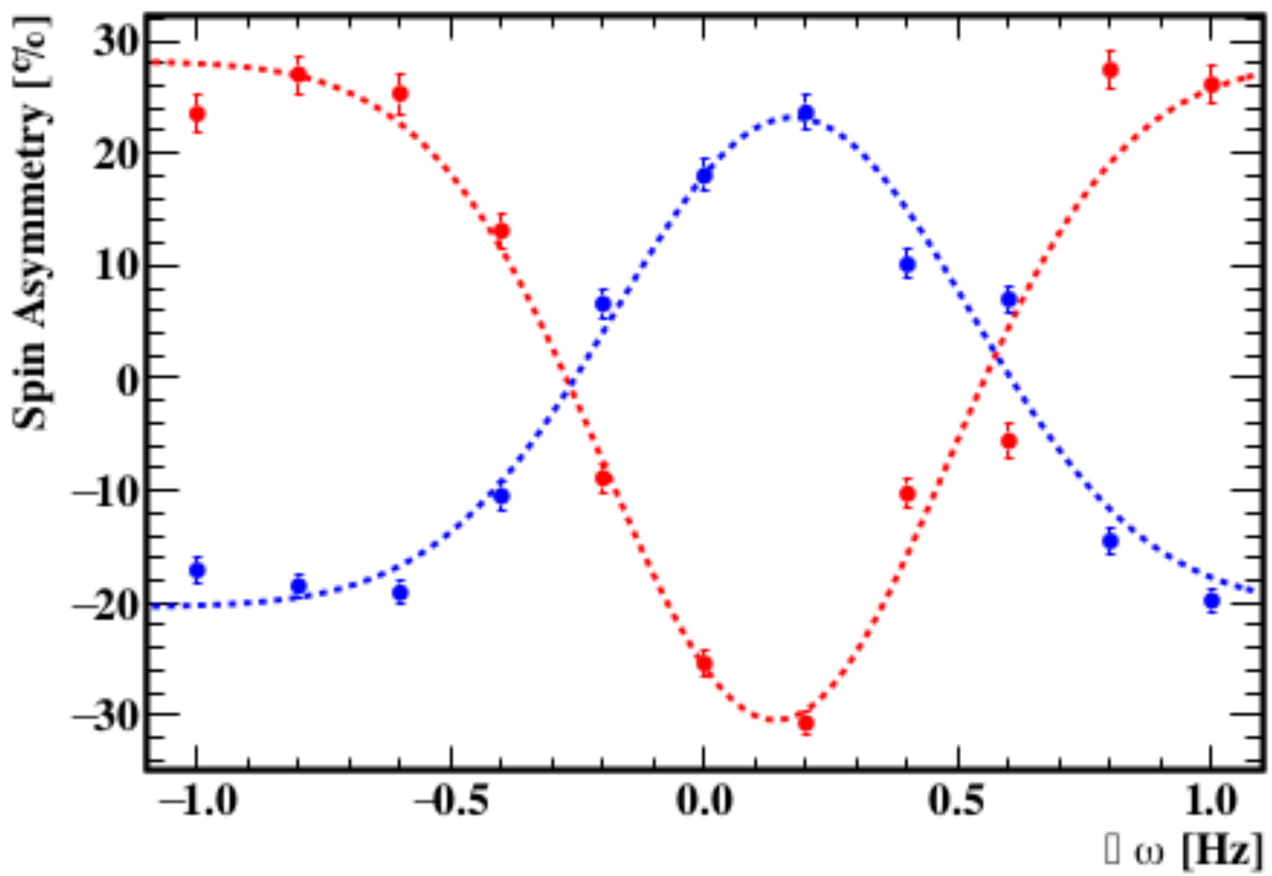
T_1 with dPS coated cell



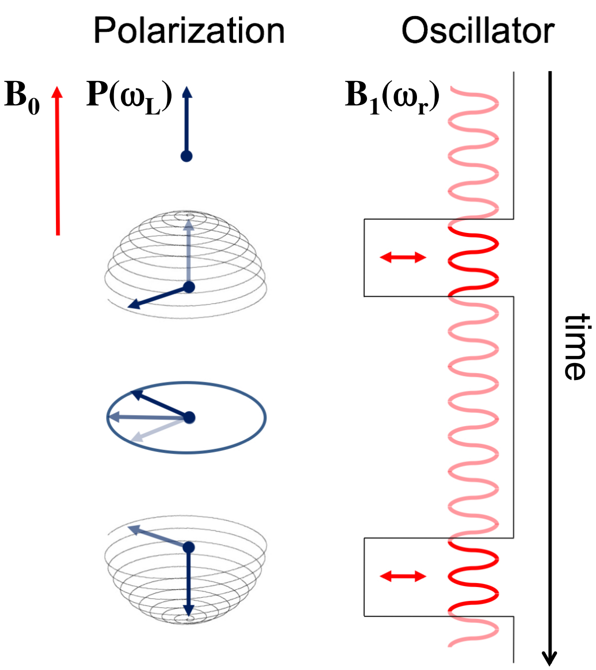


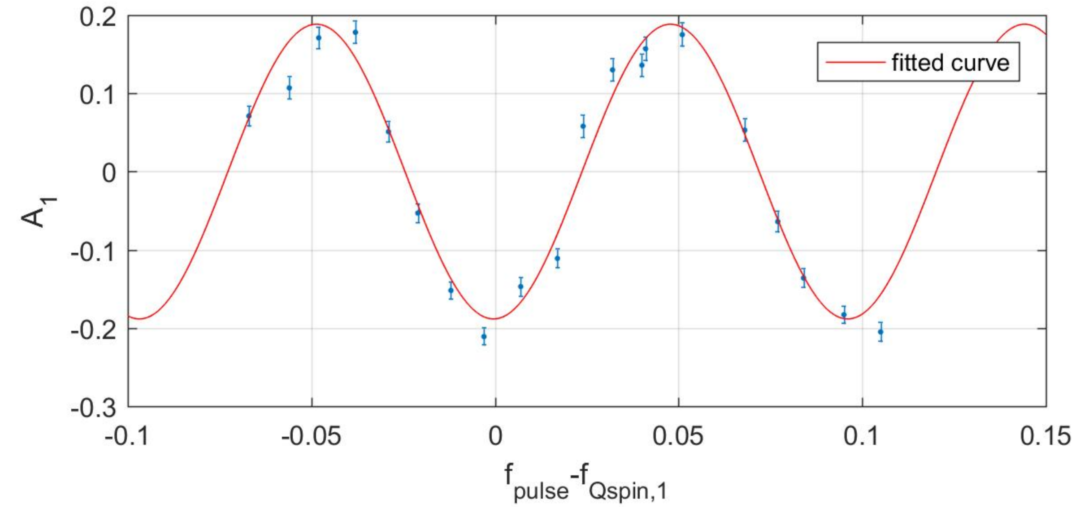
The measured T1 indicates a field gradient of 100 nT/m, much worse than the measured gradient of a few nT/m in the absence of the cell and electrodes. This indicates existence of some localized magnetization.

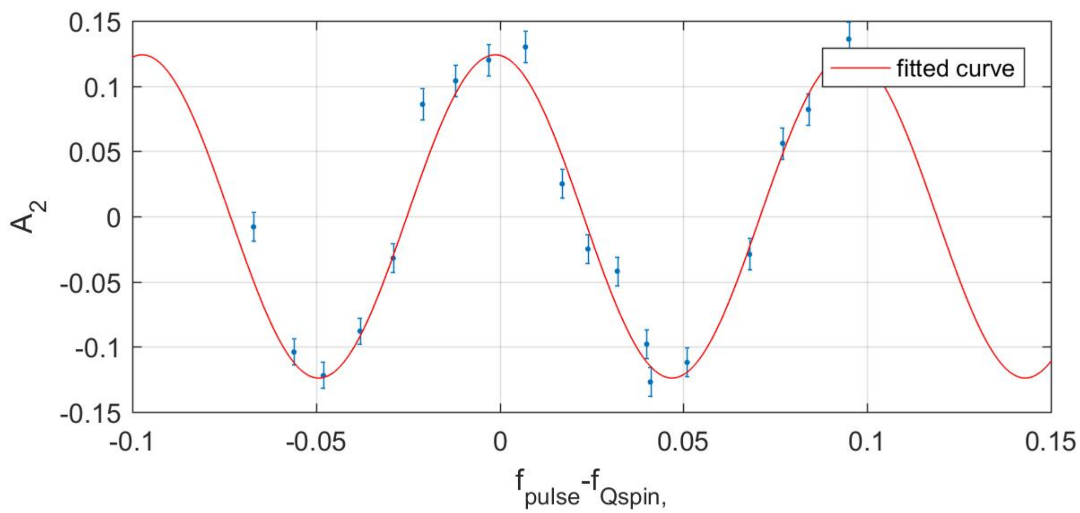
Rabi measurement



Ramsey curve with τ=10 s







T2 ~ 20 s

LANL nEDM Magnetic field specs

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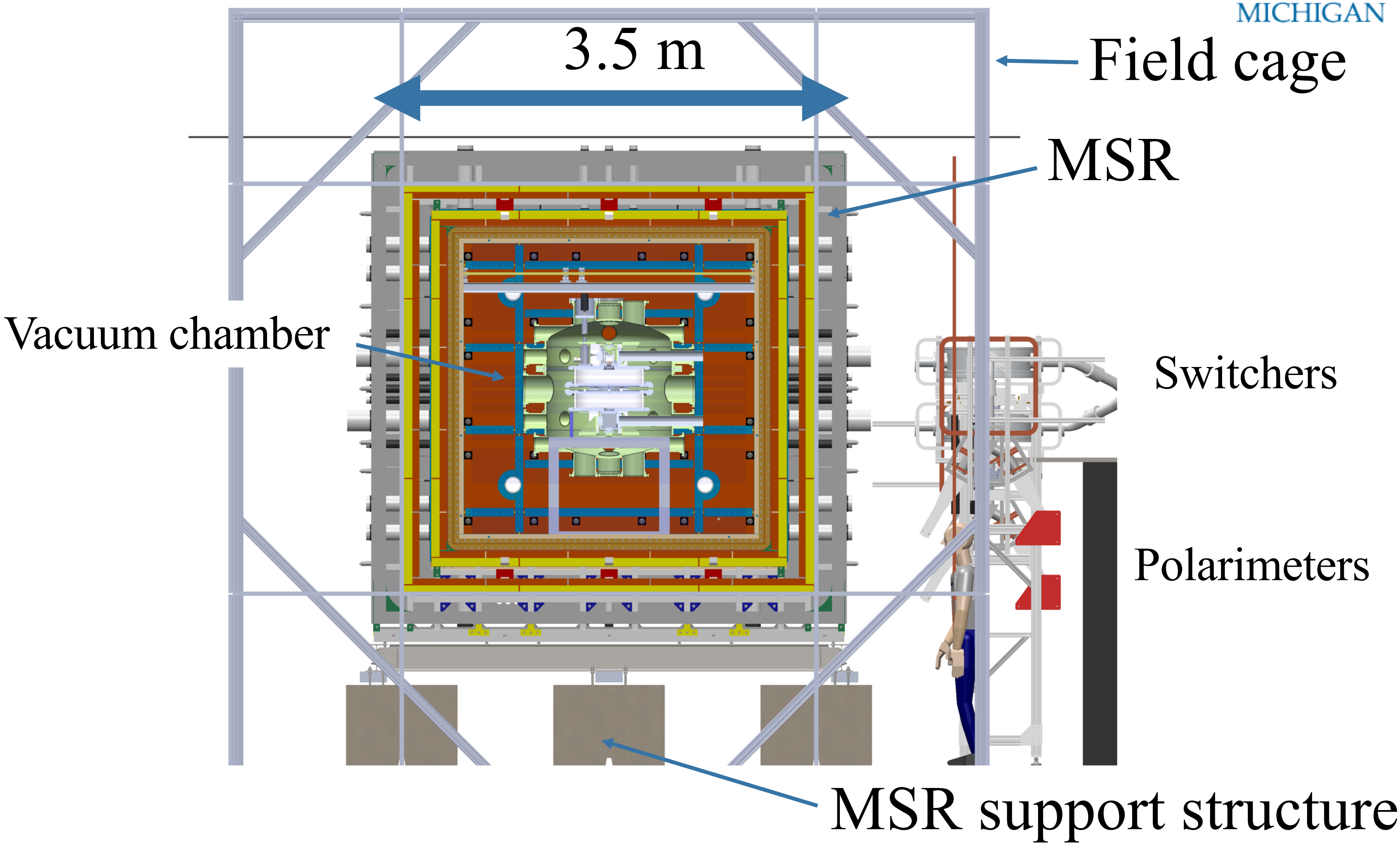
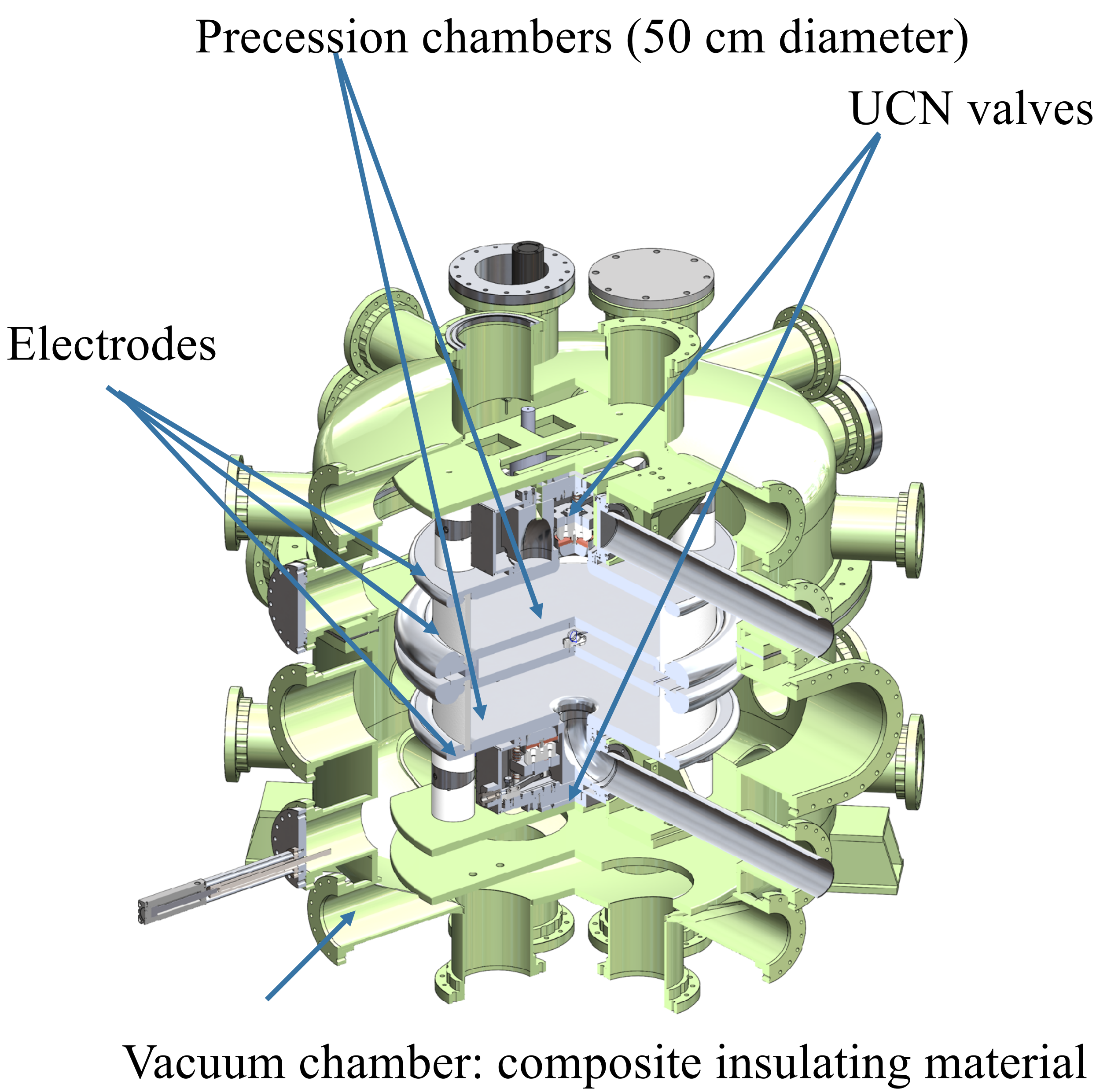
Parameter	Symbol	Units	Values
Electric field	E	kV/cm	12
UCN per chamber	N		39,000
Free Precession Time	T_{free}	s	180
Cycle Time	T_{cycle}	s	300
Polarization Product	$\alpha = AP_0$		0.8
B-field gradient	∇B	(nT/m)	0.3
B-field stability	ΔB	(fT/500 s)	50
Gradient/stability monitorng		**(fT/15 cm/500 s)**	**100**

Overview



3.5 m
Field cage
MSR
Vacuum chamber
Switchers
Polarimeters
MSR support structure

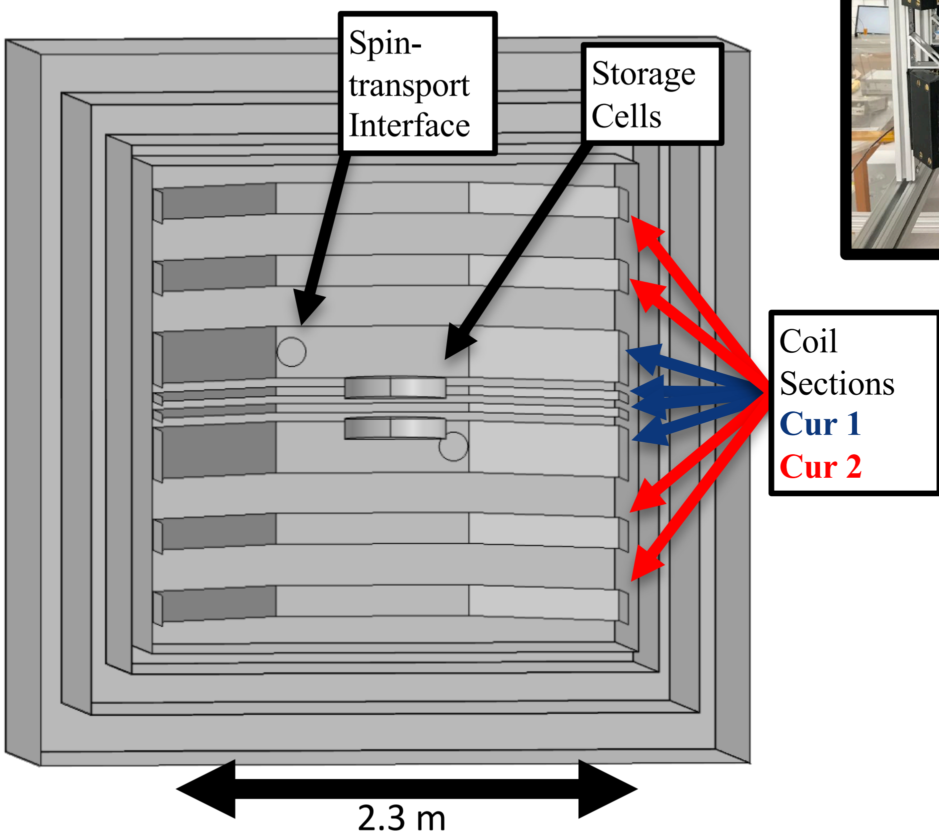
Vacuum and internal design

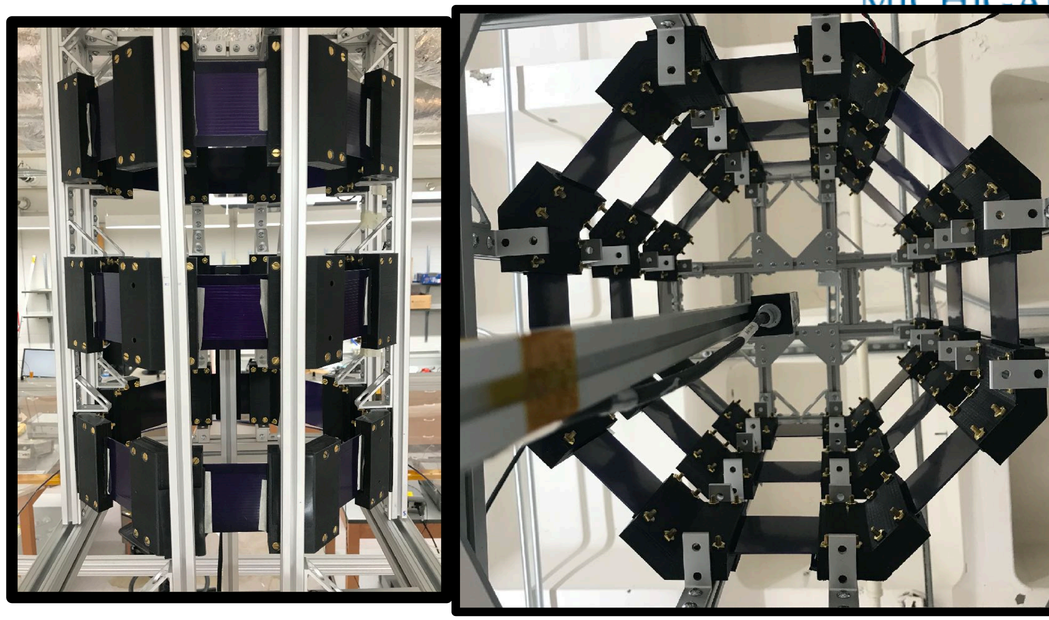


Vacuum and internal design

B_0 Coil (J. Brewinton, A. Palamure, B. Plaster)

- Octagon-shaped multi-gap solenoid
- Spin-transport coil interface
- Comsol modeled





$1/7^{th}$ scale prototype

1/2 scale prototype will be tested in the small MSR

Spin transport into MSR and B_0

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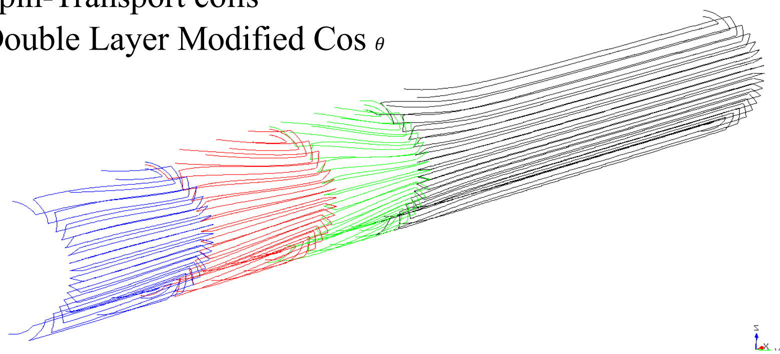
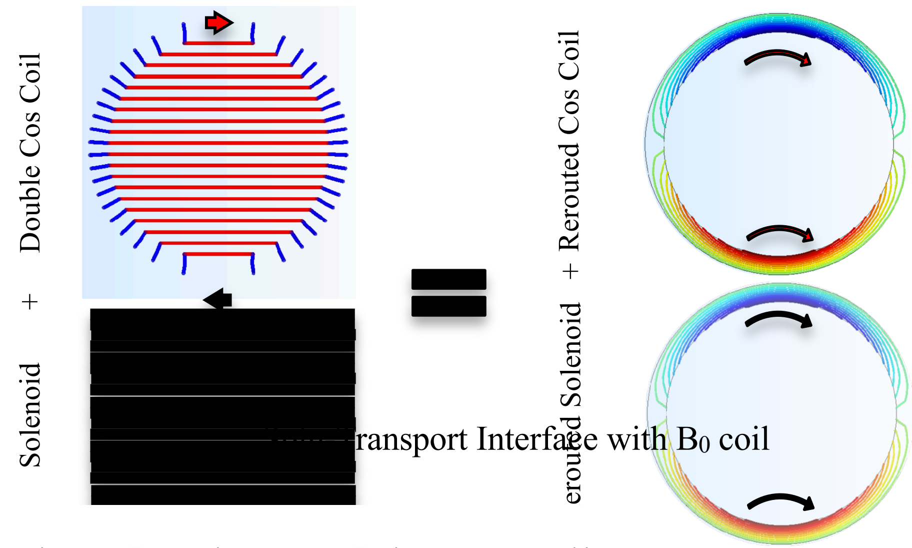
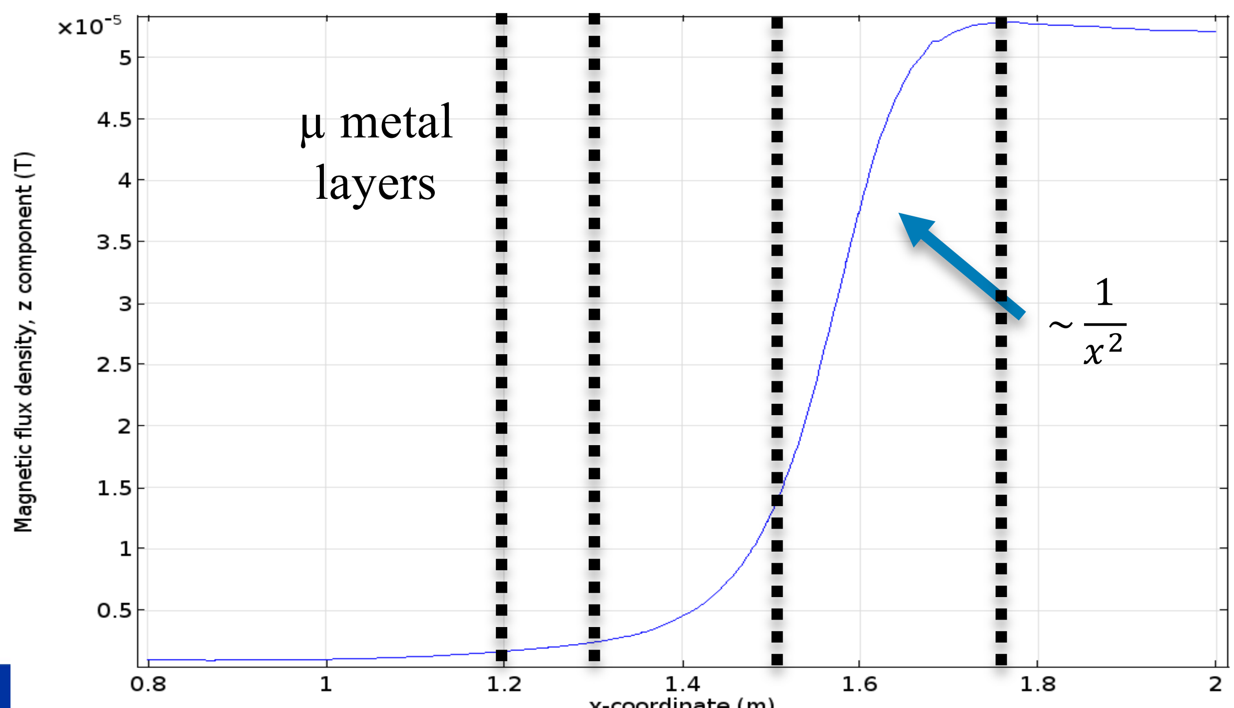
Spin-Transport coils
Double Layer Modified Cos θ

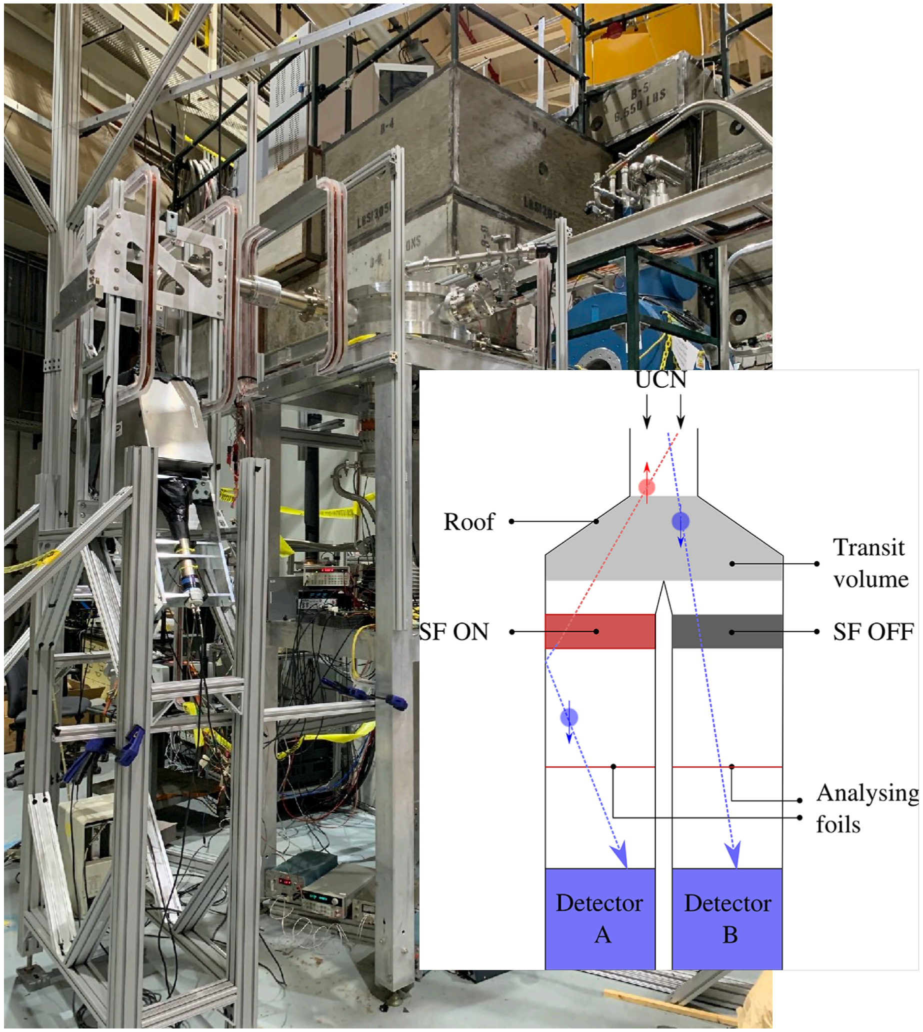


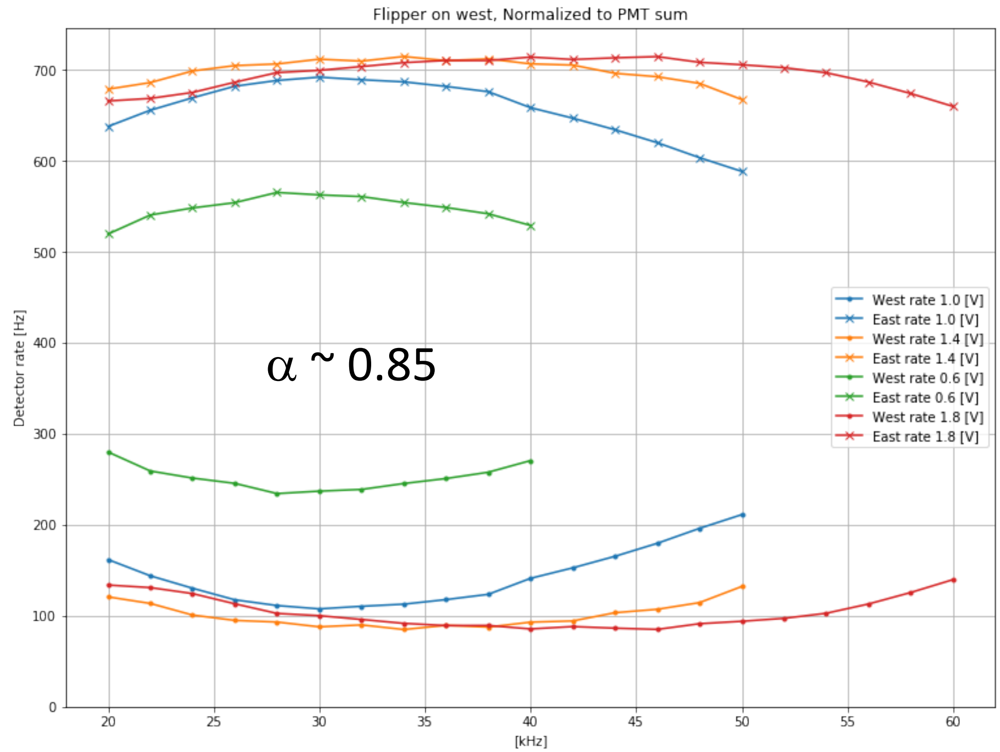




University of Kentucky

Polarimeter – measures two spin states





$\alpha \sim 0.85$

MSR
Designed in collaboration with MSL;
Constructed in UK, installation underway MSC

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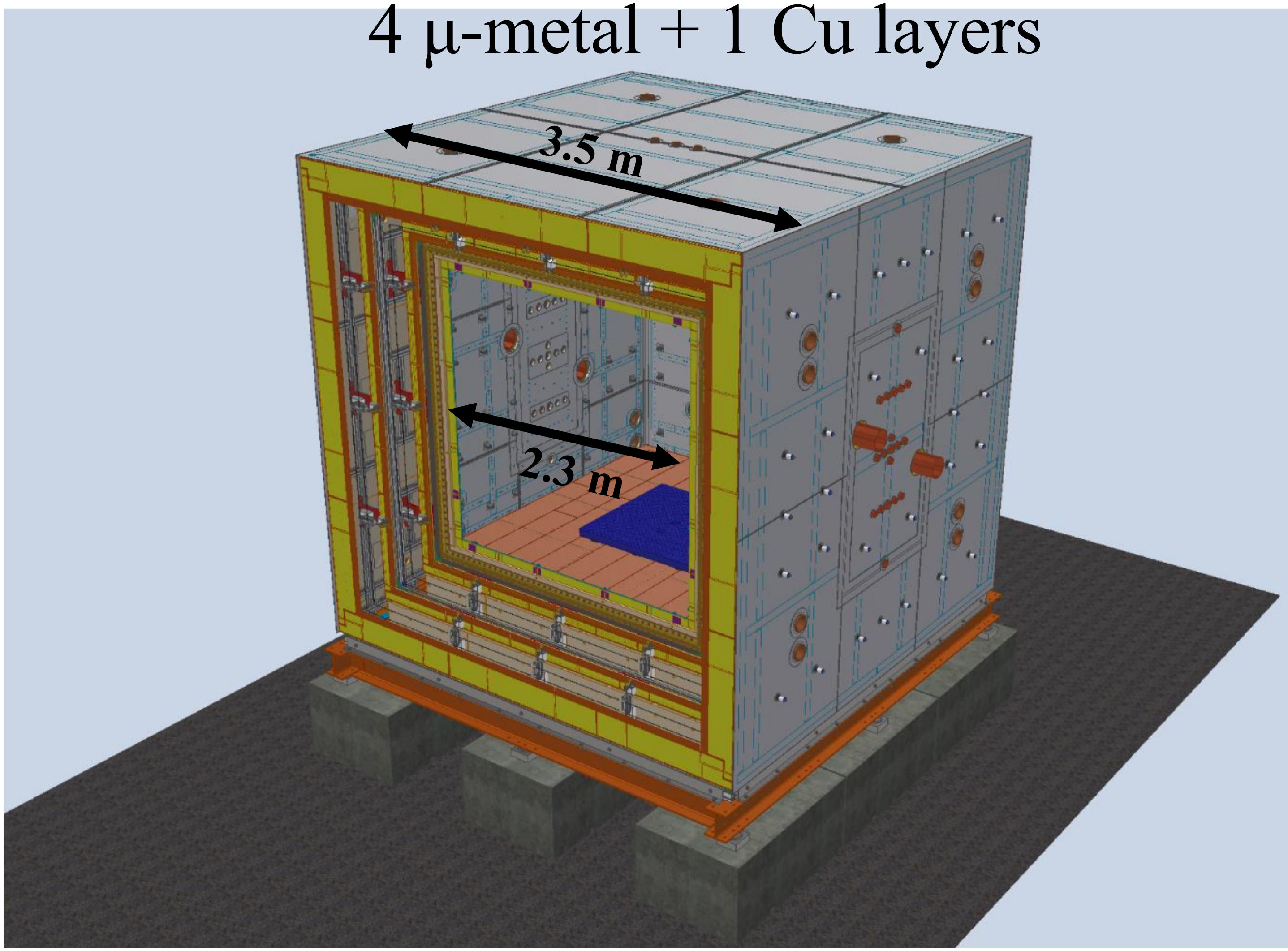
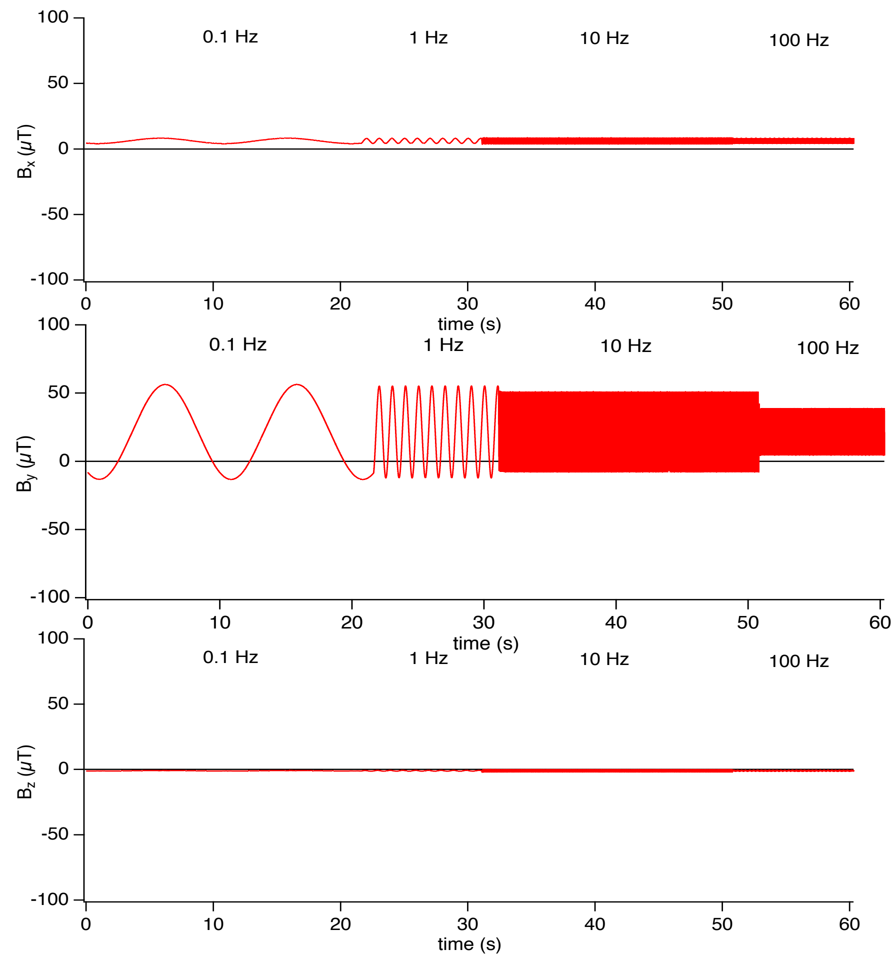


Frequency (Hz)	SF
0.01	100,001
0.1	100,001
1	1,000,001
10	10,000,001
100	10,000,001

Field cage MSR Evaluation and cancellation of external fields:

y-coil



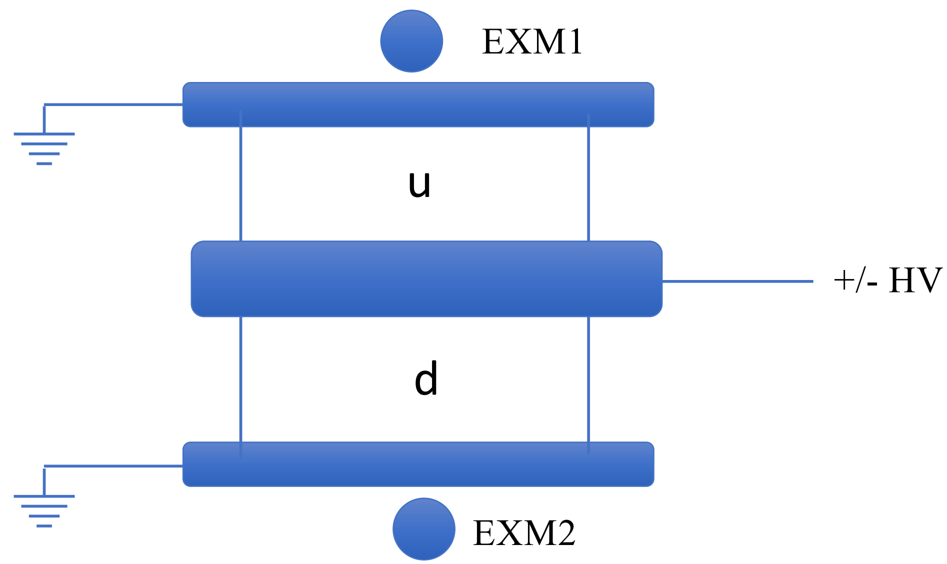
Magnetometry Requirements

UCNs

$$\omega_{u/d}^{+/-} = \gamma_n \left(B^{+/-} + \frac{\partial B^{+/-}}{\partial z} \Delta z_n \right) + 2\frac{d_n E}{\hbar}$$

Magnetometers

$$\omega_{X1/2}^{+/-} = \gamma_X \left(B^{+/-} + \frac{\partial B^{+/-}}{\partial z} \Delta z_X \right) + \Delta\omega_{X1/2}^{+/-}$$



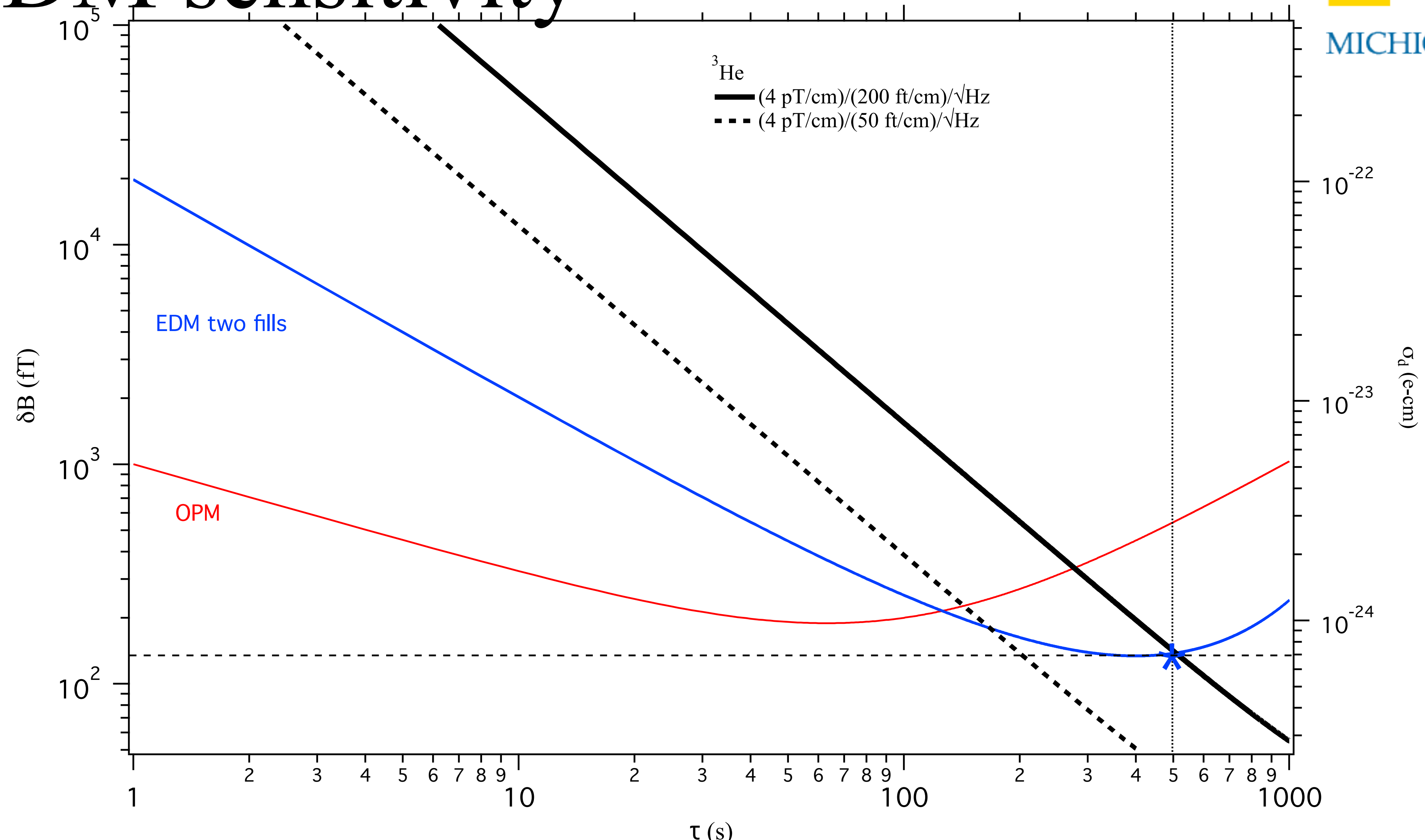
9 Unknowns

$$B^{+},\ B^{-},\frac{\partial B^{+}}{\partial z},\ \frac{\partial B^{-}}{\partial z},\ \Delta\omega_{X1}^{+},\ \Delta\omega_{X2}^{+},\ \Delta\omega_{X1}^{-},\ \Delta\omega_{X2}^{-},\ d_n$$

Magnetometer drift

$$\Delta\omega_1 - \Delta\omega_2 << \frac{\gamma_X}{\gamma_n}\frac{2E\sigma_d}{\hbar}$$

EDM sensitivity

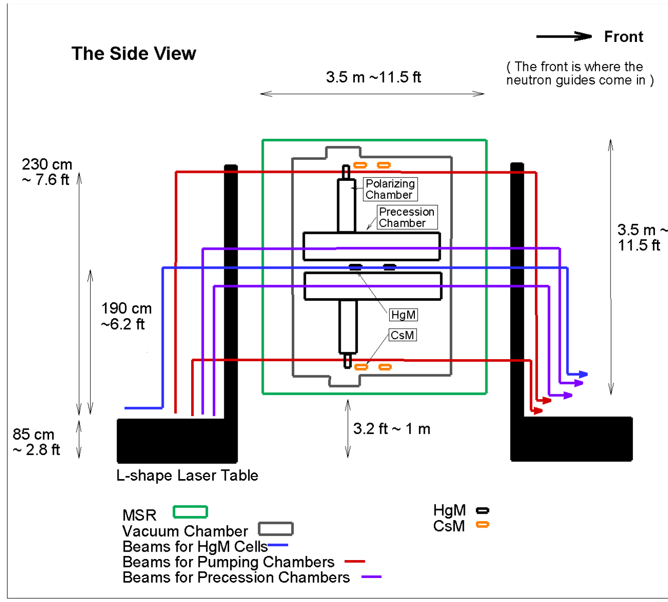


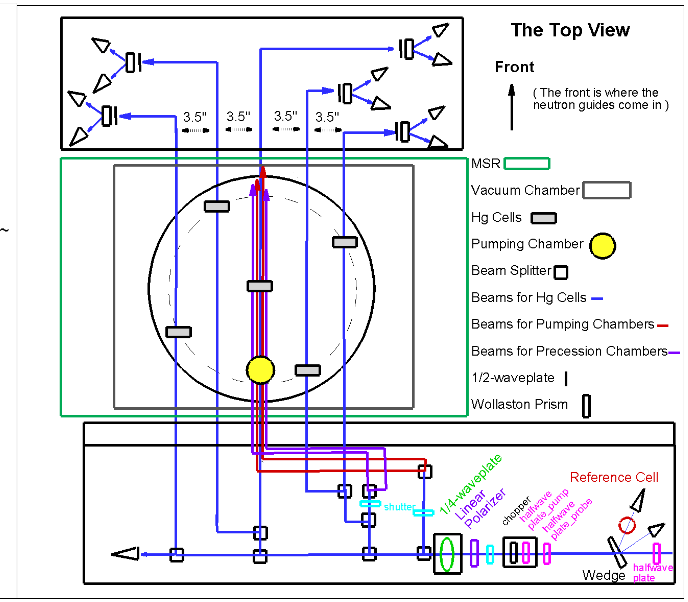
Combine commercial OPMs and custom ^{199}Hg Magnetometers

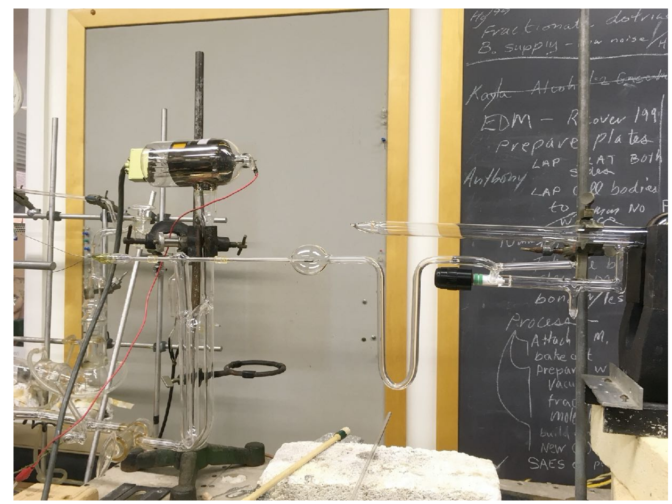
^{199}Hg (^{3}He) comagnetometry incorportated in design

Hg-199 (co) magnetometers: (J Chen, IU)

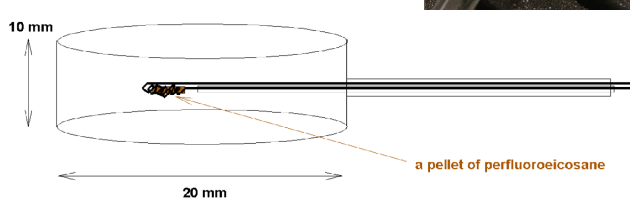
- Optics setup for nEDM@LANL
- Hg cells fabrication and study.
  - Perfluoroeicosane (C20F42) as the wall coating towards the HV mercury cell
  - Reference cell with natural Hg and Helium for feedback laser signal
- Design and fabricate the feedback locking circuit so the laser locks at two frequencies during the pump and probe phases with a Hg reference cell.



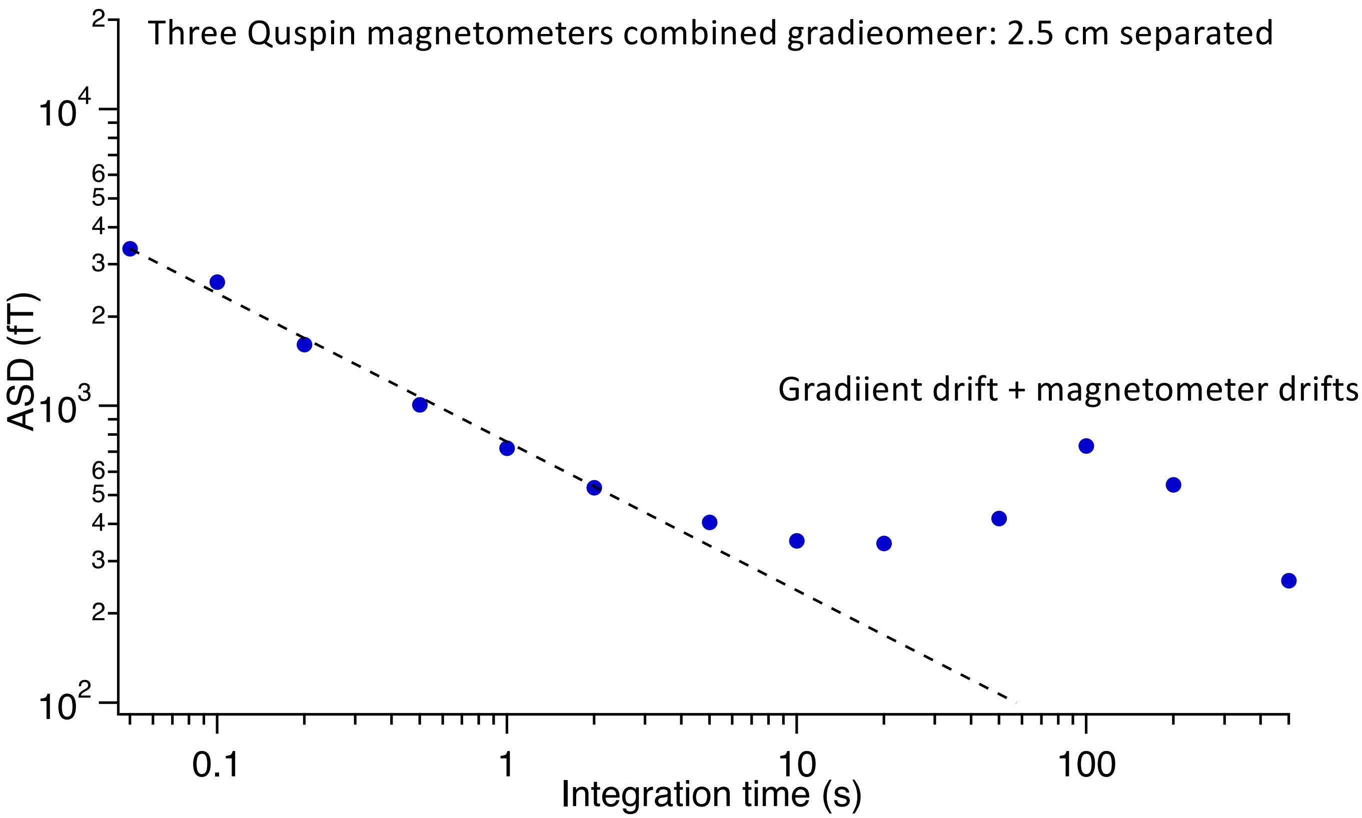




Filament system for evaporating perfluoroeicosane

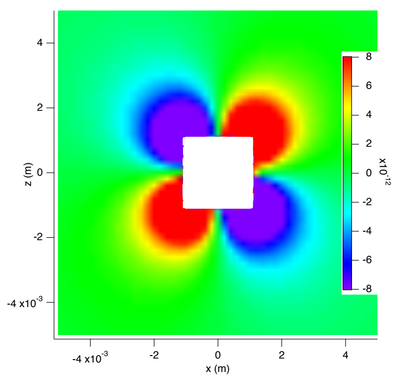


OPMs: Optically pumped alkali magnetometers (Rb, Cs): F. B. Hills



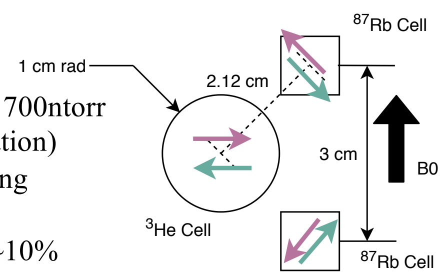
Hybrid magnetometry (Heil, Bison, …)

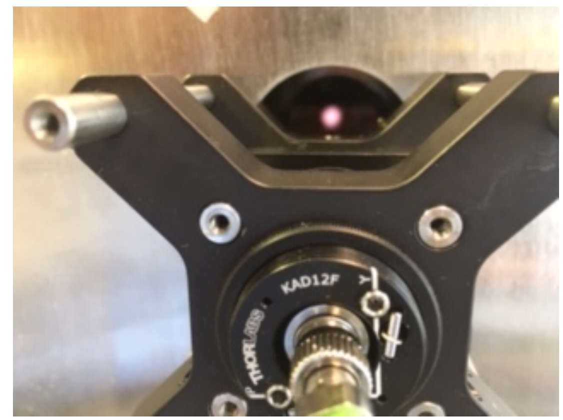
- ^{3}He is "nearly perfect 2-state system"
- Collaboration with Twinleaf LLC (M. Limes, T. Kornack) (pump-probe ^{87}Rb gradiometer - OMG)



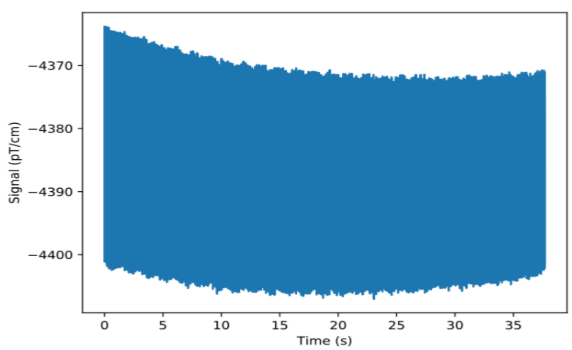
SEOP Pumped: 700ntorr
(<0.1% polarization)
Hours of pumping

MEOP: 2 torr ~10%
< 1 min pumping

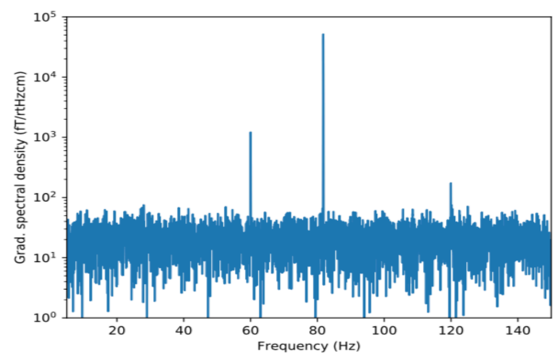




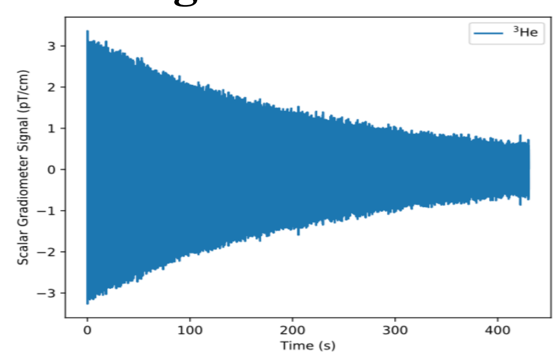
Gradiometer data



FFT



Filtered gradiometer data.



Area B Today

Outlook

September 2021:
MSR Installation complete
B0 and Gradient coils

End 2021:
UCN transport complete / UCN Tests
Central electrode Hg and OPMs

Winter/Spring 2022
Commissioning

June 2022:
First EDM data

5 YEARS TO 10^{-27} E-CM

Fingers crossed!!!