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PSI

High RR Lecture Heidelberg

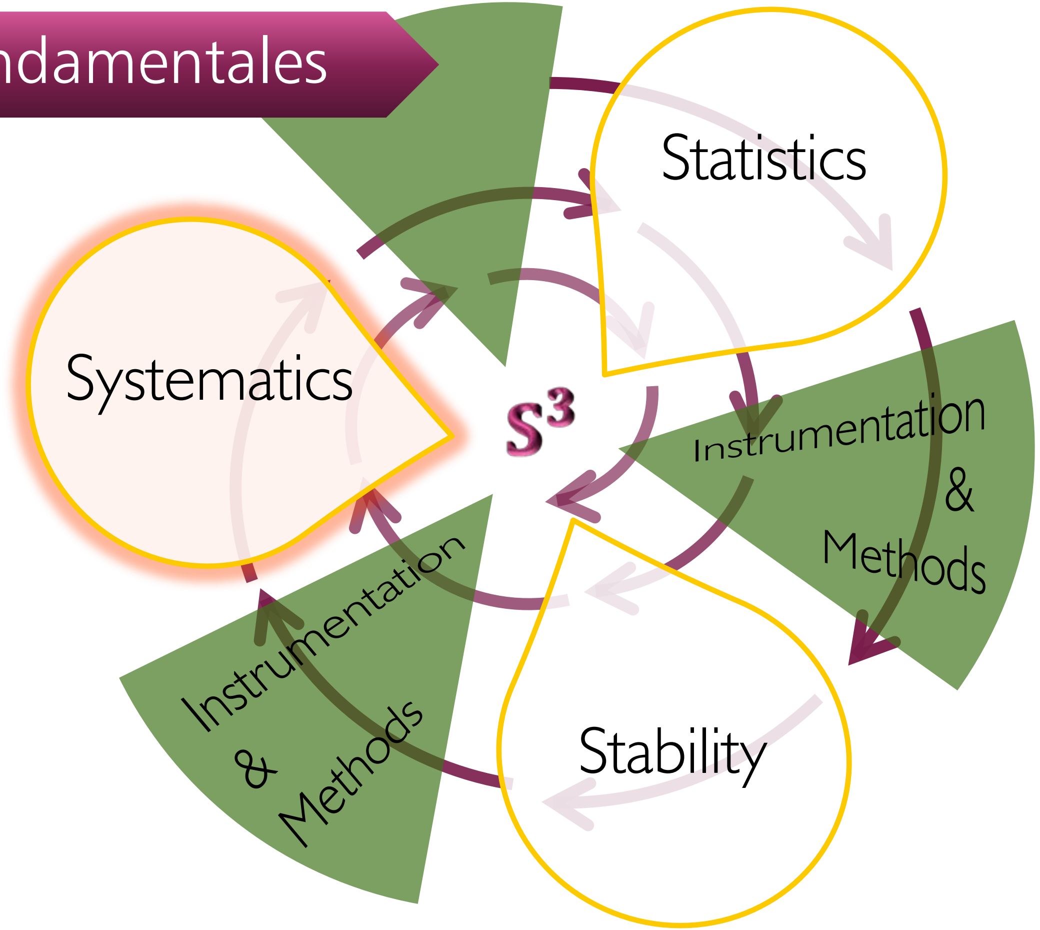
How Neutron EDM-Experiments Really Work III

philipp.schmidt-wellenburg@psi.ch

Outline of the nEDM lecture

Motivation & History

Fundamentales



Lecture I:

Motivation & Fundamentales

Lecture II&III:

The spiral to ultimate sensitivity

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Systematic effects

Express EDM with ratios:

$$d_n = \frac{\hbar\langle\omega_{Hg}\rangle}{4E}(R_+ - R_-)$$

$$R_\pm = \frac{f_n}{f_{Hg}} = \left|\frac{\gamma_n}{\gamma_{Hg}}\right|\left(1 \pm \delta_{EDM} \pm \delta_{EDM}^{false} + \delta_Q + \delta_G + \delta_T + \delta_E + \delta_{LS} + \delta_I + \delta_P + \delta_{AC}\right)$$

E-field ($\pm \delta_{EDM} \pm \delta_{EDM}^{false} + \delta_Q$) — B-field ($+\delta_G + \delta_T$) — Secondary effects ($+ \delta_E + \delta_{LS} + \delta_I + \delta_P + \delta_{AC}$)

- nEDM
- HgEDM

Linear effect ($v \times E$)

- "geometric phase"
- Ordered motion

Quadratic effect (neutron and Hg, random motion)

ll E-

n all

Secondary effects cancel unless correlated with E-field.

$v \times E$ the dominant systematic

- Motional magnetic field from $B_{\mathrm{m}} = -\frac{v \times E}{c^2}$
- Naively no contribution as $\bar{v} = 0$ for UCN?
- In non-uniform B-field and E-field:

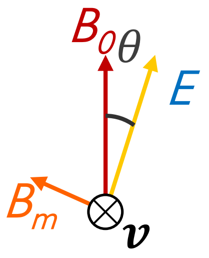
  Rabi: Spin rotation due to oscillating horizontal field.
  This leads to a shift (Ramsey, Bloch, Siegert) of the resonance frequency by

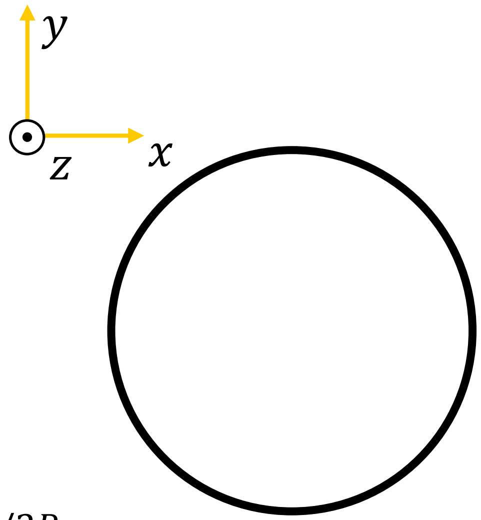
$$\Delta\omega = \frac{(\gamma_n B_\perp)^2}{2(\gamma_{\mathrm{n}} B_0 - \omega_r)}$$

with

$$B_\perp = \frac{\partial B_z}{\partial z}\frac{r}{2} + \frac{v_r E}{c^2}$$

and the oscillation ω_r is a result of rapidly changing trajectories, e.g. $\omega_r = v_r / 2R$





J.M. Pendlebury et al., PRA 70 (2004) 032102
G. Pignol and S. Roccia, PRA 85 (2012) 042105

$v \times E$ the dominant systematic

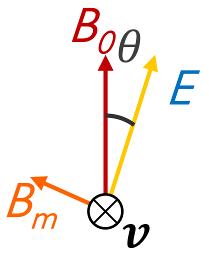
- Motional magnetic field from $B_{\mathrm{m}} = -\frac{v \times E}{c^2}$
- In non-uniform B-field and E-field:

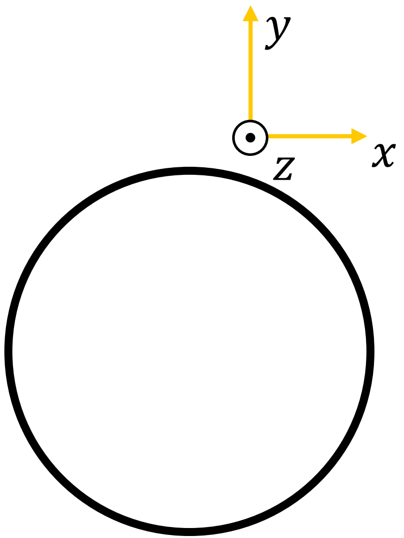
$$B_{\perp}(r)^2 = \left(\frac{\partial B_z}{\partial z}\frac{r}{2}\right)^2 + r\,\frac{\partial B_z}{\partial z}\frac{v_{\perp}E}{c^2} + \left(\frac{v_{\perp}E}{c^2}\right)^2$$

- The term linear in E will lead to a electric field induced shift of precession frequency, **an EDM like signal.**

$$\Delta\omega_{\mathrm{f}} = \gamma^2 r\,\frac{\partial B_z}{\partial z}\,\frac{v_{\perp}E}{2c^2(\gamma_{\mathrm{n}}B_0 - \omega_r)}$$

Different for neutrons (adiabatic), and mercury (ballistic/non-adiabatic)





J.M. Pendlebury et al., **PRA** 70 (2004) 032102

Dominant systematic

- Typical B-field gradients: ∼10 pT/cm
- Dominant effect from mercury transferred to neutron by correction

$$\Delta\omega_{\mathrm{f}}^{\mathrm{adiabtic}} \approx \frac{\pi v_{\perp}^{2}}{48\mathrm{c}^{2}\mathrm{B}^{2}} \frac{\partial \mathrm{B_z}}{\partial z} E$$

$$\Delta\omega_{\mathrm{f}}^{\mathrm{n-adiabtic}} \approx \frac{\gamma^{2} R^{2}}{8\pi \mathrm{c}^{2}} \frac{\partial \mathrm{B_z}}{\partial z} E$$

$$d_{\mathrm{n}}^{\mathrm{false}} / \frac{\mathrm{pT}}{\mathrm{cm}} = 1.5 \times 10^{-28} e\mathrm{cm}$$

$$d_{\mathrm{n}}^{\mathrm{false}} / \frac{\mathrm{pT}}{\mathrm{cm}} = 1.15 \times 10^{-27} e\mathrm{cm}$$

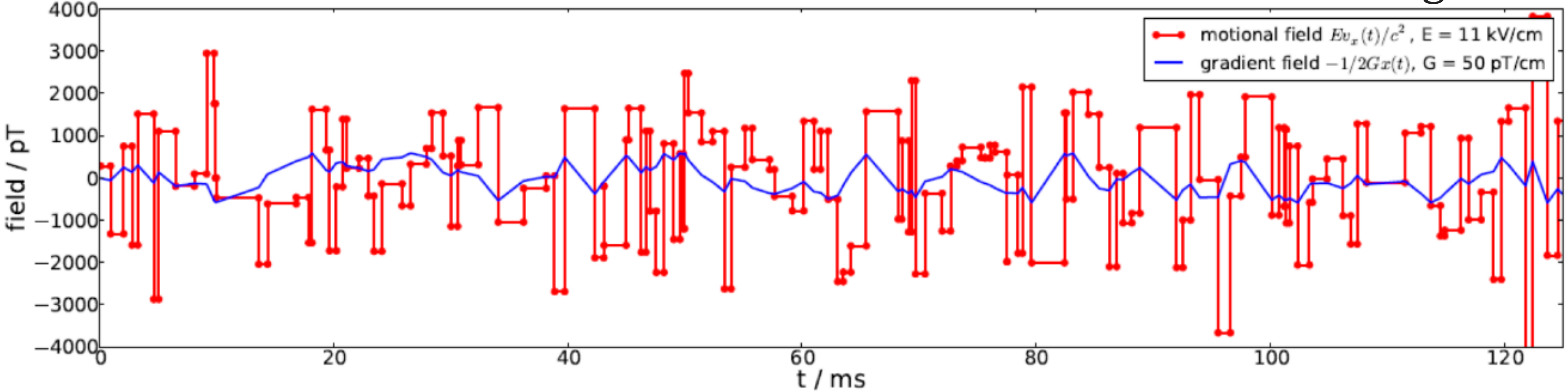
$$d_{\mathrm{Hg}\rightarrow\mathrm{n}}^{\mathrm{false}} / \frac{\mathrm{pT}}{\mathrm{cm}} = -4.4 \times 10^{-27} e\mathrm{cm}$$

nEDM strategy → Measure nEDM as function of B-Field gradient

Afach et al., EPJD(2015)69:225

Motional false effect from ^{199}Hg

The dominant effect is transferred from ^{199}Hg to neutron: $d^{\text{false}}_{\text{n}\leftarrow\text{Hg}}$



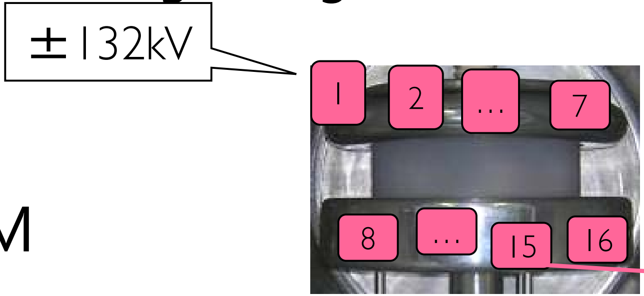
$$d^{\text{false}}_{\text{n}\leftarrow\text{Hg}} = \frac{\hbar\gamma_{\text{n}}\gamma_{\text{Hg}}}{2c^2}\langle xB_x + yB_y\rangle = \frac{\hbar\gamma_{\text{n}}\gamma_{\text{Hg}}}{32c^2} D^2 G_{1,0}$$

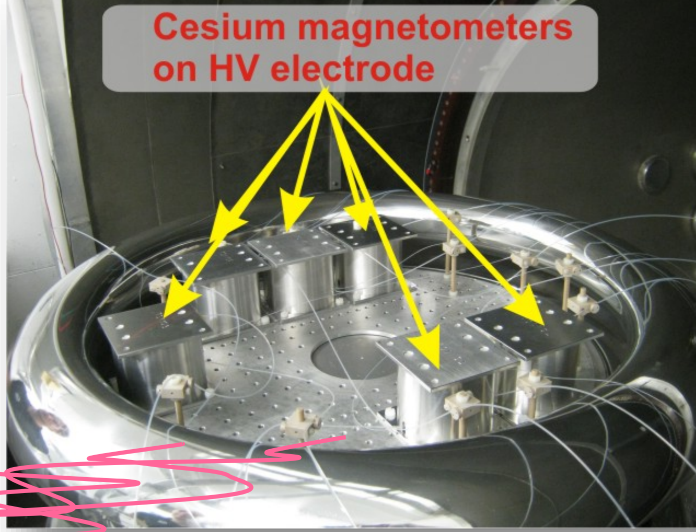
with D = 47cm

$$d^{\text{false}}_{\text{n}\leftarrow\text{Hg}} = -G_{1,0}\, 4.4 \times 10^{-27} e\, \frac{\text{cm}^2}{\text{pT}}$$

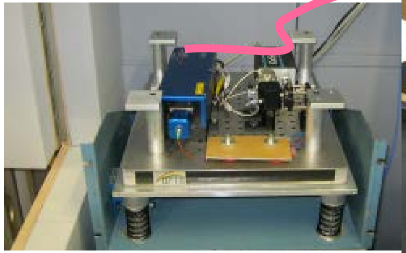
G. Pignol and S. Roccia, **PRA** 85 (2012) 042105
Guillaume Pignol, **PLB** 793 (2019) 440

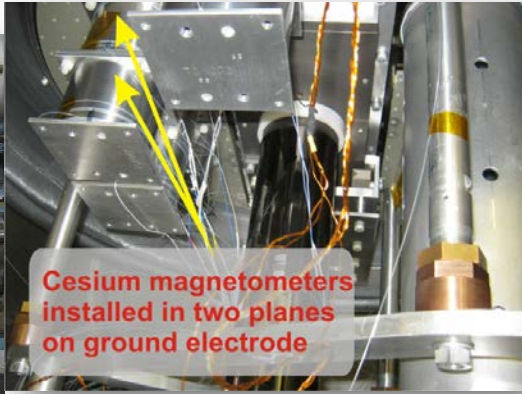
Monitoring of vertical magnetic gradients





- 7 HV CsM
- 9 ground CsM
- Stabilized laser
- PID phase locked DAQ



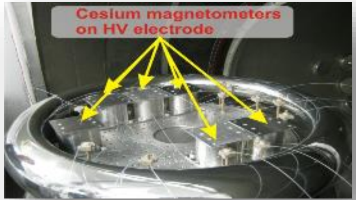


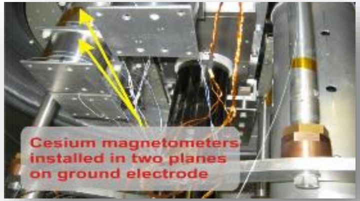
Accuracy:

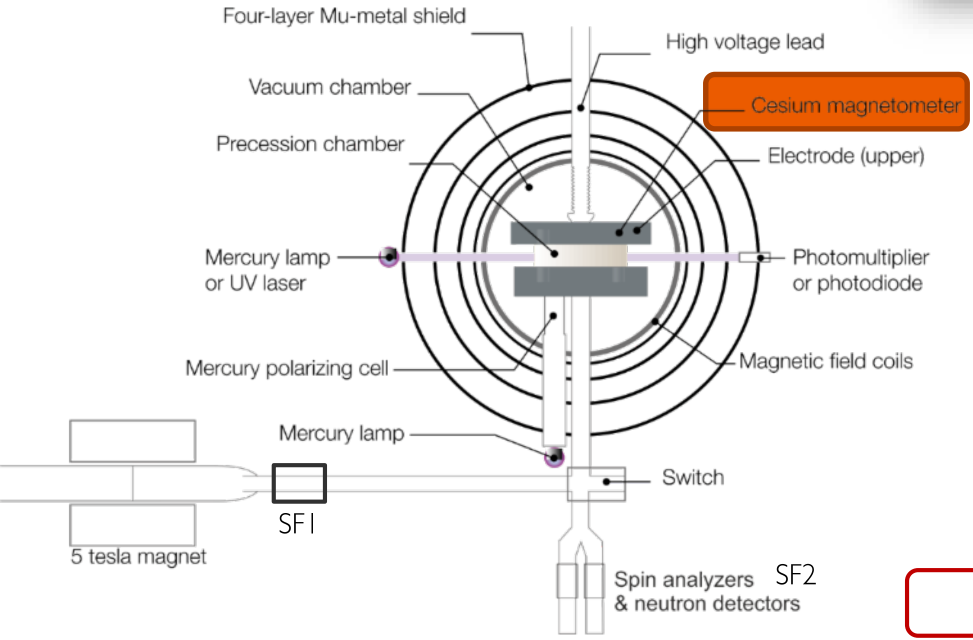
$$\sigma(g_z) \approx 10\mathrm{pT/cm}$$

Measure EDM vs $G_{1,0}$

- Cesium magnetometer array for field gradients







Use polynomial decomposition to calculate non-uniform field

$$\vec{B}(\vec{r}) = \sum_{l,m} G_{l,m} \begin{pmatrix} \Pi_{x,l,m}(\vec{r}) \\ \Pi_{y,l,m}(\vec{r}) \\ \Pi_{z,l,m}(\vec{r}) \end{pmatrix}$$

$$\sigma(G_{1,0}) \approx 8\ \mathrm{pT/cm}$$

Not sufficient to correct for systematic

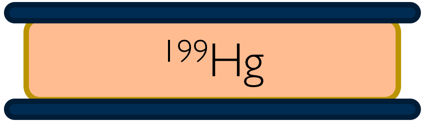
C. Abel et al., PRA 99 (2019) 042112
C. Abel et al., PRA 101 (2020) 053419

Use R-value as proxy for $G_{1,0}$

- Center of mass offset
- Non-adiabaticity

$$R_{\pm} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| \left(1 \pm \delta_{\mathrm{EDM}} \pm \delta_{\mathrm{EDM}}^{\mathrm{false}} + \delta_{\mathrm{Q}} + \delta_{\mathrm{G}} + \delta_{\mathrm{T}} + \delta_{\mathrm{E}} + \delta_{\mathrm{LS}} + \delta_{\mathrm{I}} + \delta_{\mathrm{P}} + \delta_{AC}\right)$$

$\frac{\gamma_{\mathrm{Hg}}}{2\pi} \approx 8$ Hz/μT



$\frac{\gamma_{\mathrm{n}}}{2\pi} \approx 30$ Hz/μT

$\overline{v_{\mathrm{Hg}}} \approx 160$ m/s vs. $\overline{v_{\mathrm{UCN}}} \approx 3$ m/s

$$R \cdot \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| - 1 = \delta_{\mathrm{G}} = \pm \frac{\langle z \rangle G_{1,0}}{B_0}$$

Effect of higher order gradients

$$R_{\pm} = \frac{f_{\mathrm{n}}}{f_{\mathrm{Hg}}} = \left|\frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\right| \left(1 \pm \delta_{\mathrm{EDM}} \pm \delta_{\mathrm{EDM}}^{\mathrm{false}} + \delta_{\mathrm{Q}} + \delta_{\mathrm{G}} + \delta_{\mathrm{T}} + \delta_{\mathrm{E}} + \delta_{\mathrm{LS}} + \delta_{\mathrm{I}} + \delta_{\mathrm{P}} + \delta_{AC}\right)$$

$$\delta_{\mathrm{G}} = \pm \frac{\langle z \rangle G_{1,0}}{|B_0|}$$

and

$$d_{\mathrm{n}\leftarrow\mathrm{Hg}}^{\mathrm{false}} = \frac{\hbar \gamma_{\mathrm{n}} \gamma_{\mathrm{Hg}}}{32 c^2} D^2 G_{1,0}$$

is not the full story, but… … neither.

But instead:

$$\delta_{\mathrm{G}} = \frac{\langle z \rangle G_{\mathrm{g}}}{|B_0|}$$

with

$$G_{\mathrm{g}} = \mathrm{G}_{10} + \mathrm{G}_{30}\left(\frac{3H^2}{20} - \frac{3D^2}{16}\right) + \cdots$$

$$d_{\mathrm{n}\leftarrow\mathrm{Hg}}^{\mathrm{false}} = -\frac{\hbar \gamma_{\mathrm{n}} \gamma_{\mathrm{Hg}}}{32 c^2} \sum_{l \text{ odd}} G_{l0} \langle \rho \Pi_{\rho l m} \rangle$$

$$= \frac{\hbar \gamma_{\mathrm{n}} \gamma_{\mathrm{Hg}}}{32 c^2} D^2 \left[G_{10} - G_{30}\left(\frac{D^2}{8} - \frac{H^2}{4}\right)\right.$$

Correcting systematic by G_g and $\hat{G}$

The crossing point analysis takes care of a large part of the motional false EDM:

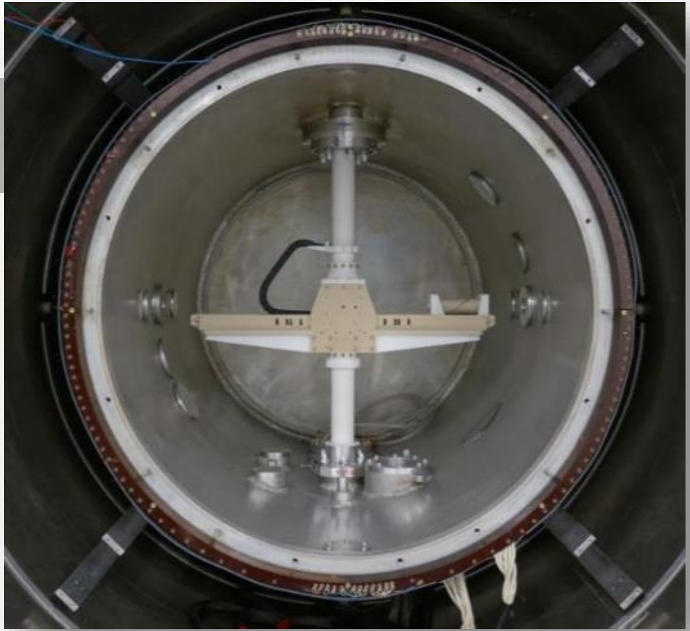
$$d_{n\leftarrow Hg}^{false} = \frac{\hbar\gamma_n\gamma_{Hg}}{32c^2}D^2\left[G_g + G_{30}\left(\frac{D^2}{16}+\frac{H^2}{10}\right) + G_{50}\left(\frac{H^4}{28}-\frac{D^2H^2}{96}-\frac{5D^4}{256}\right)\right]$$

Corrected by crossing point fit

$$\hat{G} \coloneqq \hat{G}_{30} + \hat{G}_{50}$$

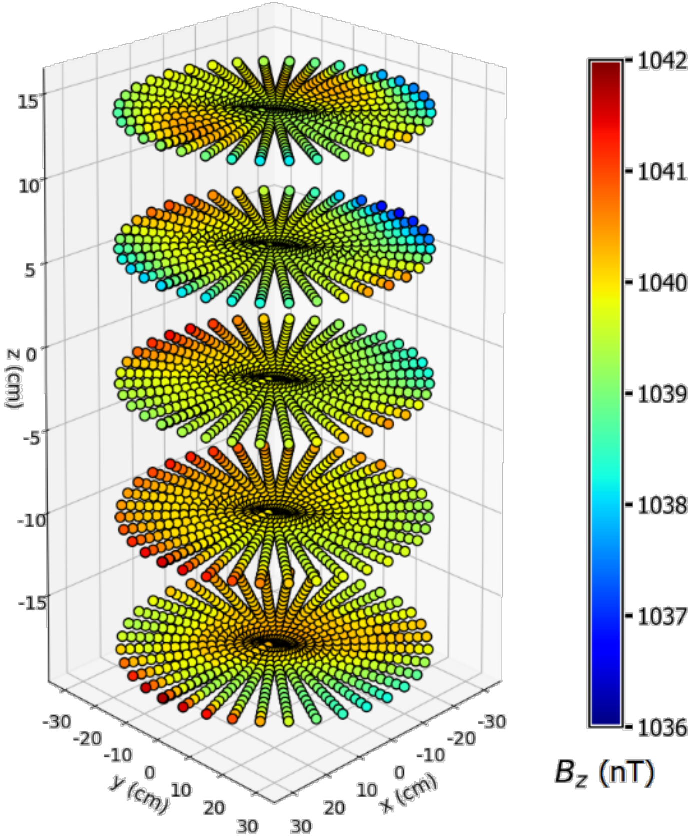
Corrected set for set using map analysis

Magnetic field maps



Mapping with fluxgate

- $-20 < z < 20$,
- $-10 < r < 30$,
- $\Delta\phi = 5°$



- Fit to order $l = 7$
- Extract $\langle B_T^2 \rangle$ for each base configuration
- Extract $\delta_G(\hat{G})$ for each base configuration

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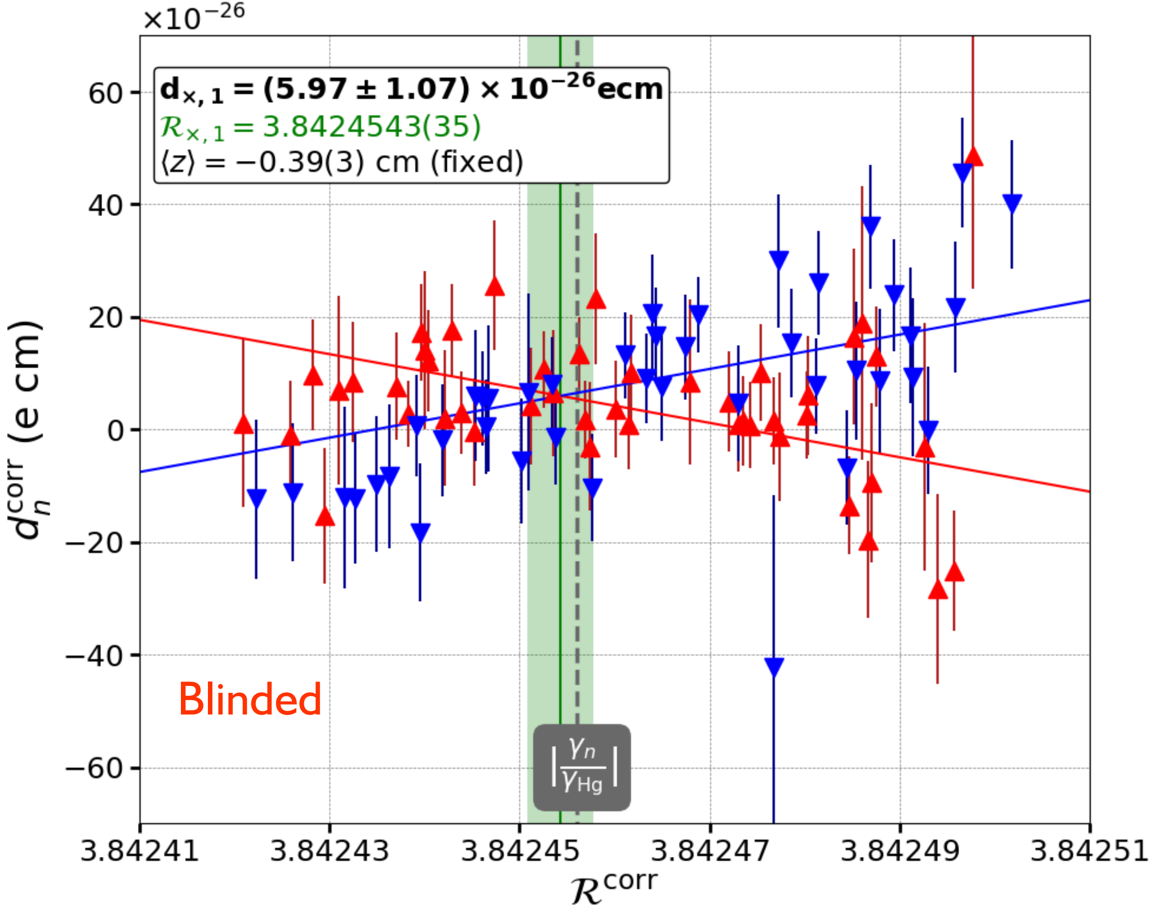
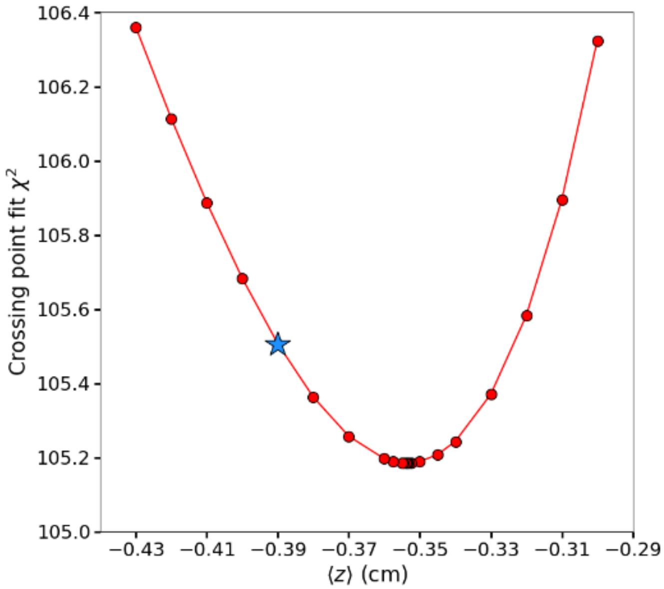
Crossing point analysis





Use R-value as proxy for $G_{1,0}$

- Center of mass offset
- Non-adiabaticity

$$R_\pm = \frac{f_\mathrm{n}}{f_\mathrm{Hg}} = \left|\frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}\right| \left(1 \pm \delta_\mathrm{EDM} \pm \delta_\mathrm{EDM}^\mathrm{false} + \delta_\mathrm{Q} + \delta_\mathrm{G} + \delta_\mathrm{T} + \delta_\mathrm{E} + \delta_\mathrm{LS} + \delta_\mathrm{I} + \delta_\mathrm{P} + \delta_{AC}\right)$$

$$\frac{\gamma_\mathrm{Hg}}{2\pi} \approx 8\ \mathrm{Hz/\mu T}$$

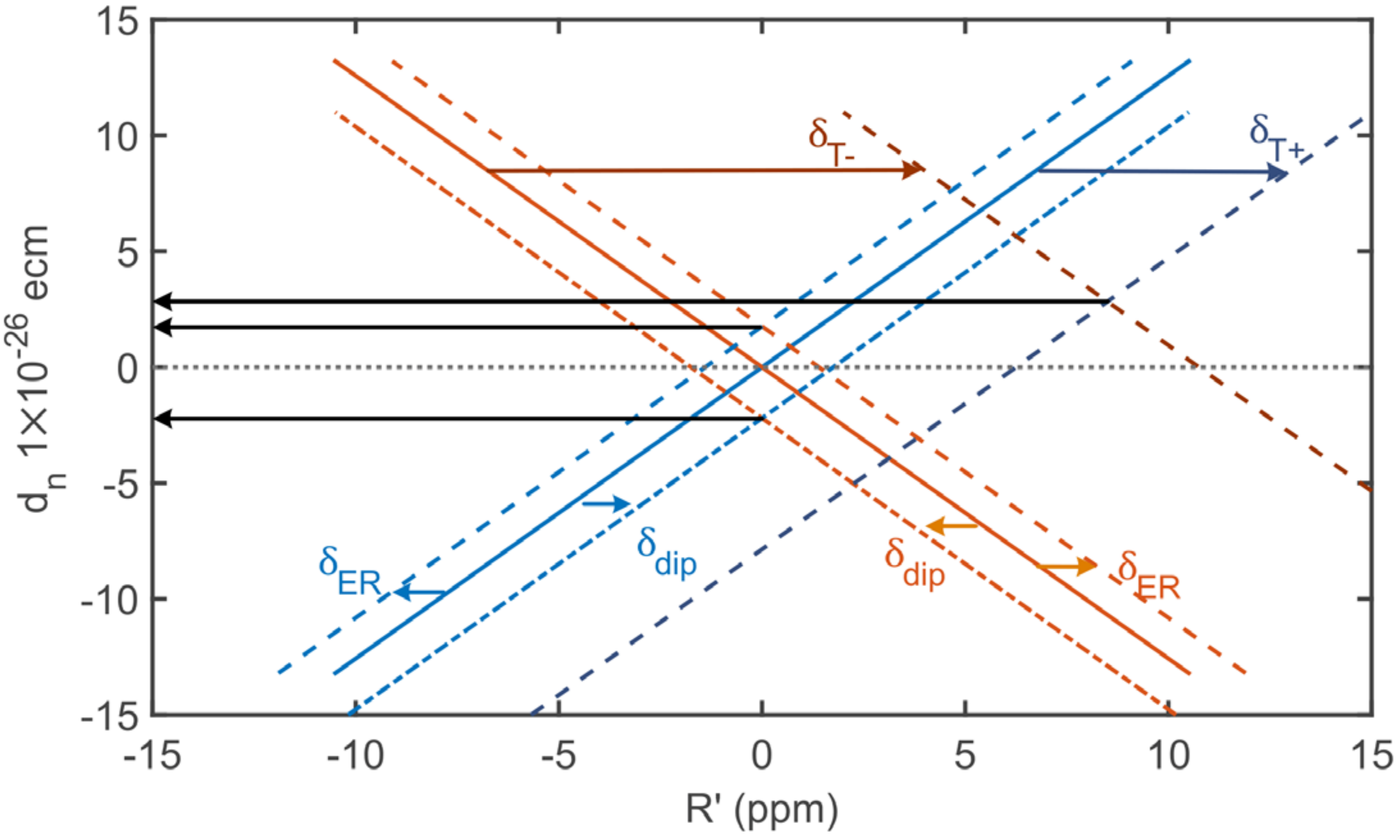
$$\frac{\gamma_\mathrm{n}}{2\pi} \approx 30\ \mathrm{Hz/\mu T}$$

$\overline{v_\mathrm{Hg}} \approx 160$ m/s vs. $\overline{v_\mathrm{UCN}} \approx 3$ m/s

$$R \cdot \left|\frac{\gamma_\mathrm{n}}{\gamma_\mathrm{Hg}}\right| - 1 - \delta_\mathrm{G} = +\delta_\mathrm{T} = \frac{\langle B_\mathrm{T}^2 \rangle}{2B_0^2}$$

Needs to be known for each sequence

Crossing point analysis



Systematic effects

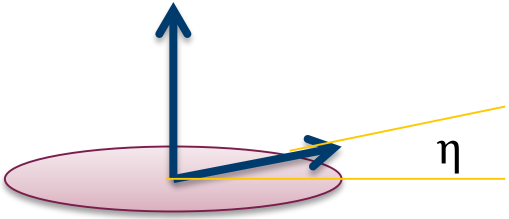
Table I: Summary of systematic effects in 10^{-28} $e$cm. The first three effects are treated within the crossing-point fit and are included in $d_{\times}$. The additional effects below the line are considered separately.

Group	Effect	shift	error
False Hg EDM	Error on $\langle z \rangle$	-	7
	Higher order gradients $\hat{G}$	69	10
	Transverse field correction $\langle B_T^2 \rangle$	0	5
Other effects	Hg EDM[8]	-0.1	0.1
	Local dipole fields	-	4
	$v \times E$ UCN net motion	-	2
	Quadratic $v \times E$	-	0.1
	Uncompensated G drift	-	7.5
	Mercury light shift	-	0.4
	Inc. scattering ^{199}Hg	-	7
	TOTAL		

Field mapping (Higher order gradients $\hat{G}$; Transverse field correction $\langle B_T^2 \rangle$)

Pseudo magnetic field from incoherent scattering length

$$B^* = -\frac{4\pi\hbar}{m_n\gamma_n}\, n b_i P \sqrt{\frac{I}{I+1}}$$

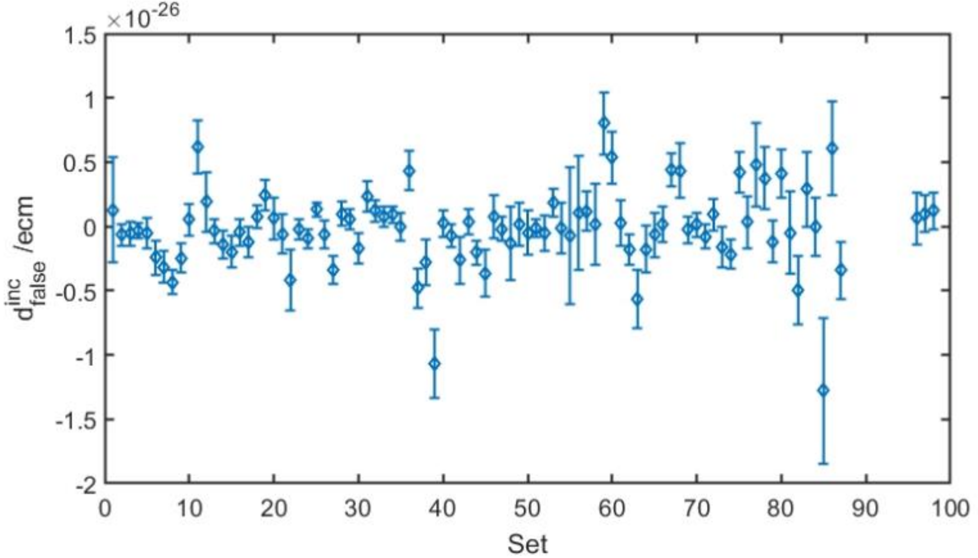


$$\delta\eta = \eta(+E) - \eta(-E)$$

- $b_i = \pm 15.5$ fm
- nP (^{199}Hg × polarization) extracted from data cycle by cycle

$$d_n^{\text{false}} = \hbar \frac{\gamma_n}{4E} B^* \cdot \delta\eta$$

$$< 7 \times 10^{-28} e\text{cm}$$



Outline of the nEDM lecture

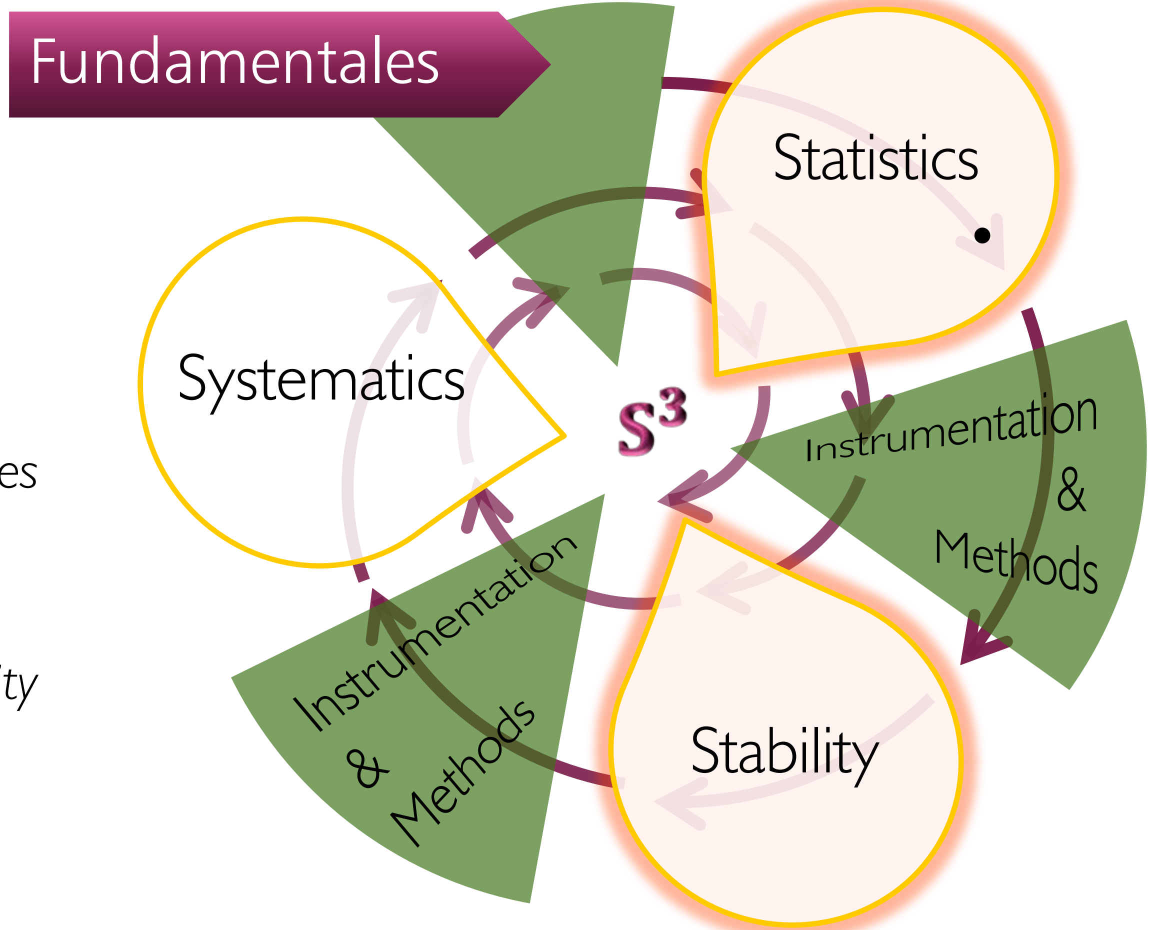
Motivation & History

Lecture I:

Motivation & Fundamentales

Lecture II&III:

The spiral to ultimate sensitivity



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What seems possible in a single shot?

Number of neutrons N:

Higher density and/or larger volume → more neutrons

New UCN sources:
- superthermal sources based on D_2 or sfHe
- Transport losses/dilution
- Ramsey cell = source

Needs matching of source volume to experiment volume, other wise too strong dilution.
Neutron spin coherence function of cell radius → good control of gradients:

$$\frac{1}{T_{2,\mathrm{mag}}} = \frac{8R^3\gamma_n^2}{9\pi v}(G_{1,-1}^2 + G_{1,1}^2) + \frac{\mathcal{H}^3\gamma_n^2}{16v}G_{1,0}^2$$

C. Abel et al., PRA99(2019)042112

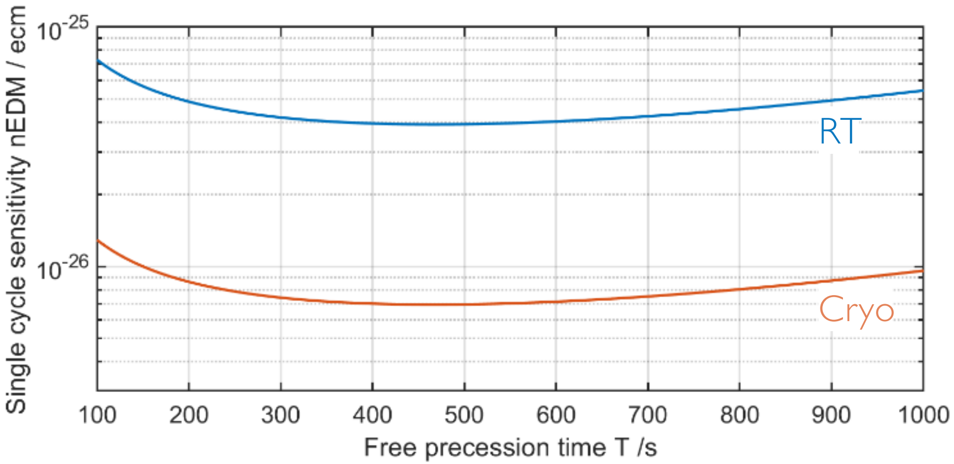
What seems possible in a single shot?

Number of neutrons	N:	10^7
Electric field	RT:	20 kV/cm **Cryogenic:** 80kV/cm
Coherence time	T_2:	3000 s
Storage times	t_s, t_f:	(100, 300) s

100 times larger (SuperSun, TRIUMF, SNS)

8 times larger (SNS, former CryoEDM)

C. Abel et al., PRA99(2019)042112



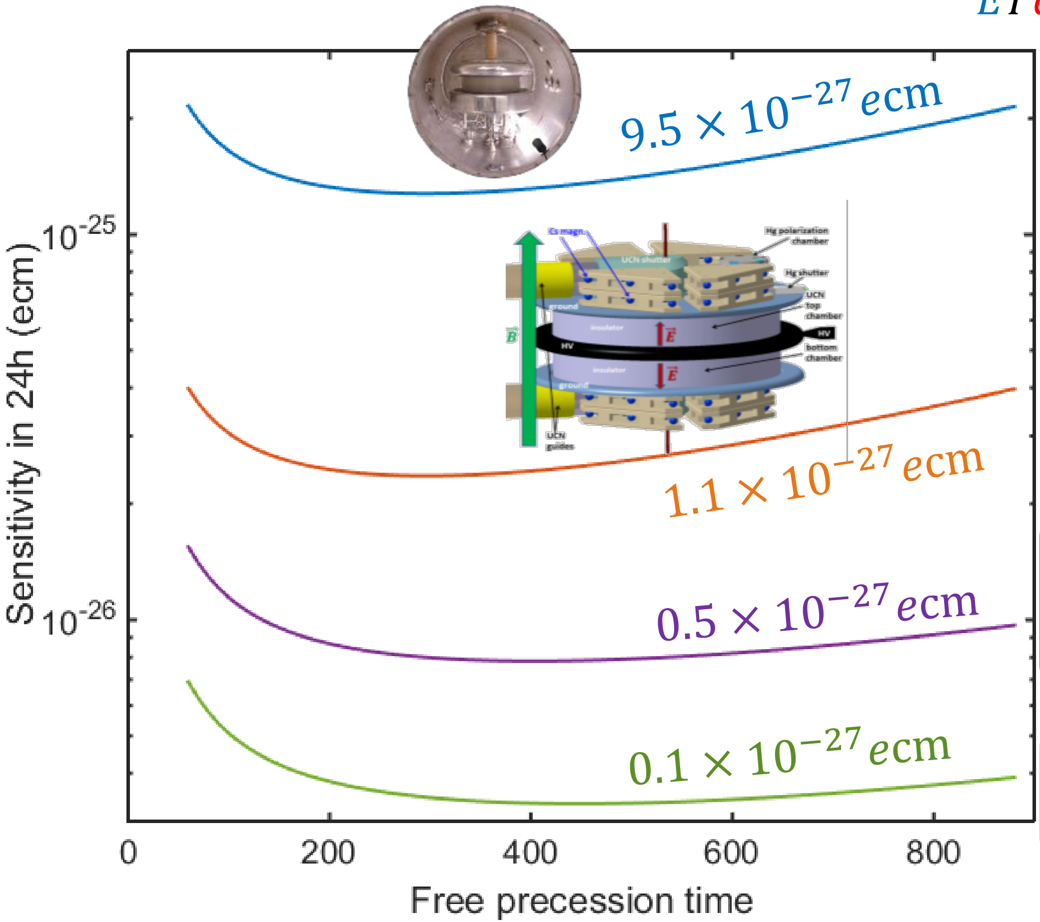
After 4 years with 200 days each:

$$\sigma_{\mathrm{RT}} \approx 1 \times 10^{-28} ecm$$

$$\sigma_{\mathrm{Cryo}} \approx 0.2 \times 10^{-28} ecm$$

Sensitivity at PSI:

$$\sigma(d_n) = \frac{\hbar}{E T \alpha_0 e^{-T/T_2} \sqrt{2 N_0 \left(e^{-T/\tau_s} + e^{-T/\tau_f}\right)}}$$



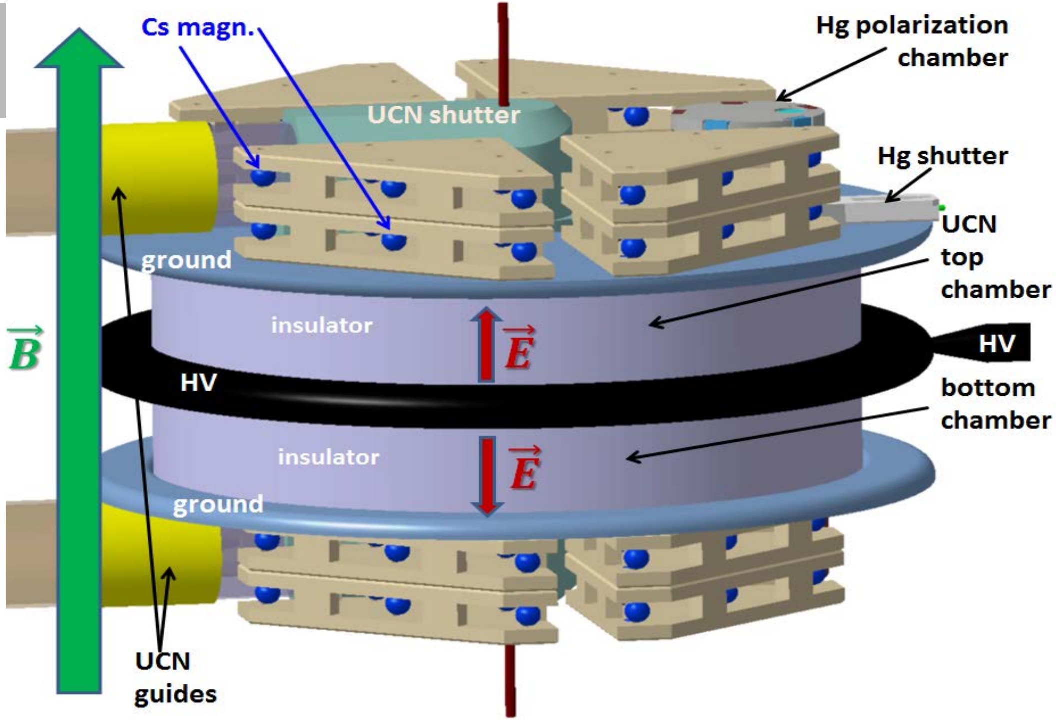
Performance in 2015/2016

Prospect TDR (start 2021)
$E = 15\ \mathrm{kV/cm}$, $N = 8 \times N_{2016}$

Possible final performance at PSI
$E = 18\ \mathrm{kV/cm}$, improved UCN source, optimal magnetic field tuning

New source? At ESS?
$E = 20\mathrm{kV/cm}$, $N = 128 \times N_{2016}$

Main features of the new instrument



$$\sigma(d_{\mathrm{n}}) \approx 1 \times 10^{-27} ecm$$

Inspired by Gatchina double-chamber setup
I.Altarev et al. JETP Lett.44(1986)460
and based on **years of experience with** our **own operating experiment:**

- 2 neutron precession chambers

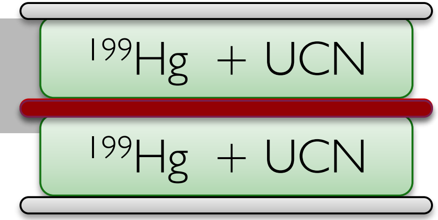
- Hg co-magnetometer in both chambers with laser read out

- Baseline scenario: UCN chamber with materials and coatings as present chamber, but larger diameter of storage volume - upgrades in development

- Surrounded by calibrated Cs arrays on ground potential (~ 100 sensors)

- large NiMo (^{58}NiMo) coated UCN guides

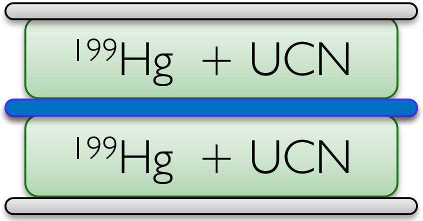
Analysis: Frequency ratio $R = f_{\mathrm{n}}/f_{\mathrm{Hg}}$



$\langle z \rangle_t$

$\langle z \rangle_b$

double chamber - linear ∂B/∂z is almost perfectly compensated but due to different h_t and h_b gradient fluctuations still cause an error on a lower level though

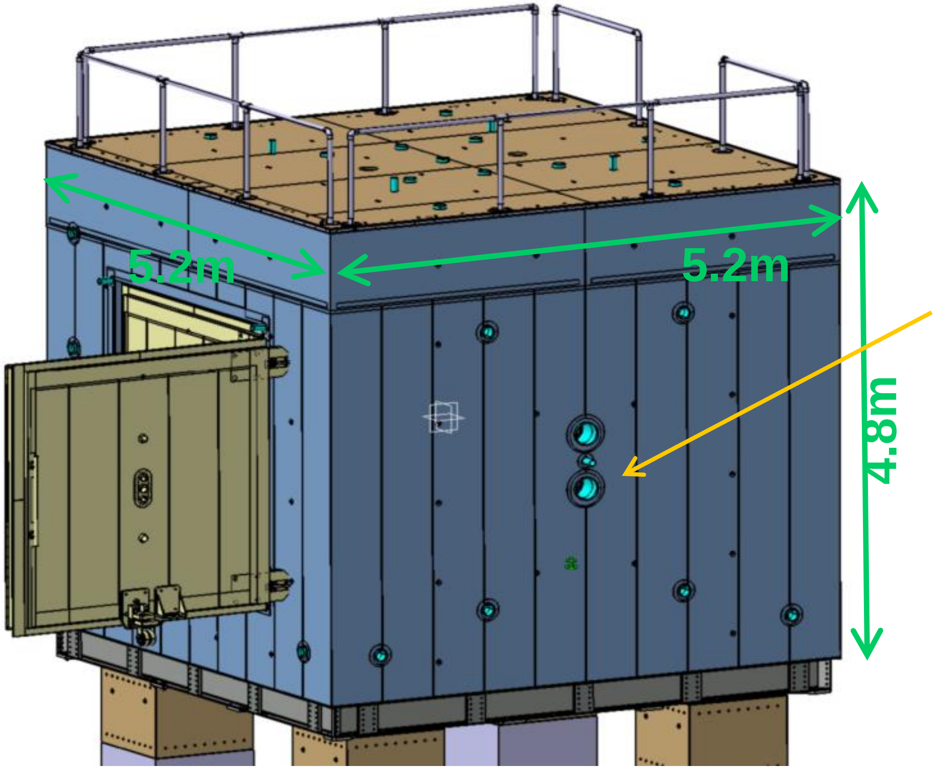


$$R^{+\mathrm{T}} - R^{+\mathrm{B}} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(2\delta_{\mathrm{EDM}} + \left(\langle z \rangle_{\mathrm{T}} - \langle z \rangle_{\mathrm{B}}\right)\frac{g^{+}}{B_0} + \cdots\right)$$

$$R^{-\mathrm{T}} - R^{-\mathrm{B}} = \frac{\gamma_{\mathrm{n}}}{\gamma_{\mathrm{Hg}}}\left(-2\delta_{\mathrm{EDM}} + \left(\langle z \rangle_{\mathrm{T}} - \langle z \rangle_{\mathrm{B}}\right)\frac{g^{-}}{B_0} + \cdots\right)$$

Analysis: based on (R^T - R^B) as function of dB/dz extrapolate to 0

Magnetically Shielded Room



setup features:
- (2 + 4) layers mu-metal
- Al eddy current shield
- 78 openings for experiment use
- largest openings ID=220mm for 2 UCN guides for 2 main pumping ports

expected performance:
- quasi-static shielding factor guaranteed >70'000 (expected >100'000)
- central B-field < 0.5nT
- central gradient < 0.3 nT/m

nEDM@SNS

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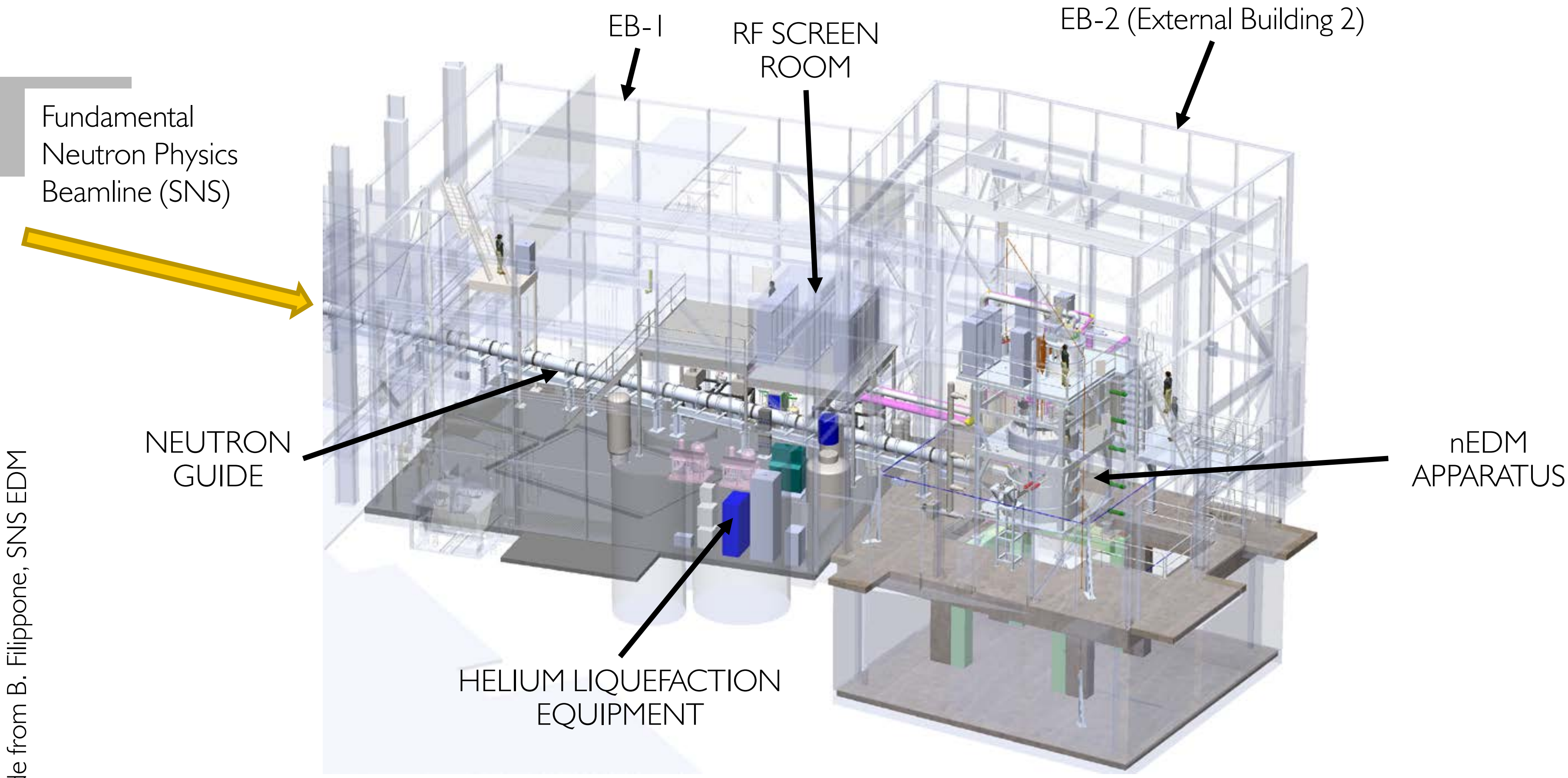


Slide from B. Filippone, SNS EDM

But … New Techniques = New Challenges

- Cryogenic system introduces challenges
  - Cold vacuum leaks & SFHe leaks are tough to find
  - AC spin dressing field virtually forbids metals/conductors in central volume due to eddy-current heating
  - Superconducting components distort B-fields

- Magnetic field gradients must be minimized
  - Components near central volume must use *really* non-magnetic material (316 SS, brass, … don't count)
  - Measurement cells must be free of "magnetic" dust

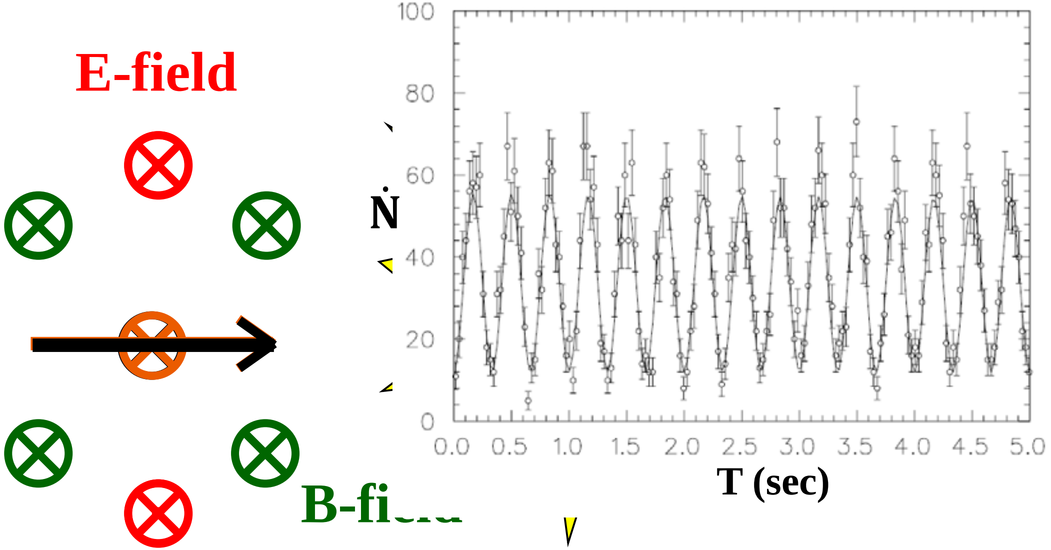
- Because of above most components near central volume are made from G10, PMMA, PEEK, Torlon, …
  - Challenging materials for machining, vacuum, thermal contraction, …

- Little previous work on large scale HV in superfluid
  - Requires significant R&D (past, present & future)

Slide from B. Filippone, SNS EDM

New Technique for n-EDM

1. Inject polarized neutron & polarized ^{3}He
2. Rotate both spins by 90°
3. Measure n+^{3}He capture vs. time (note: $\sigma_{\downarrow\uparrow} >> \sigma_{\uparrow\uparrow}$)
4. Flip E-field direction



$$\omega_{\rm rel} = (\gamma_3 - \gamma_n)B_0 + 2d_n E/\hbar.$$

^{3}He functions as "co-magnetometer"

Since ^{3}He EDM shielded by atomic electrons

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Dressed spin of polarized ^{3}He in a cell

P.-H. Chu,[1,*] A. M. Esler,[1] J. C. Peng,[1] D. H. Beck,[1] D. E. Chandler,[1] S. Clayton,[1] B.-Z. Hu,[3] S. Y. Ngan,[2] C. H. Sham,[2] L. H. So,[1,2] S. Williamson,[1] and J. Yoder[1]
[1]*Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA*
[2]*Department of Physics, The Chinese University of Hong Kong, Hong Kong, China*
[3]*Department of Physics, Soochow University, Taipei, Taiwan*
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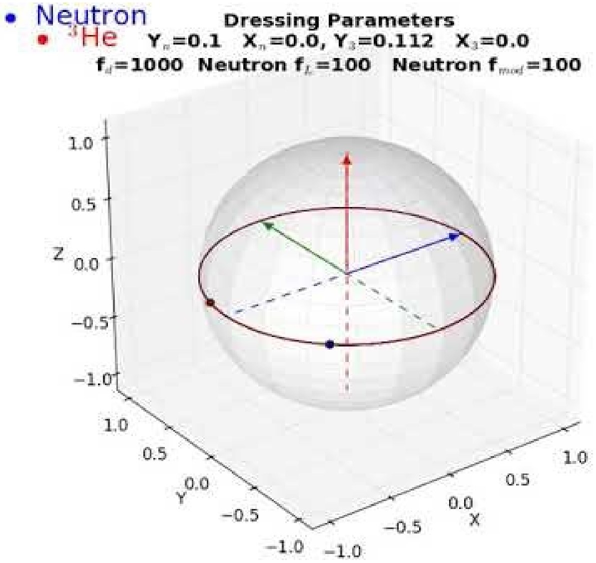
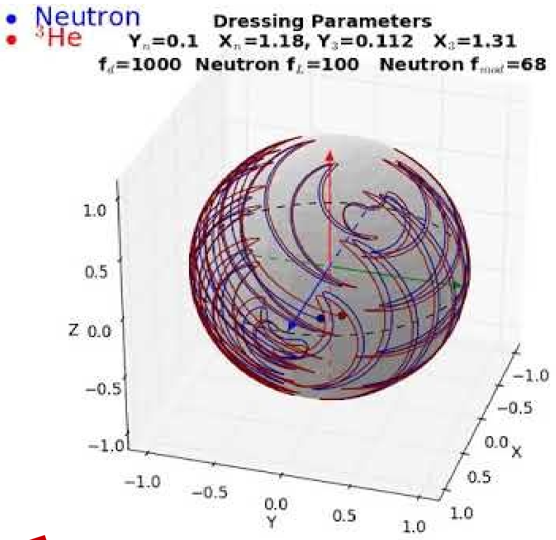
Without "dressing"



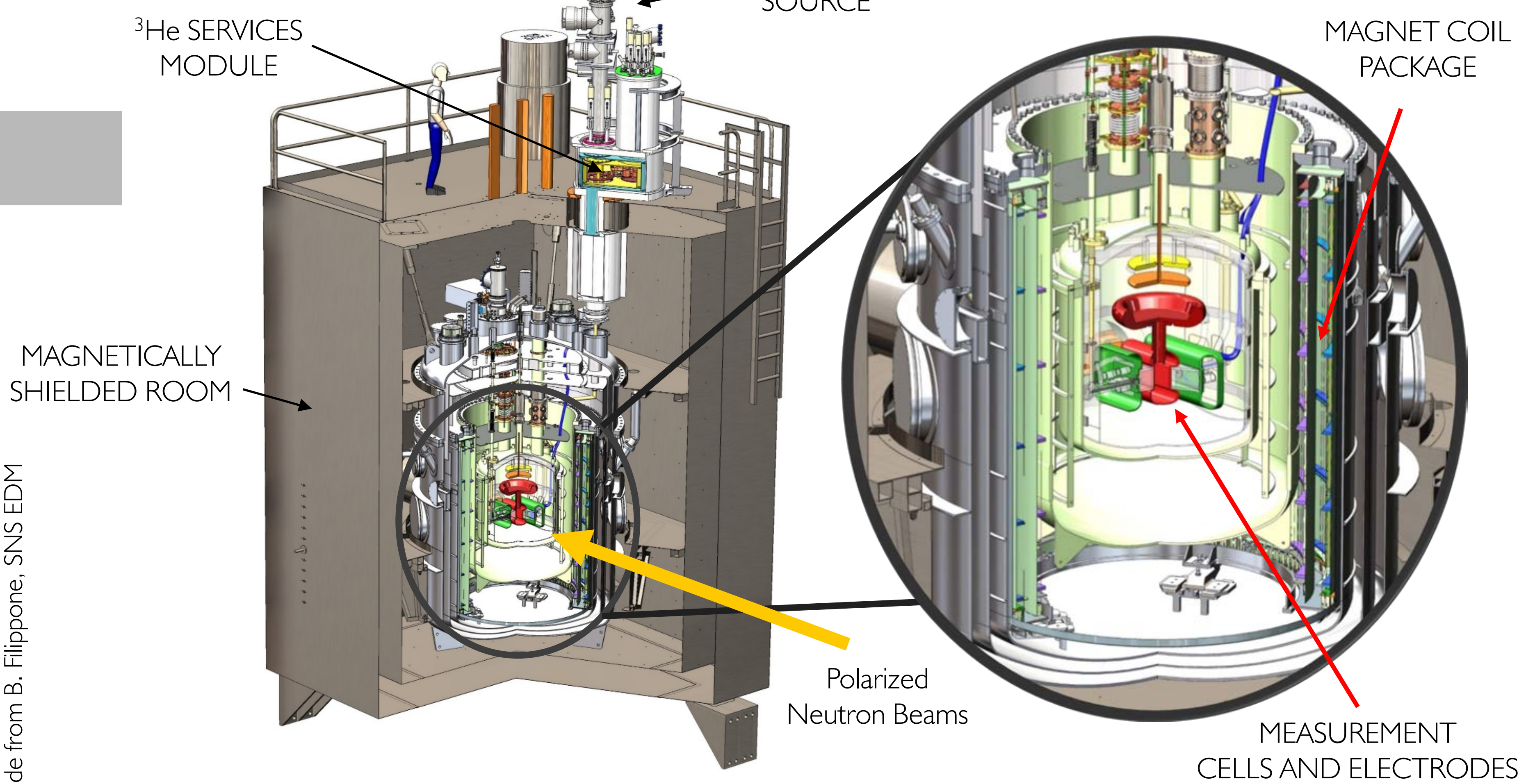
With dressing



$$\omega_{\rm rel} = \cancel{(\gamma_3 - \gamma_n)B_0} + 2d_n E/\hbar .$$

Simulations by Reza Tavakoli Dinani

Overall Apparatus



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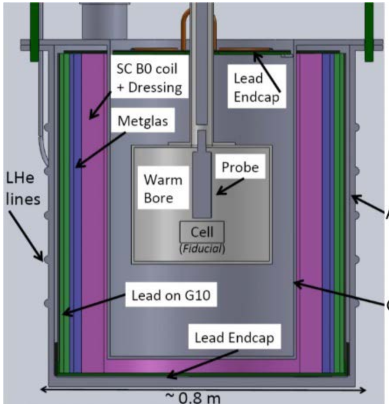
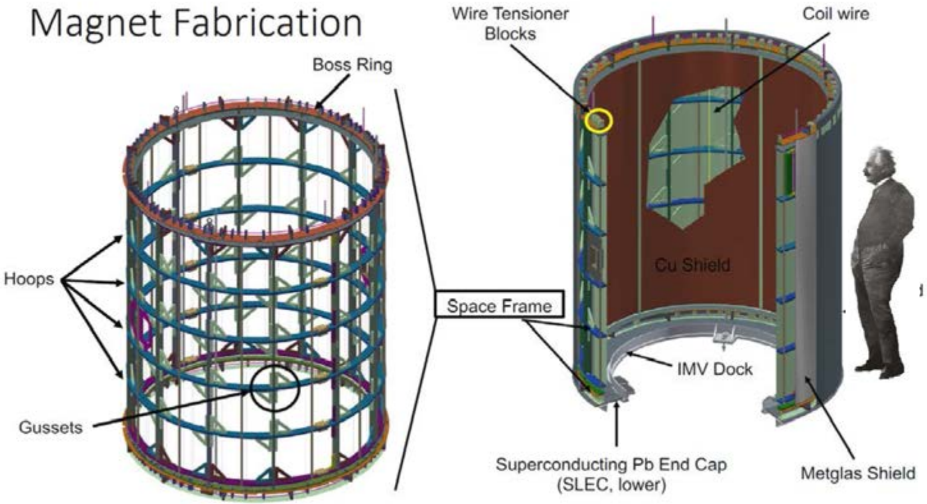
- Achieved required specs for uniformity, heat load and maximum temperature in 1/3 Scale prototype
  - – Achieved full-scale spec for fractional B-field uniformity for B_0: $3x10^{-6}$/cm and spin dressing B_{SD}: $9x10^{-5}$/cm
  - – Achieved acceptable heat load while maintaining temperature of < 6.2K



- Full-scale Magnet Design



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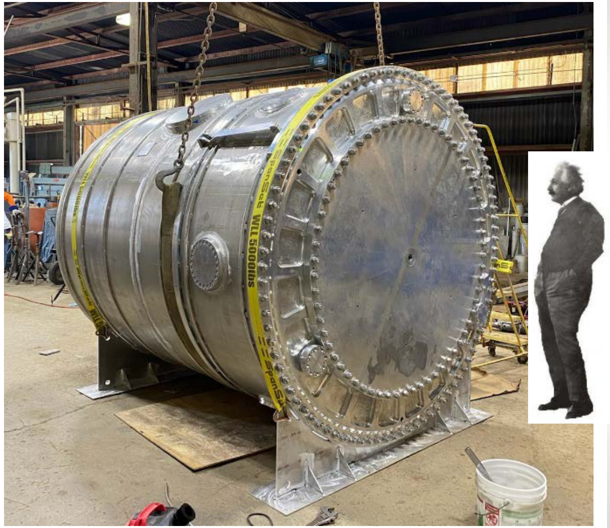
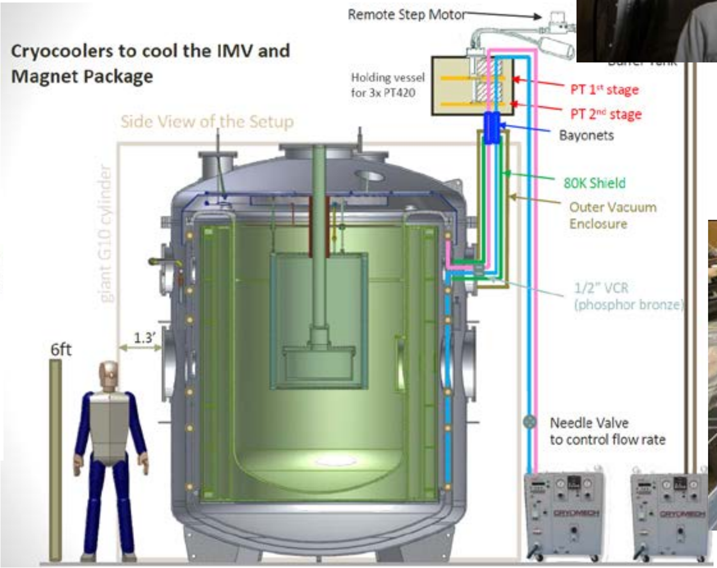
Magnetic Fields System

Construction of full-scale Magnet System underway

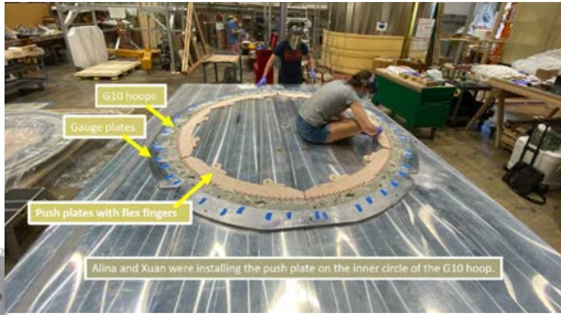
Outer Vacuum Vessel Tested to 80K

Inner Magnet Volume ready to ship





G10 Magnet Components being Vacuum Laminated



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Central Detector System (CDS)

- Small-scale HV system provides info on breakdown field geometric scaling
- Medium-scale HV (1/5 full-scale) system achieved 85 kV/cm
  - Goal is 75 kV/cm in full-scale
- Half-scale HV system under construction
  - Two acrylic measurement cells with central HV electrode to optimize electrode design and study candidate materials
- Many CDS subsystems have achieved near required performance
  - Low noise SQUID system developed
  - Acrylic measurement cell tested with 1800 s ultra-cold neutron wall-loss lifetime
  - Cryogenic Si photomultiplier system achieved > 20 photo-electrons equiv.
  - Superfluid tight non-conducting, non-magnetic valves tested
  - Cryogenic HV multiplier under construction

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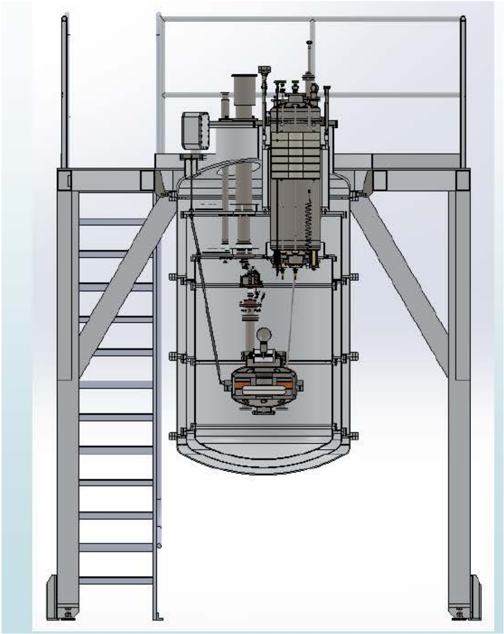
Central Detector System (CDS)

Half-Scale High Voltage System assemble & beginning testing



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Polarized ^{3}He System

- Produce highly polarized (>97%) ^{3}He and delivers it into purified L^{4}He
  - Atomic Beam Source built; testing & optimization underway
  - Developed working Superfluid film burner
- Transport polarized ^{3}He via phonon wind (aka heat flush) to measurement cells
  - Small scale heat flush system successfully tested
  - Large volume heat flush tests underdevelopment
- Empty measurement cells of reduced polarization ^{3}He and re-purify to 10^{-12} fractional ^{3}He density
- Design, build & test non-magnetic high-cooling-power dilution refrigerator (DR)

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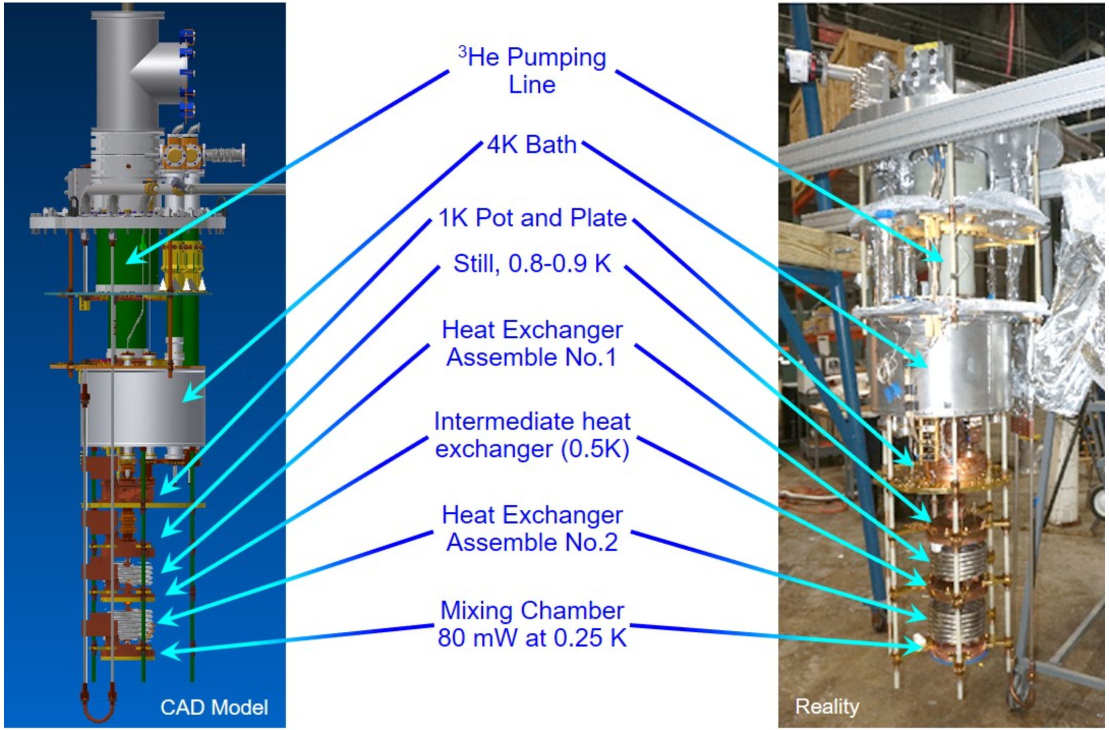
Dilution Refrigerators (DR)

- First DR (for 3He system) complete and being tested
  - Measured 75mW at .25K
- 2^{nd} DR for (CDS) being constructed



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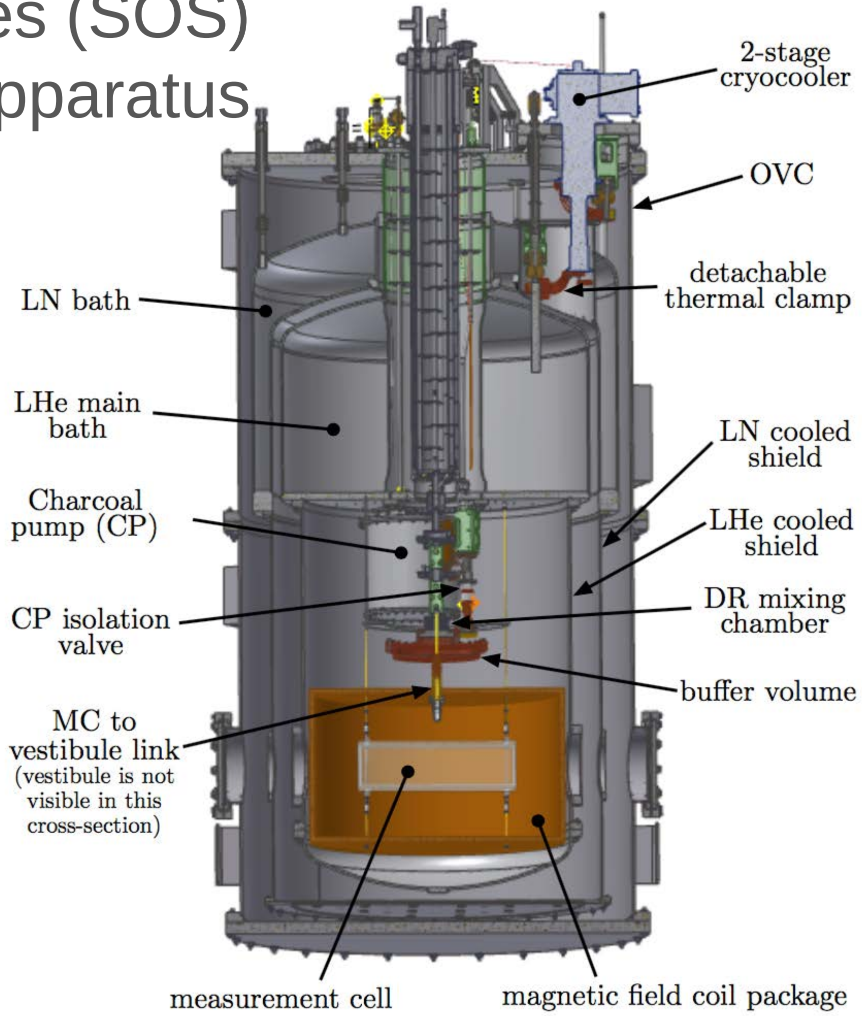
Systematics & Operational Studies (SOS) Apparatus

- Located at PULSTAR → teaching reactor at NCSU
- Mini-nEDM@SNS
  - One full-size measurement cell
  - No electric field
  - Full magnetic field capability
  - Relaxed ^{3}He polarization requirements
  - Relatively small size → rapid thermal cycling
- Goals:
  - validate production measurement cells
  - Develop spin manipulation techniques
  - Characterize geometric phase effect



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nEDM@SNS Sensitivity

- Free Precession Measurement (SQUIDs)
  - Sensitivity : 3.3×10^{-28} e-cm
  - 90% CL : 5.4×10^{-28} e-cm

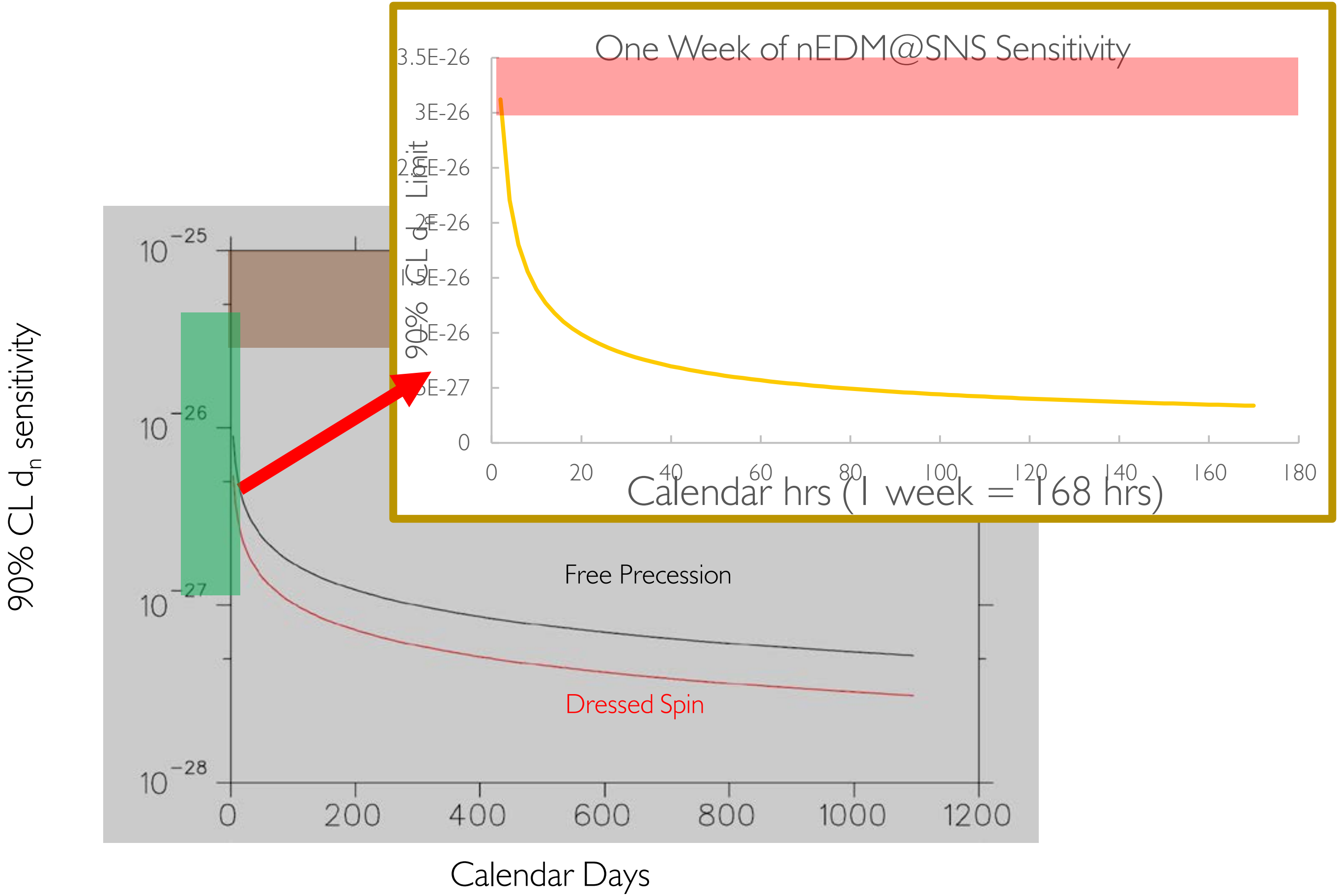
  300 live-days ~ 3 yrs

- Dressed Spin Measurement (AC Field)
  - Sensitivity : 1.6×10^{-28} e-cm
  - 90% CL : 2.6×10^{-28} e-cm

  300 live-days ~ 3 yrs

Systematic Uncertainties $< 1.5 \times 10^{-28}$ e-cm

Time to 90% CL Sensitivity



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Systematic Uncertainties

Uncertainty Source	Systematic uncertainty (e-cm)	Comments	Key Parameters
Linear (E x v)	$< 1 \times 10^{-28}$	Uniformity of B_0 field	B field gradient Temperature
Quadratic (E x v)	$< 0.5 \times 10^{-28}$	E field reversal accuracy < 1%	
Pseudomagnetic field effects	$< 1 \times 10^{-28}$	Modulation, comparing two cells	^{3}He density, $\pi/2$ pulse, modulation
Gravitational Offset	$< 0.2 \times 10^{-28}$	with 1 nA leakage current	
^{3}He inhomogeneity due to leakage current heating	$< 1.5 \times 10^{-28}$	leakage $< 1pA$	Temperature B field gradient

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