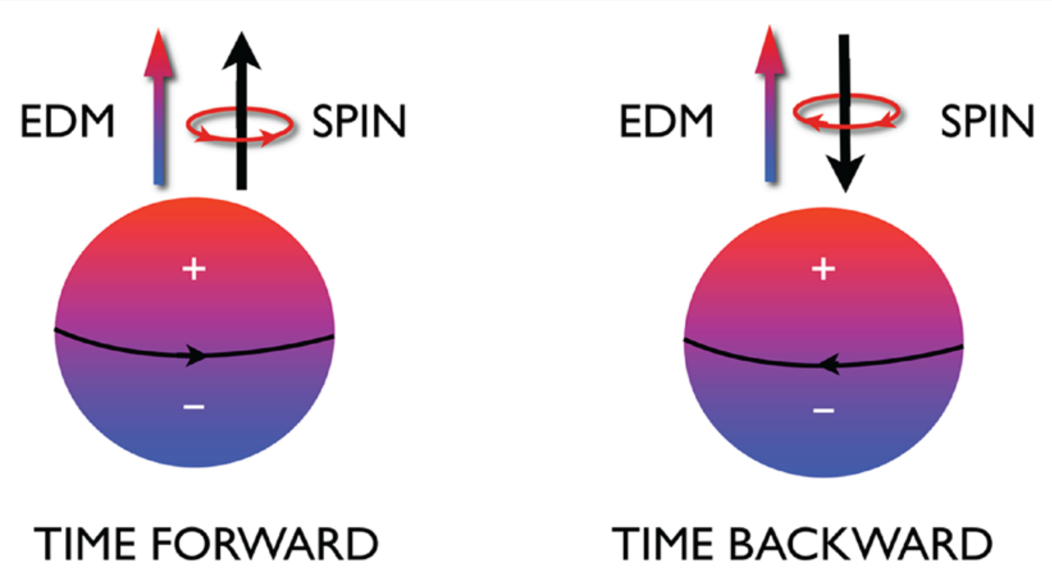
Neutron EDM



- Past, Present & Future of neutron EDM

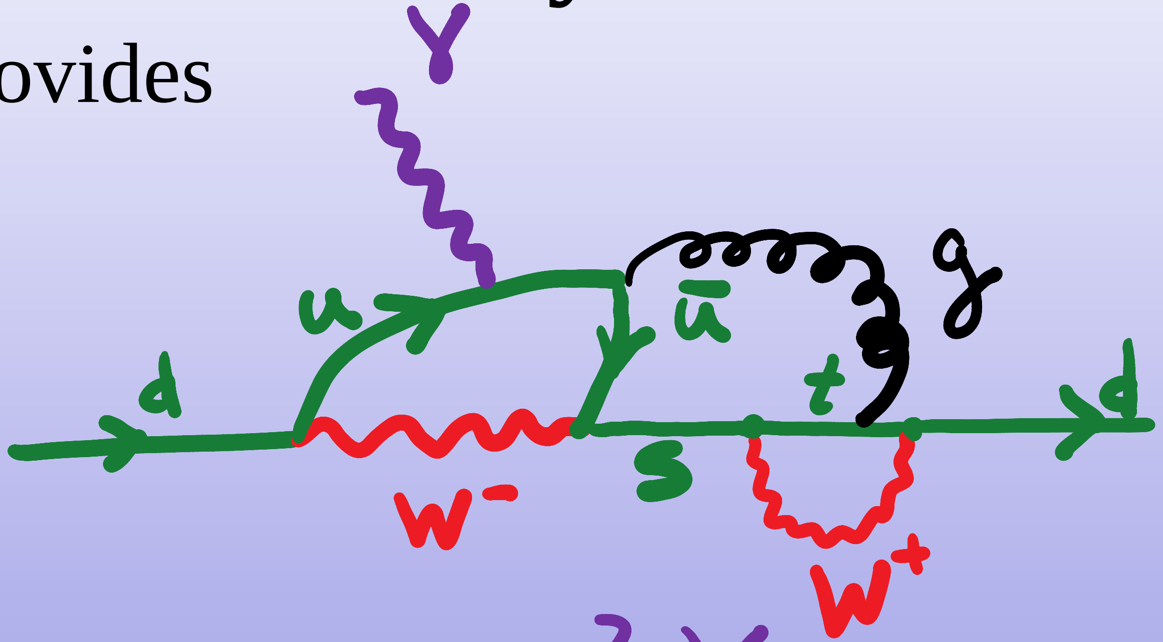
B. Filippone
Symmetry Tests in Nuclei & Atoms
KITP 9/20/2016

Neutron EDM & New Physics

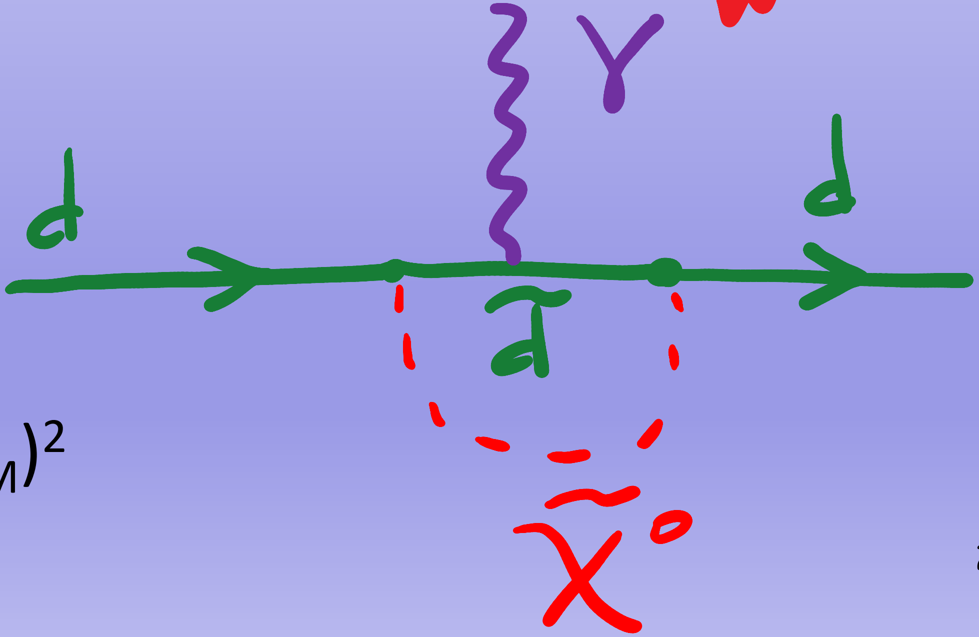
- Small EDM in standard model provides negligible "background" signal

$$d_n^{SM} < 10^{-31}\ \text{e - cm}$$

$$d_n^{\text{exp}} < 3 \cdot 10^{-26}\ \text{e - cm}$$



- New CP violation "natural" in new physics



e.g. $d_n \sim 10^{-25}$ e-cm x $\sin\varphi_{CP}(1\ \text{TeV}/M_{BSM})^2$

But … Theory Remains Essential

- How to interpret measured EDM in terms of new physics/elementary EDMs
  - Extraction from p, n, atom EDMs
    - E.g. Lattice QCD (This workshop & program!)
    - Calculation of enhancement factors for certain species
  - Model constraints based on EDM limits/observations
  - Identify source of EDM

$$\mathcal{L}_{eff} = \frac{g_s^2}{32\pi^2}\,\bar{\theta}\, G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{1}{3}w\ f^{abc}G^a_{\mu\nu}\tilde{G}^{\nu\beta,b}G_\beta{}^{\mu,c} - \frac{i}{2}\sum_{i=e,u,d,s} d_i\,\overline{\psi}_i(F\sigma)\gamma_5\psi - \frac{i}{2}\sum_{i=u,d,s}\tilde{d}_i\,\overline{\psi}_i g_s(G\sigma)\gamma_5\psi + \cdots$$

Searching for a Neutron EDM

E. M. Purcell

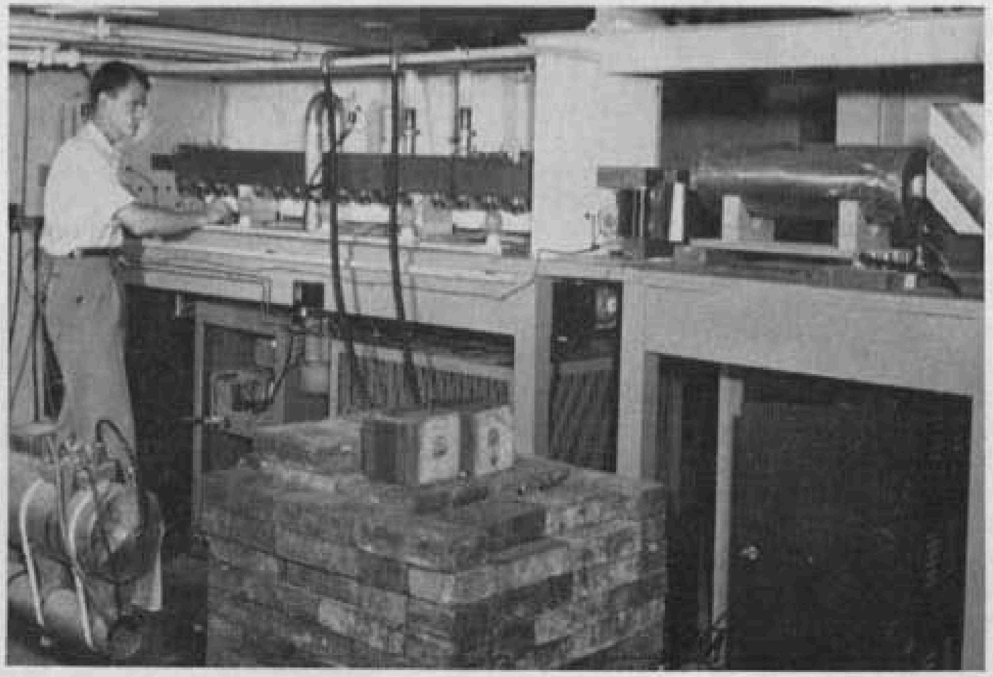
N. F. Ramsey

- E.M. Purcell and N.F. Ramsey, *Phys. Rev.* **78**, 807 (1950)
  - Looking for Parity Violation in Neutron Scattering
  - Pioneered Neutron Beam Magnetic Resonance

THE OAK RIDGE NATIONAL LABORATORY NEWS

A Publication by and for the ORNL Employees of Carbide and Carbon Chemicals Division, Union Carbide and Carbon Corporation

Vol. 3—No. 13 OAK RIDGE, TENNESSEE Friday, September 29, 1950



HARVARD UNIVERSITY SPONSORS PROGRAM HERE — James H. Smith, Harvard University graduate student in physics, is shown as he adjusts a neutron beam apparatus at the south face of the Oak Ridge Pile. Using the Pile as a source of neutrons, Mr. Smith is engaged in a project jointly sponsored by Harvard University and Oak Ridge National Laboratory for the purpose of determining if neutrons have permanent electric dipole moments.

Harvard University Conducts Important Research at ORNL

The growing importance of Oak Ridge National Laboratory as a research center is manifested particularly in its assistance to universities and technical schools on various projects in which nuclear research is involved. An example of such relationship is its present collaboration with Harvard University in an investigation to determine if neutrons have permanent electric dipole moments.

The work of the project is under the direction of Professors E. M. Purcell and Norman F. Ramsey of the Harvard University Physics Department and is being conducted on the Laboratory area by James H. Smith, a

PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

Experimental Limit to the Electric Dipole Moment of the Neutron

J. H. Smith,* E. M. Purcell, and N. F. Ramsey
Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Harvard University, Cambridge, Massachusetts

(Received May 17, 1957)

An experimental measurement of the electric dipole moment of the neutron by a neutron-beam magnetic resonance method is described. The result of the experiment is that the electric dipole moment of the neutron equals the charge of the electron multiplied by a distance $D=(-0.1\pm2.4)\times10^{-20}$ cm. Consequently, if an electric dipole moment of the neutron exists and is associated with the spin angular momentum, its magnitude almost certainly corresponds to a value of D less than 5×10^{-20} cm.

sensitive neutron-beam resonance experiment for the detection of an electric dipole moment.

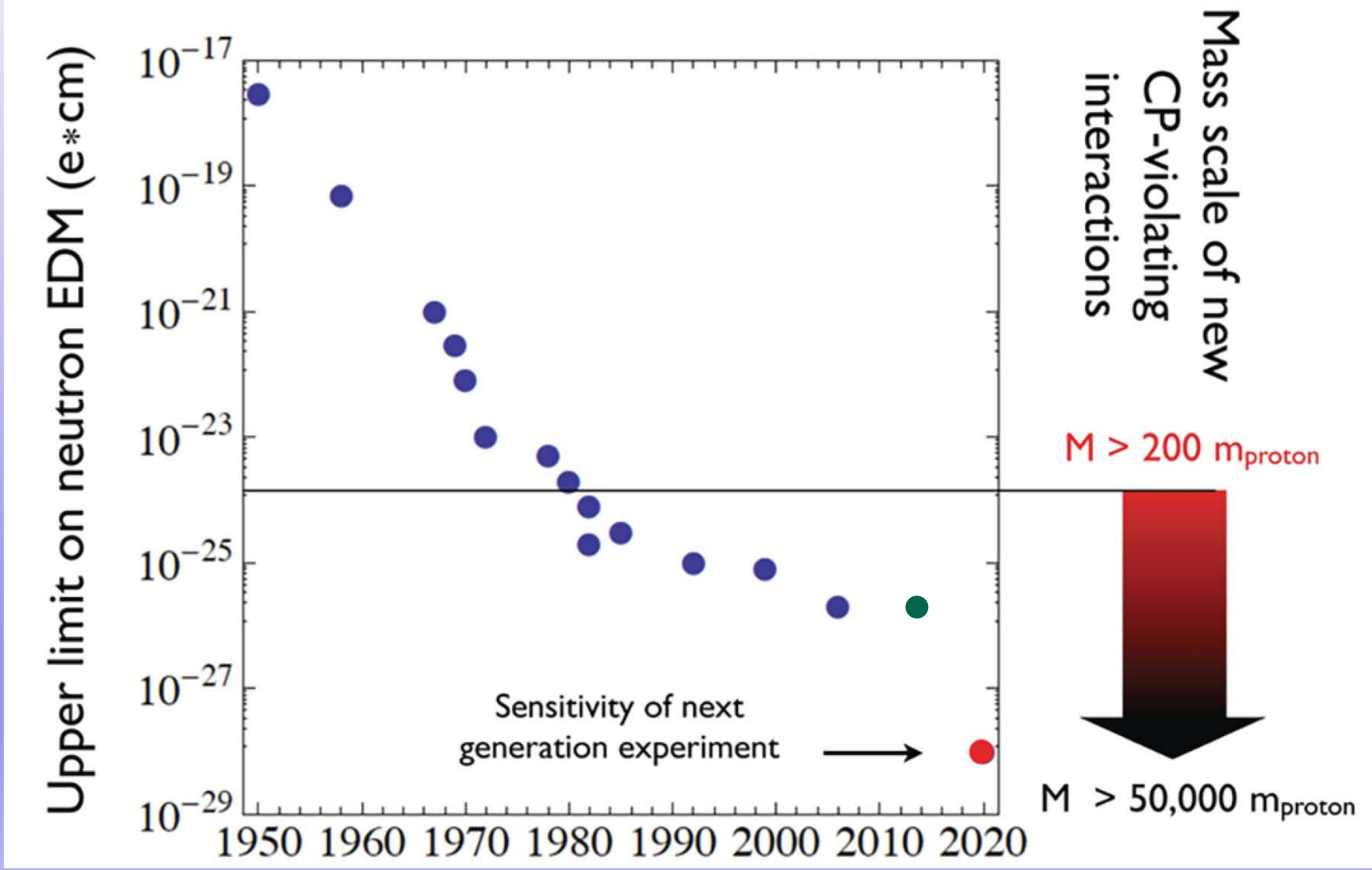
This experiment was successfully completed several years ago. However, the negative results of the experiment were in accordance with the then widely accepted views on parity so the detailed description[4] of the experiment was not published. The upper limit to the electric dipole moment determined in this experiment has occasionally been quoted in other publications.[5,6]

Lee and Yang[6] have analyzed the effects of parity nonconservation on the angular distributions of beta

---

* Now at the University of Illinois, Urbana, Illinois.
[1] E. M. Purcell and N. F. Ramsey, Phys. Rev. **78**, 807 (1950).
[2] Havens, Rabi, and Rainwater, Phys. Rev. **72**, 634 (1947).
[3] E. Fermi and L. Marshall, Phys. Rev. **72**, 1139 (1947).

Moore's Law for Neutron EDM Searches

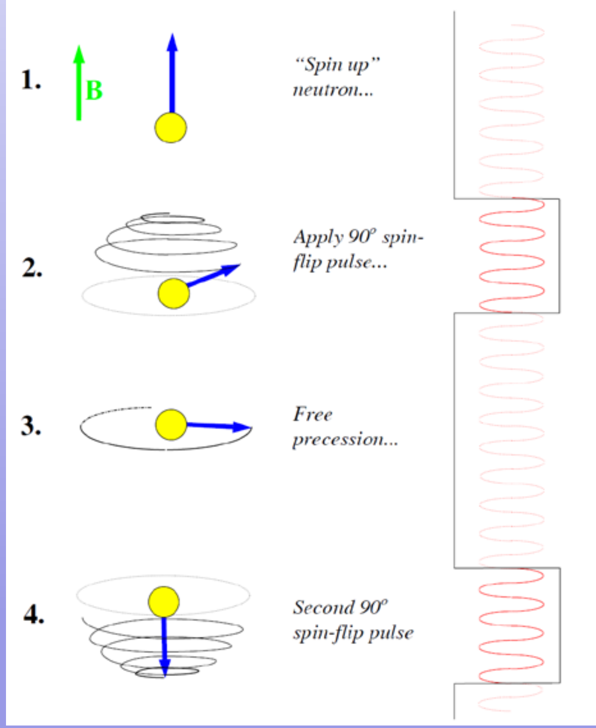


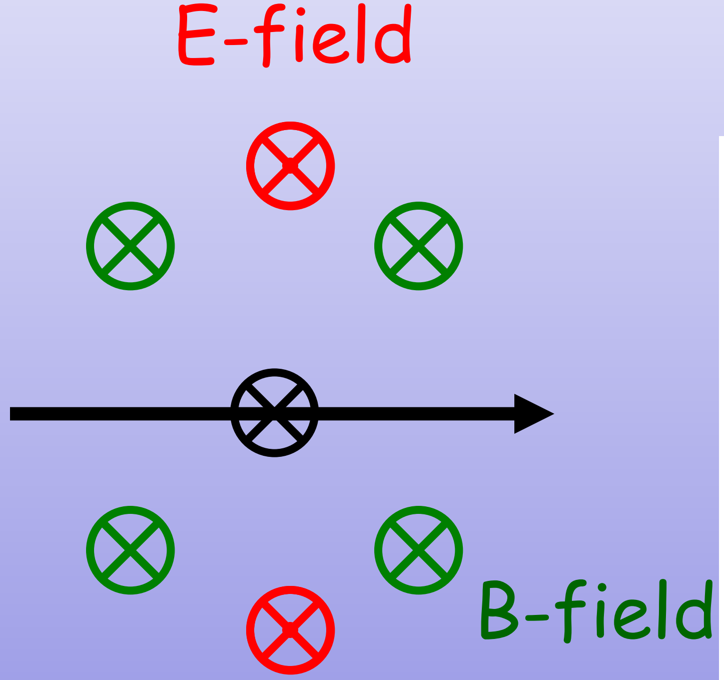
Simplified Measurement of EDM

"…always measure a frequency"

How to measure a small frequency?

- Ramsey Separated Oscillatory Fields (SOF)

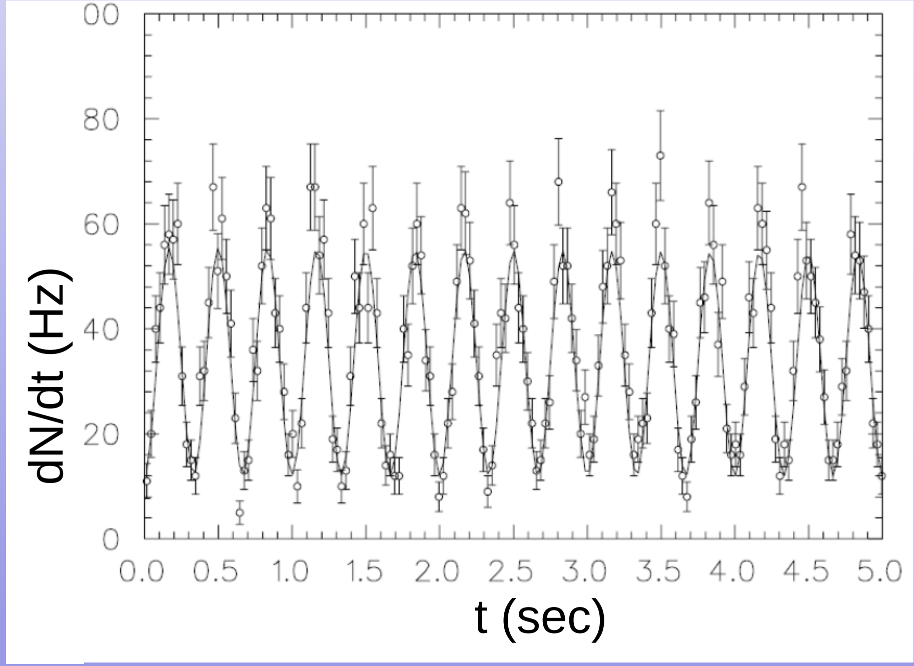




$$\nu = \frac{2\vec{\mu}\cdot\vec{B} \pm 2\vec{d}\cdot\vec{E}}{h}$$

How to measure a small frequency?

- Observation of free precession



Measure $\vec{n}$ + $\overrightarrow{^3He}$ capture vs. time with $\sigma_{\downarrow\uparrow} >> \sigma_{\uparrow\uparrow}$

What is the precision for an EDM measurement?

$$E = \hbar\omega = 2\vec{\mathbf{d}}\cdot\vec{\mathbf{E}}$$

Uncertainty in d: $\sigma_d \sim \frac{\Delta E}{2|\vec{E}|}$

$$\Delta E \Delta t \sim \hbar$$

Precise energy measurement requires long coherence/ measurement time, giving

Coherence time

$$\sigma_d \sim \frac{\Delta E}{2|\vec{E}|} \sim \frac{\hbar}{2|\vec{E}|T_m}$$

Plus shot noise = counting statistics $\propto \frac{1}{\sqrt{\mathbf{N}}}$

Sensitivity: $\boldsymbol{\sigma_d^{tot}} \sim \frac{\hbar}{\mathbf{2|\vec{E}|T_m\sqrt{mN}}}$

E – Electric Field
T_m – Time for single measurement
m – total # of measurements
N – Total # of counts/meas.

Best Present Limit on nEDM

Baker et al. Phys. Rev. Lett. 97, 131801 (2006)
Pendlebury et al. Phys. Rev. D 92, 9092003 (2015)

$d_n < 3.0 \times 10^{-26}$ e-cm
@ 90% Confidence Limit

→ Ramsey SOF & trapped Ultra-Cold Neutrons from ILL Reactor

	EDM @ ILL
N (detected n/cycle)	1.3×10^4
$\lvert\vec{E}\rvert$	10 kV/cm
T_m	130 s
m (cycles/day)	270
σ_d (e-cm)/day	3×10^{-25}

$$\sigma_d^{tot} \sim \frac{\hbar}{2\,|\vec{E}|\,T_m\sqrt{mN}}$$

Neutron EDM Experiments Worldwide

Neutron EDM Searches

Experiment	UCN source	cell	Measurement techniques	σ_d Goal (10^{-28} e-cm)
				Present neutron EDM limit < 300
ILL-PNPI	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for ω E=0 cell for magnetometer	Phase1<100 < 10
ILL Crystal	Cold n Beam	solid	Crystal Diffraction Non-Centrosymmetric crystal	< 100
PSI EDM	Solid D_2	Vac.	Ramsey for ω, external Cs & Hg comag. Xe or Hg comagnetometer	Phase1 ~ 50 Phase 2 < 5
Munich FRMII	Solid D_2	Vac.	Room Temp. , Hg Co-mag., also external 3He & Cs mag.	< 5
RCNP/TRIUMF	Superfluid ^{4}He	Vac.	Small vol., Xe co-mag. @ RCNP Then move to TRIUMF	< 50 < 5
SNS nEDM	Superfluid ^{4}He	^{4}He	Cryo-HV, ^{3}He capture for ω, ^{3}He co-mag. with SQUIDS & dressed spins, supercond.	< 5
JPARC	Solid D_2	Vac.	Under Development	< 5
JPARC	Solid D_2	Solid	Crystal Diffraction Non-Centrosymmetric crystal	< 10?
LANL	Solid D_2	Vac.	R & D, Ramsey SOF, Hg co-mag.	~ 30

= sensitivity < 5 x 10^{-28} e-cm

LANL nEDM

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J. Ramsey, A. Saunders, Z.Tang
Los Alamos National Laboratory

C.-Y. Liu, J. Long, W. Snow
Indiana University

B. Plaster
University of Kentucky

S. K. Lamoreaux
Yale University

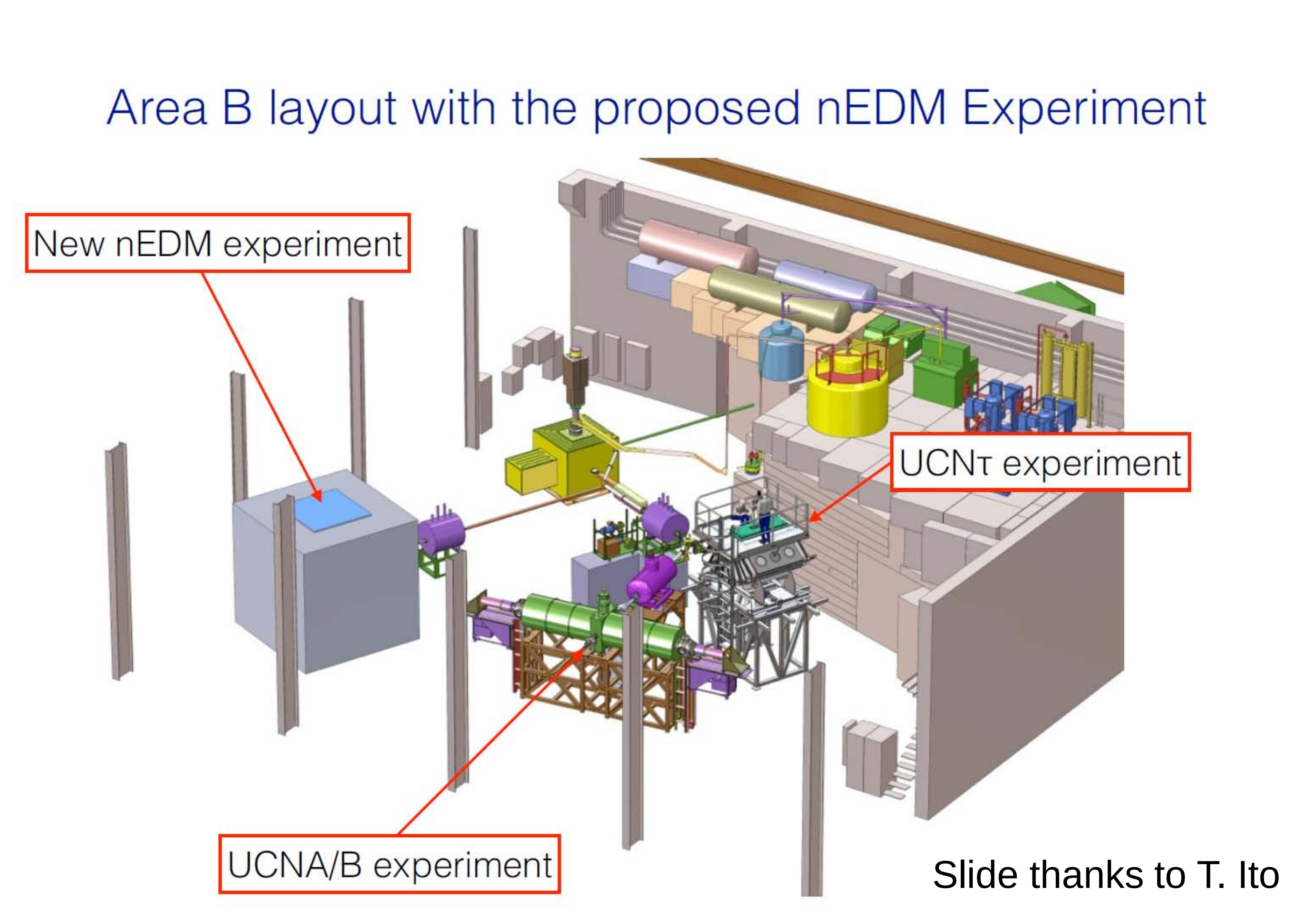
E. Sharapov
Joint Institute of Nuclear Research

Concept for nEDM experiment at LANL

- A neutron EDM experiment with a sensitivity of $\delta d_n \sim O(10^{-27})$ e-cm based on already proven room temperature Ramsey's separated oscillatory field method could take advantage of the existing LANL SD_2 UCN source
  - nEDM measurement technology for $\delta d_n \sim O(10^{-27})$ e-cm exists. What is holding up the progress is the lack of UCN density.
  - The LANL UCN source currently provides a UCN density of ~ 60 UCN/cc at the exit of the biological shield
  - A 5-10 fold improvement in the delivered UCN density is required for an nEDM experiment with $\delta d_n \sim O(10^{-27})$ e-cm
- Such an experiment could provide a venue for the US nEDM community to obtain physics results, albeit less sensitive, in a shorter time scale with much less cost while development for the SNS nEDM experiment continues.

Slide thanks to T. Ito

Based on LANL UCN Source in Area B



Slide thanks to T. Ito

Expected achievable statistical sensitivity with the current LANL UCN source **without the upgrade**

Parameters	Values
E (kV/cm)	12.0
N (per cell)	14,700
T_{free} (s)	180
T_{duty} (s)	300
α	0.80
σ/day/cell (10^{-25} e-cm)	**0.93**
σ/year/cell (10^{-27} e-cm)	**4.8**
σ/year* (10^{-27} e-cm) (for double cell)	**3.4**
90% C.L./year* (10^{-27} e-cm) (for double cell)	**5.6**

This estimate is based on the following:

- The estimate for N is based on the results of the UCN storage test performed in January 2016 and **is not assuming the source upgrade.**
- The estimate for E, T_{free}, T_{duty}, and α is based on what has been achieved by other experiments.

*** "year" = 365 live days. In practice it will take 3+ years to achieve this**

Slides thanks to T. Ito

Schedule

- Present - August 2016: Installation of the new UCN source and guides
- September 2016-January 2017: Commissioning and operation of the new UCN source

Ultracold Neutrons at TRIUMF

T. Adachi[1], E. Altiere[2], T. Andalib[3,4], C. Bidinosti[3,8], J. Birchall[4], M. Chin[5], C. Davis[5], F. Doresty[4], M. Gericke[4], S. Hansen-Romu[3,4], K. Hatanaka[6], T. Hayamizu[2], B. Jamieson[3], S. Jeong[1], D. Jones[2],
K. Katsika[5], S. Kawasaki[1], T Kikawa[5,6,1], A. Konaka[5,8], E. Korkmaz[7] , M. Lang[3], T. Lindner[5], L. Lee[4,5],
K. Madison[2], J. Mammei[4], R. Mammei[3], J.W. Martin[3], Y. Masuda[1], R. Matsumiya[6], K. Matsuta[8], M. Mihara[8],
E. Miller[2], T. Momose[2], S. Page[4], R. Picker[5], E. Pierre[6,5], W.D. Ramsay[5], L. Rebenitsch[3,4],
J. Sonier[9], I. Tanihata[6], W.T.H. van Oers[4,5], Y. Watanabe[1], and J. Weinands[2]

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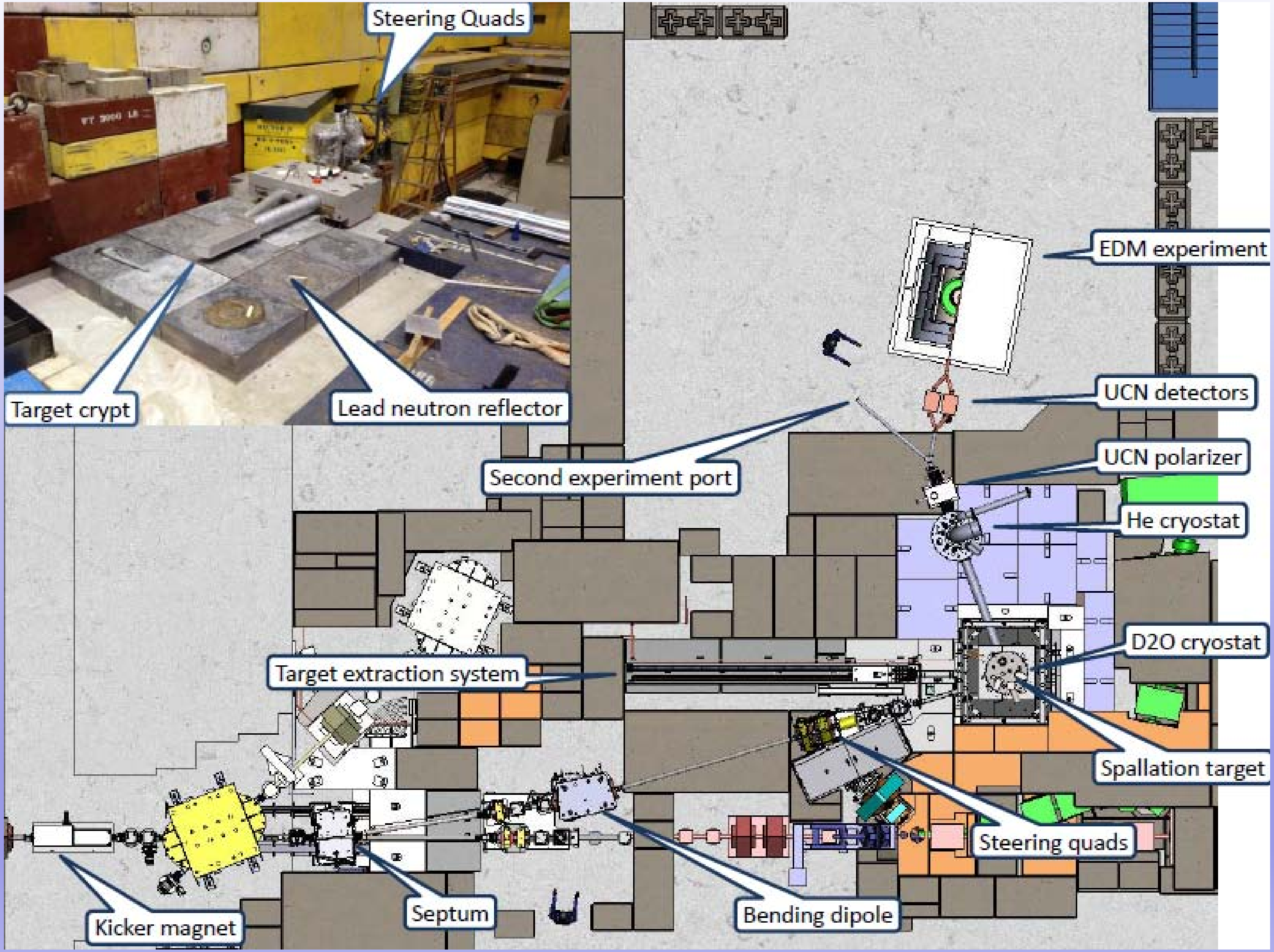
[2]The University of British Columbia, Vancouver, BC, Canada
[3]The University of Winnipeg, Winnipeg, MB, Canada
[4]The University of Manitoba, Winnipeg, MB, Canada
[5]TRIUMF, Vancouver, BC, Canada
[6]RCNP, Osaka, Japan (Osaka University, Osaka, Japan)
[7]The University of Northern BC, Prince George, BC, Canada
[8]Osaka University, Osaka, Japan
[9]Simon Fraser University, Burnaby, BC, Canada

Slide thanks to J. Martin

TRIUMF

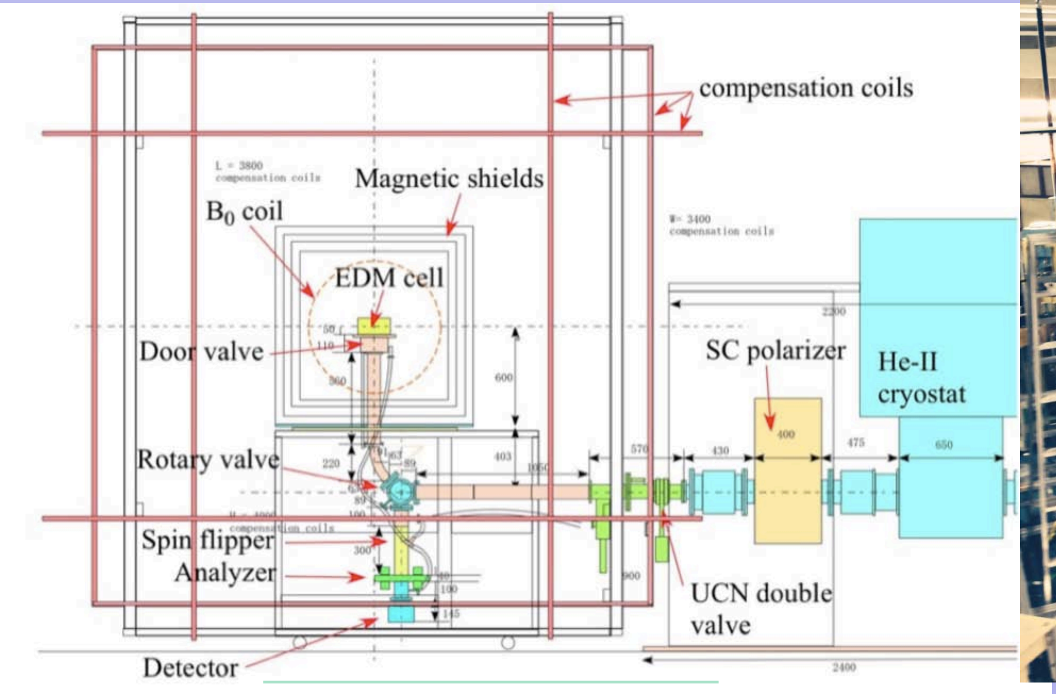


Slide thanks to J. Martin

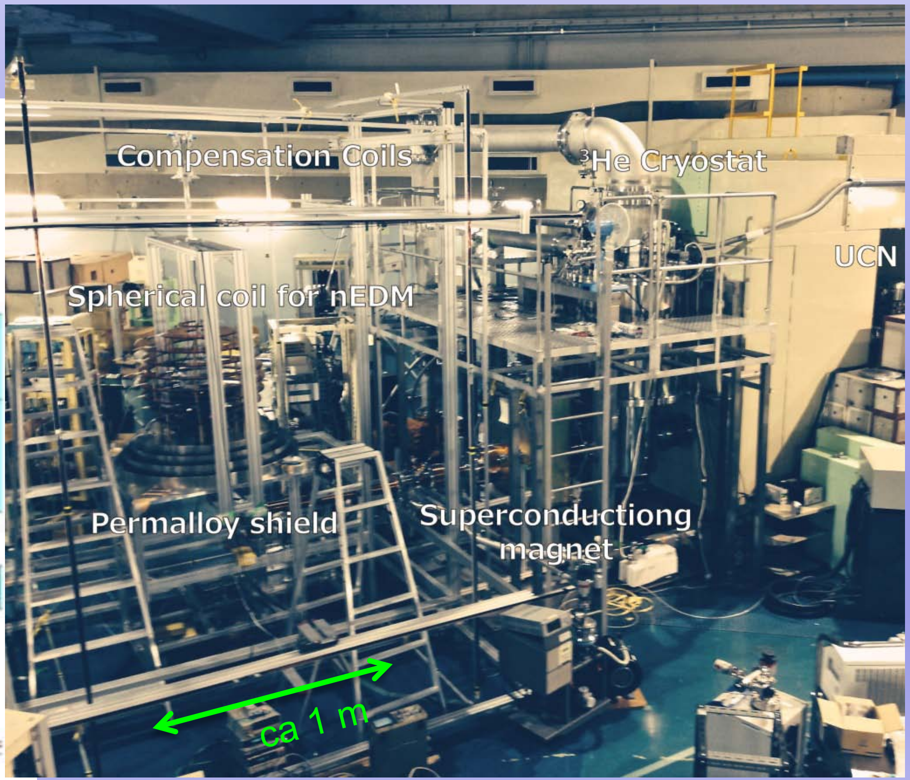
“Phase 1” – what will exist in 2017

- use **existing** EDM Ramsey **apparatus** from RCNP, Osaka
- exploit **higher UCN density** at TRIUMF (also more beamtime available)
- room temperature, **1 small cell**, vertical loading, spherical B_0 coil
- small incremental improvements until replaced by Phase 2
  - **Active magnetic compensation system**
  - **high voltage**
  - **comagnetometer**
  - **high-flux detector**

Slide thanks to J. Martin



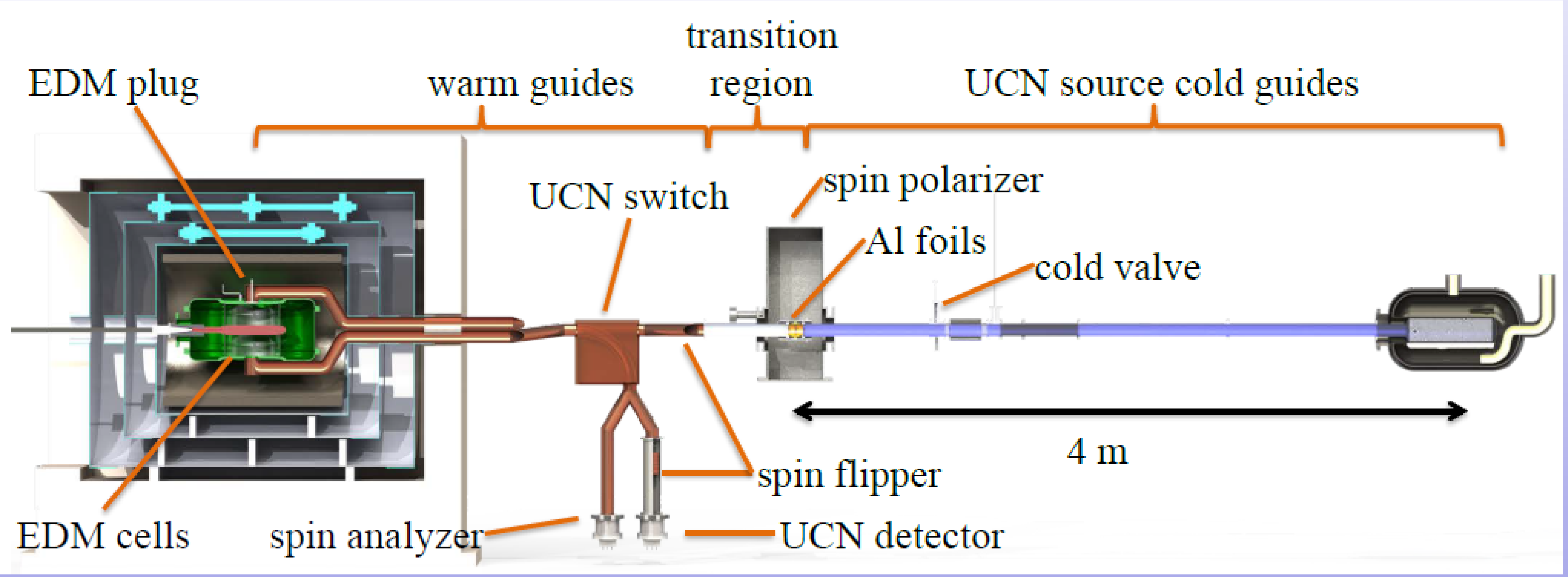
EDM Phase 1 schematic



EDM Phase 1 at RCNP

"Phase 2" – to implement by 2020

R&D on Hg and Xe co-magnetometers is underway



Phase 2 sensitivity $\delta d_n \sim 10^{-27}$ e-cm

- LD_2 moderator, to increase cold flux entering the superfluid
- New high-quality guides.
- World-competitive nEDM experiment apparatus

CFI Innovation Fund application in progress, in Canada. Scale $16M.

Slide thanks to J. Martin

TUM nEDM

@PTB Berlin

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@Forschungneutronenquelle Heinz Meier-Leibnitz

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Slide thanks to P. Fierlinger

Optimistic (but in principle possible) plan towards a physics result

Move Inner Shield to ILL (2016)
Adapt/build new UCN components, mobile Cs magnetometers
No RF shield, only manual alignment control

Installation at new Super-SUN Stage 1 w/o magnet (2017+), no co-magnetometer
Best possible results ~ 3.10^{-27} ecm (stat, 1

EDM runs at Super-SUN Stage 2 with magnet (2019+)
Best possible result ~ 8.10^{-28} ecm (stat, 1

Outer Shield at TUM
Outer magnetic shield
External field compensation
HV R&D and assembly

Magnetometer development
Magnetometer comparisons
Spin-clocks with polarized noble gases
Component optimization

Development of cryogenic chambers

Options
(i) Assembly of Inner and Outer shield with RT chamber
(ii) Cryogenic chambers with Inner Shield
(iii) Cryogenic chambers with Outer and Inner Shield
(before ~ 2022 no UCN at FRM-II EDM position)

Slide thanks to P. Fierlinger

Sensitivity potential of nEDM at Super-SUN at ILL

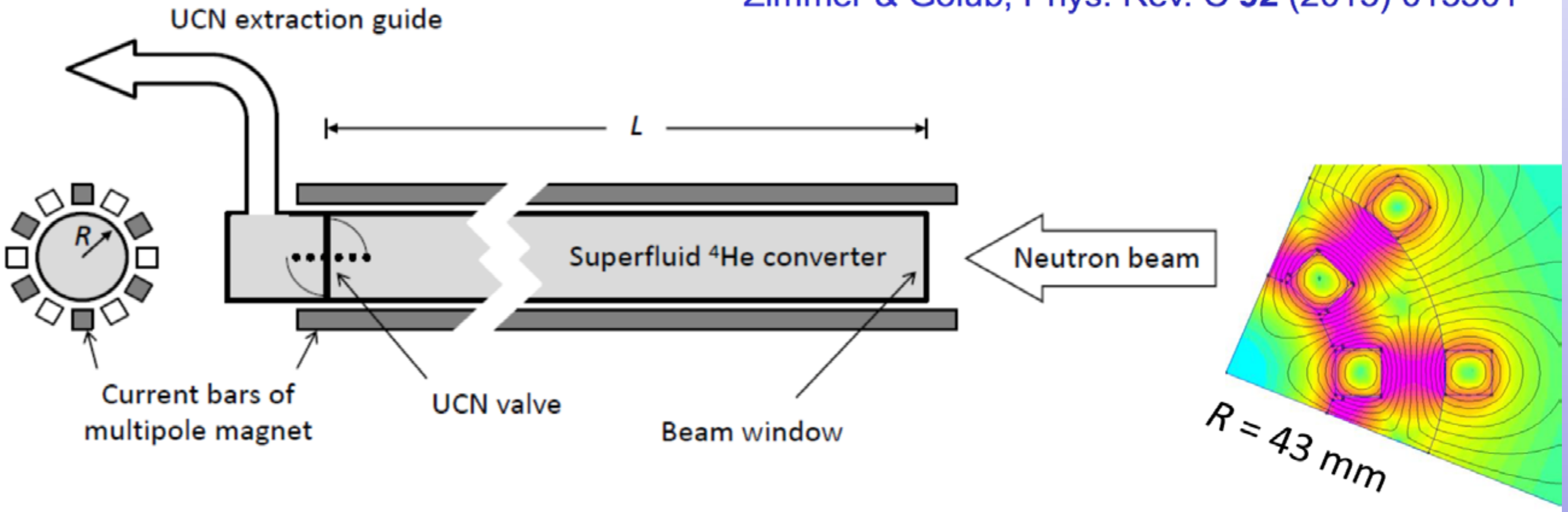
	SuperSun stage I		SuperSun stage II	
UCN density	333	1/cm3	1670	1/cm3
Diluted density	80	1/cm3	400,8	1/cm3
Transfer loss factor	3		1,5	
Source saturation loss factor	2		2	
Polarization loss factor	2		1	
Density in cells	6,7	1/cm3	133,6	1/cm3
2 EDM chamber volume	33,2	l	33,2	l
Neutrons per chamber	110556		2217760	
EDM sensitivity				
E	2,00E+04	V/cm	2,00E+04	V/cm
alpha	0,85		0,85	
T	250	s	250	s
N after time T (1/e)	398000		794000	
Number of EDM cells	2		2	
Sensitivity (1 Sigma, 1 cell)	3,9E-25	ecm	8,7E-26	ecm
Sensitivity (1 Sigma, 2 cells)	2,7E-25	ecm	6,1E-26	ecm
Preparation time	150	s	150	s
Measurements per day	216		216	
Sensitivity (1 Sigma, 2 cells) per day	1,9E-26	ecm	4,2E-27	ecm
Sensitivity 100 days	**1,9E-27**	**ecm**	**4,2E-28**	**ecm**
Limit 90% 100 days	**3,00E-27**	**ecm**	**7,00E-28**	**ecm**

Slide thanks to P. Fierlinger

The next version: Super-SUN (funded + under construction at ILL)

For calculations of UCN storage see:

Zimmer & Golub, Phys. Rev. C **92** (2015) 015501



- Single-user facility
- Converter volume: 12 litres
- UCN production rate: 10^5 s^{-1} (E < 230 neV)
- UCN saturation number: 4×10^6 (2017, fomblin spectrum) **STAGE 1**

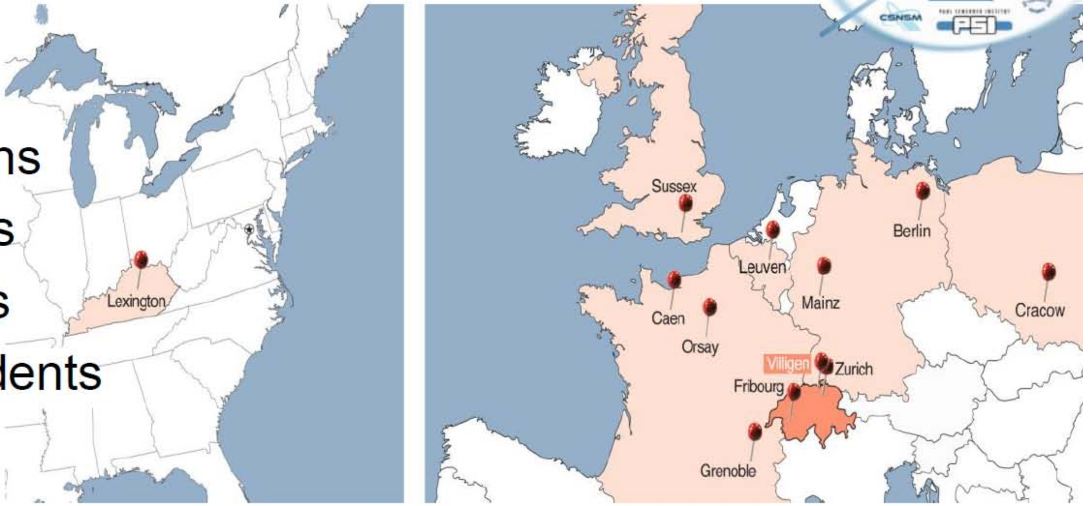
  2×10^7 (2019, polarised, E < 230 neV) **STAGE 2**

Slide thanks to P. Fierlinger

The nEDM@PSI collaboration

Presently:

- 13 Institutions
- 7 Countries
- 48 Members
- 11 PhD students



Slides thanks to K. Kirch

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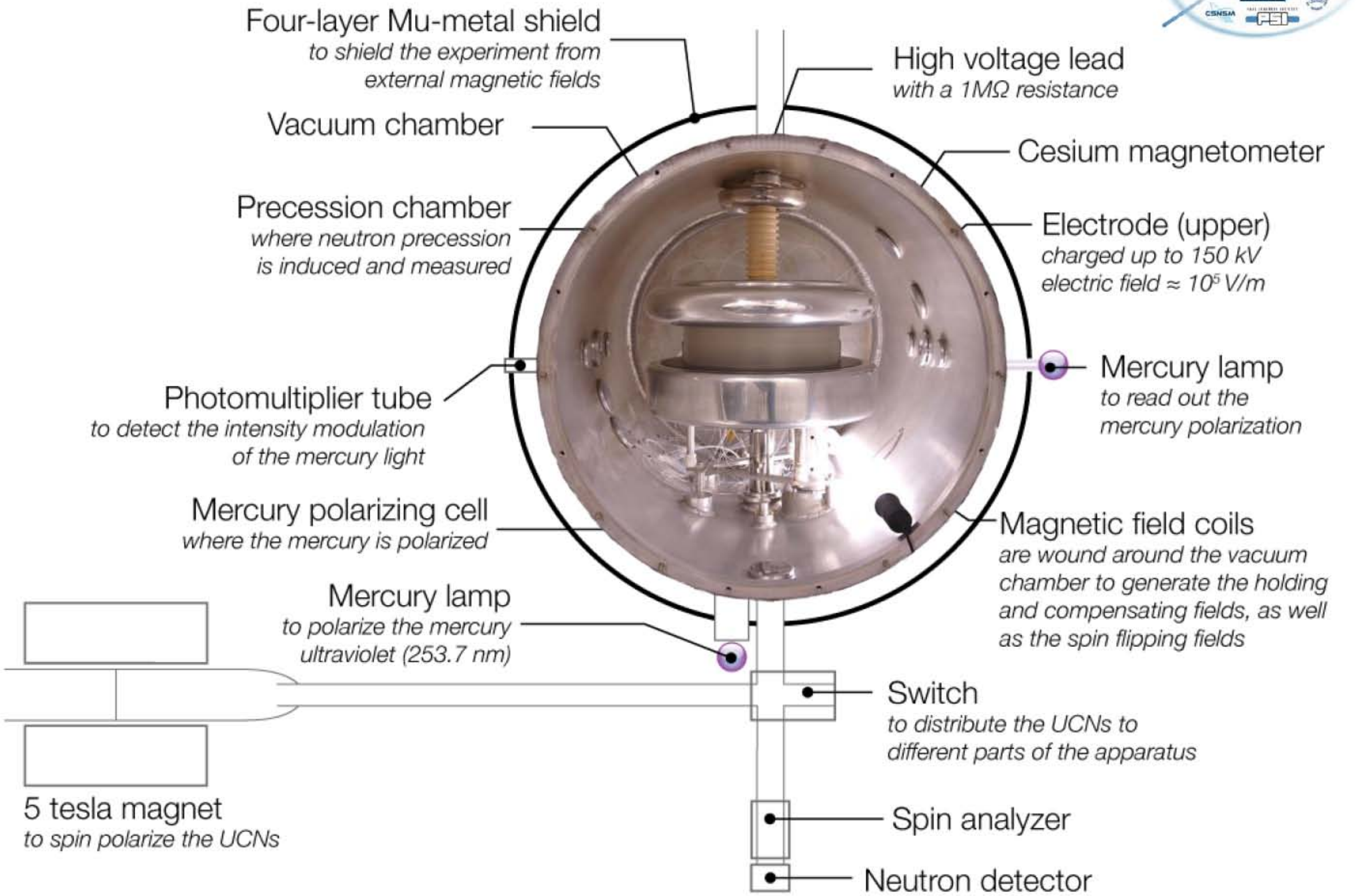
PSI: *Paul Scherrer Institut, Villigen, Switzerland*

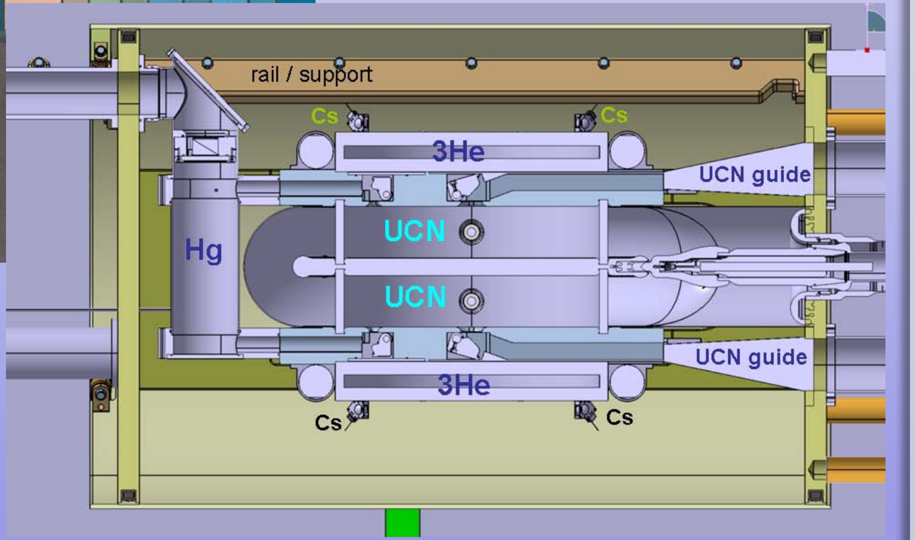
N. Hild[1,4], K. Kirch[2,4], J. Krempel, F. Piegsa, M. Rawlik[1], U. Soler[1]
ETHZ: *ETH Zürich, Switzerland*

The nEDM spectrometer



Slide thanks to K. Kirch

Towards n2EDM

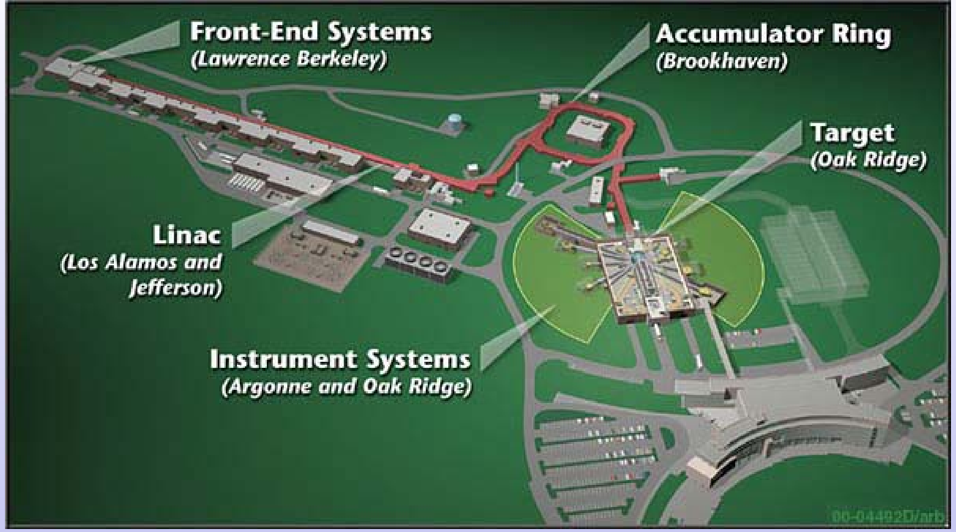


Status/Prospects:

- Taking data at $\delta d_n \sim 1\text{x}10^{-26}$ e-cm/yr
- n2EDM hopes to reach $\delta d_n \sim 4\ \text{x}10^{-27}$ e-cm/yr

- **Two UCN precession chambers with opposite electric field directions**
- **Improved magnetometry Hg – laser read out of Hg-FID to avoid light shift**
Cs – vectorial
3He – free from geometrical phase shift

nEDM Experiment at Oak Ridge Spallation Neutron Source - SNS



Concept:
R. Golub & S. K. Lamoreaux, Phys. Rep. 237, 1 (1994)

- High trapped neutron densities
  – Cold neutrons from spallation source cooled to "*Ultra-cold*" *neutrons via phonon scattering in superfluid He*

- LHe as a high voltage insulator
  – *high electric fields*

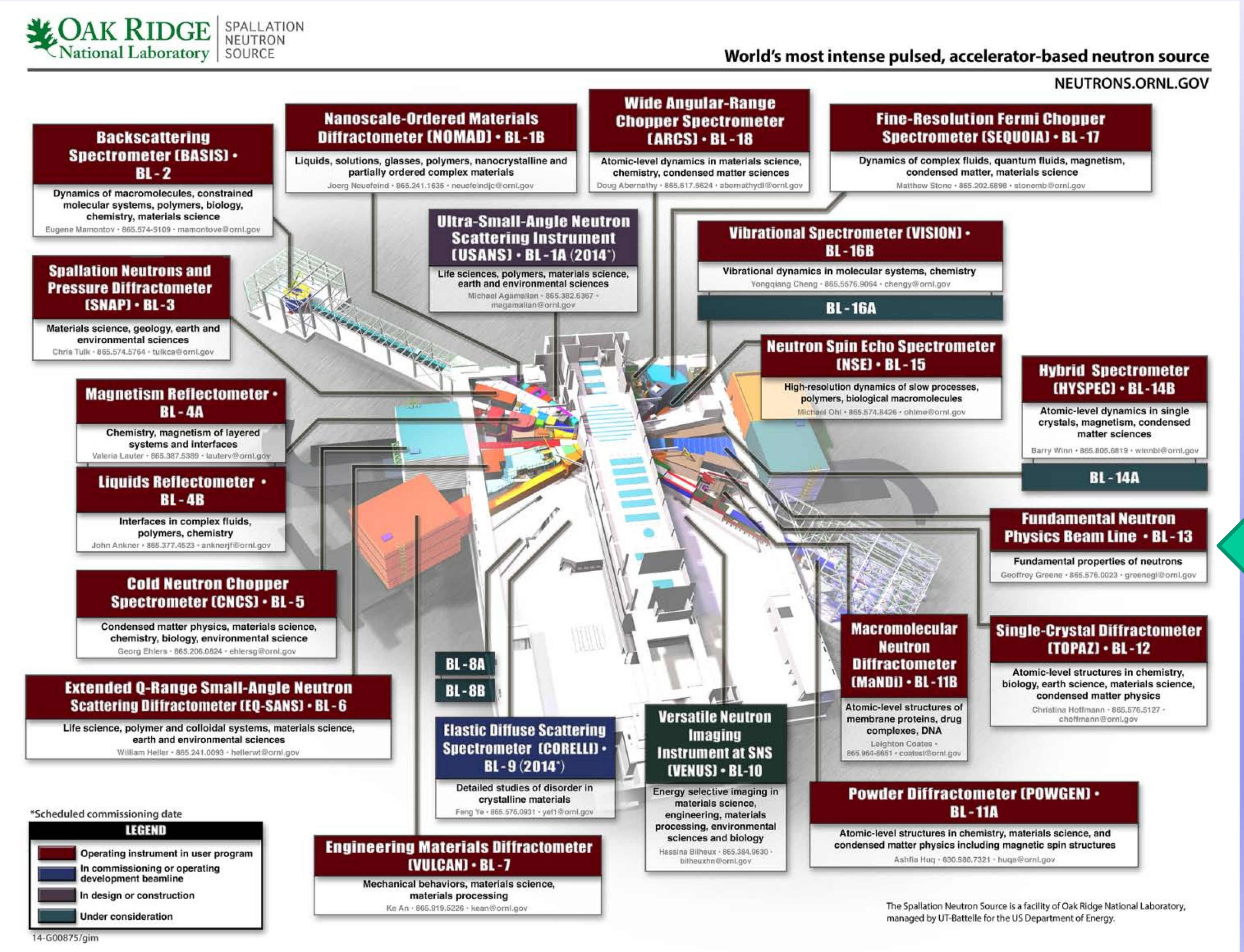
- Use of a $^{3}\overrightarrow{\mathrm{He}}$ co-magnetometer and superconducting shield
  – *Control and measure magnetic field systematics*

- Precession frequency measurement via two techniques:
  - *free precession*
  - *"dressed spin" techniques*

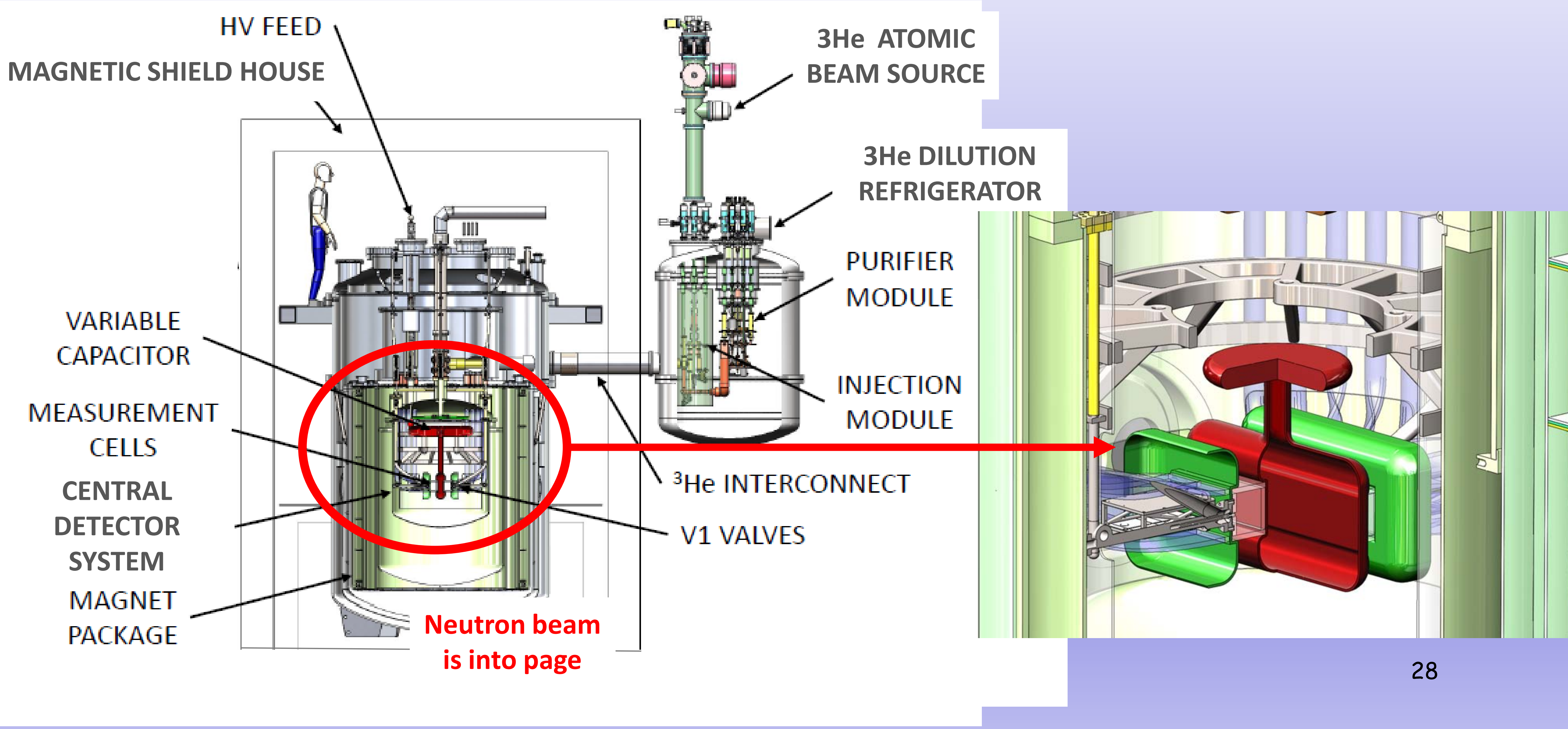
- Sensitivity reach: $d_n \sim 2 \times 10^{-28}$ e-cm (in 3 calendar yrs)

"Most ambitious nEDM experiment that is currently underway"

SNS Target Station



SNS-nEDM Experiment



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Los Alamos National Lab

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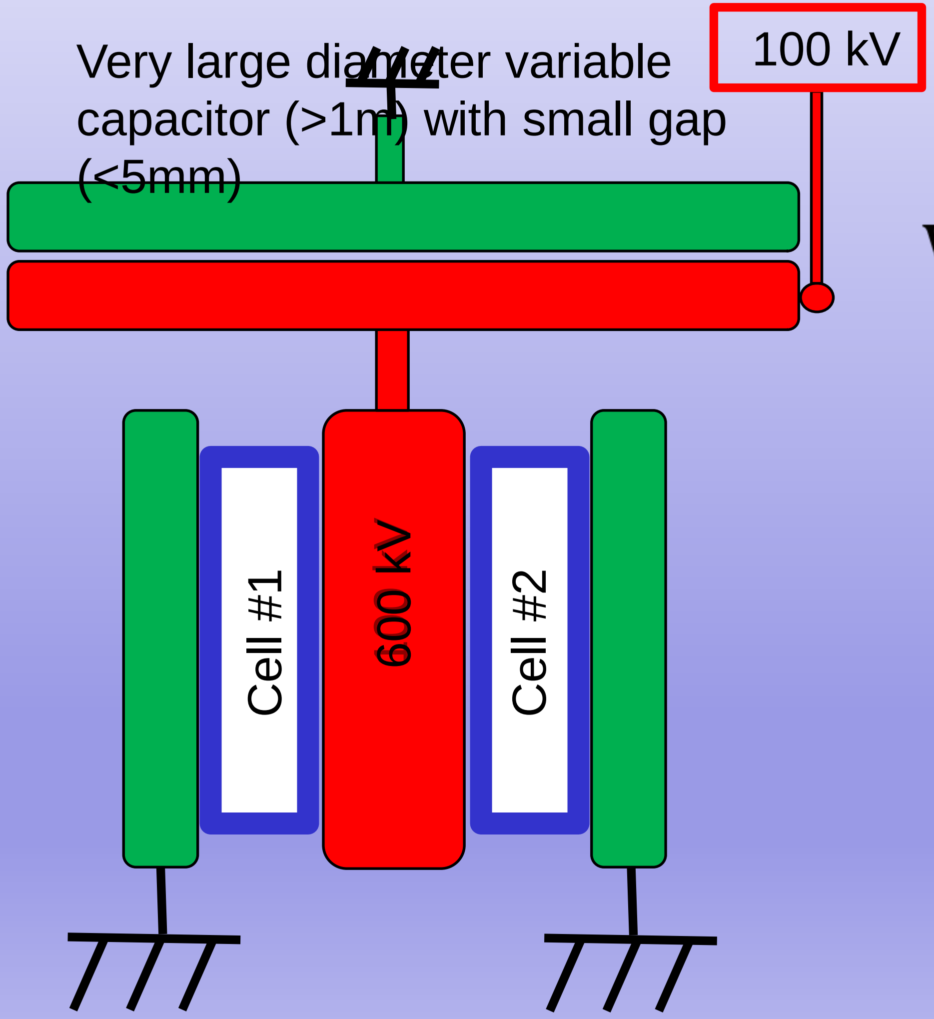
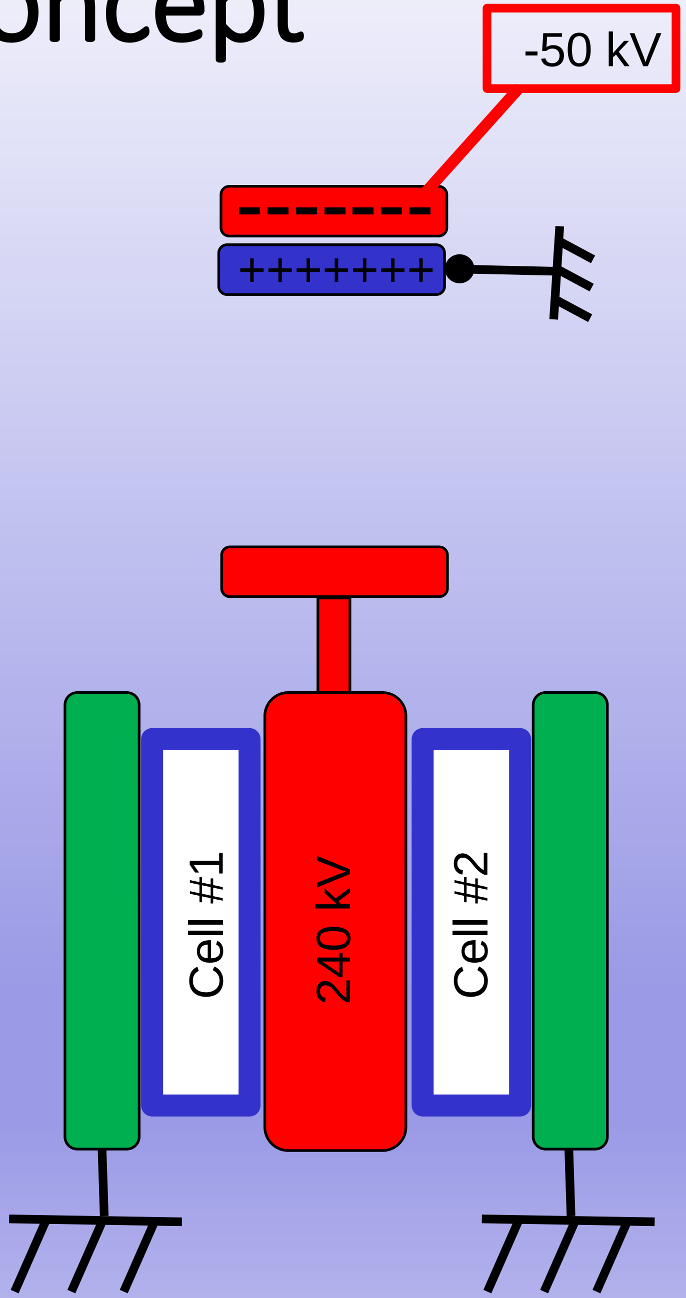
Technical Challenges for nEDM@SNS

- 1200 L of superfluid Helium @ T = 0.5K
  - Must minimize heat sources
    - Eddy-current heating from AC B-fields → minimal conducting material
  - Large cooling plant required
- Highly sensitive to magnetic field variations and gradients
  - Significant magnetic shielding required
  - B-field uniformity of ppm/cm over measurement volume
  - Low-field operation: B = 3 μT
- High electric fields: E = 75 kV/cm
  - Producing and maintaining V > 600 kV in cryogenic environment

New High Voltage Concept



$$V = \frac{Q}{C}$$



Previous concept – charging capacitor

“New” concept (Tiberius Cavallo 1795)

Status of the nEDM@SNS Experiment

- Demonstration of Critical Components is Underway (2014-2017)
  - Construction of most technically challenging pieces:
    - HV @ LANL and light detection system @ ORNL
    - Polarized ^{3}He system @ Illinois
    - Magnet system @ Caltech
    - Polarized UCN & ^{3}He test bed at NCSU PULSTAR reactor
- Large Subsystem Integration and Acquisition of Critical Components (2018-2020)
  - Begin commissioning components at Oak Ridge National Laboratory in 2019

Farther Future nEDM

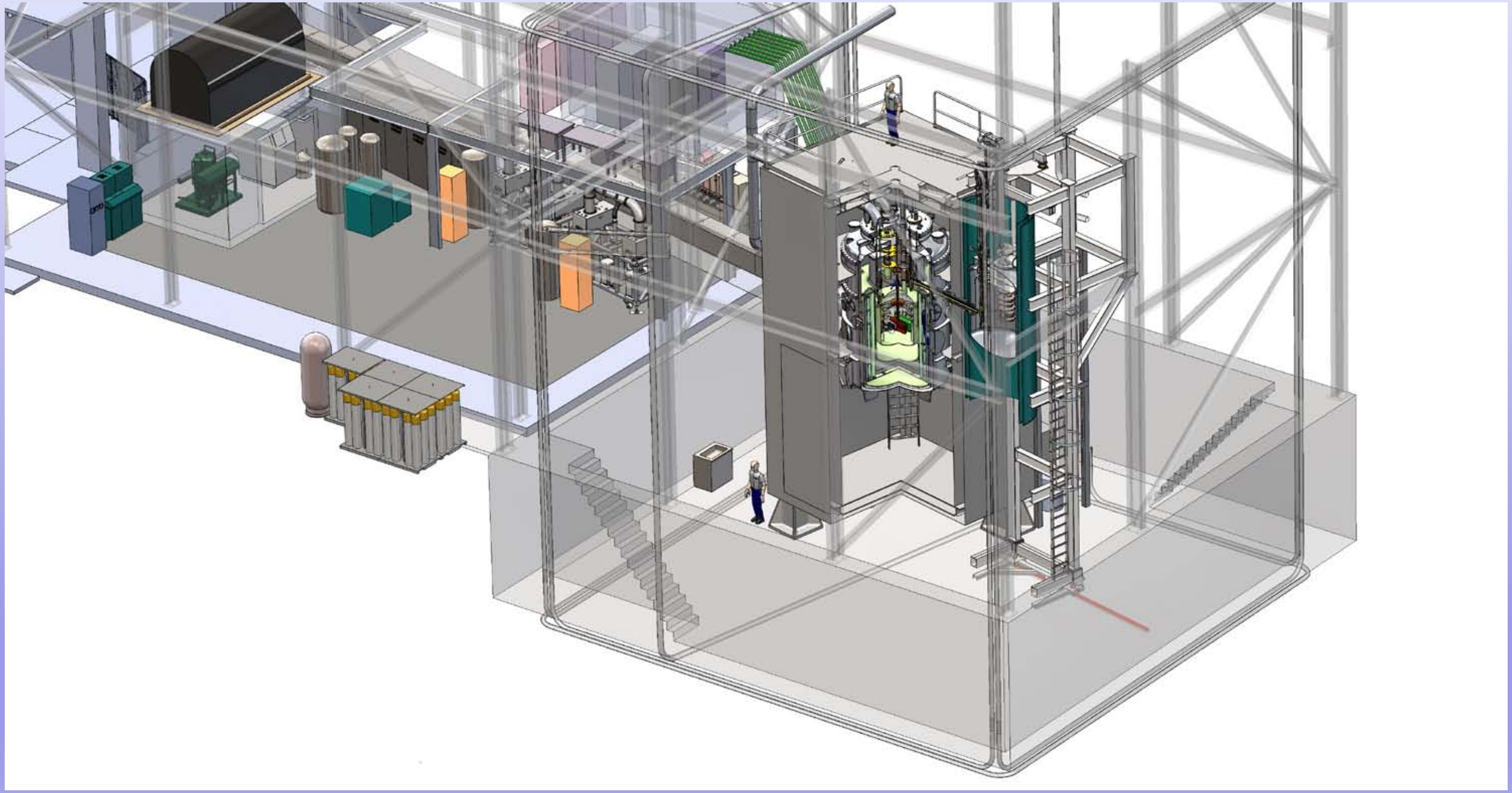
- Systematics can produce “surprises”, but if these are controlled then sensitivity is limited by counting statistics → need more neutrons
  - 2^{nd} Target station at SNS could give ~ 25x more cold neutrons
  - ESS (European Spallation Source) also promises high flux of cold neutrons for high density UCN
    - Cryogenic experiment being discussed

Summary

- A number of novel technologies are being developed to extend neutron EDM sensitivities by two orders-of-magnitude
- Anticipate:
  - A new best sensitivity within 1-2 year
  - Factor of 10 improvement within 3-4 yrs
  - Factor of 100 improvement within 7-9 yrs
  - TBD > 10 years

Extra Slides

New External Building will House the Experiment



T/CP Violation

With $\vec{\mu} = \mu \dfrac{\vec{J}}{J}$ and $\vec{d} = d\dfrac{\vec{J}}{J}$

	P	T
$\vec{\mu}$	+	-
$\vec{d}$	+	-
$\vec{E}$	-	+
$\vec{B}$	+	-
$\vec{J}$	+	-

$$H = \underbrace{\vec{\mu} \cdot \vec{B}}_{\substack{\text{P-even} \\ \text{T-even}}} + \underbrace{\vec{d} \cdot \vec{E}}_{\substack{\text{P-odd} \\ \text{T-odd}}}$$

Non-zero d violates T and CP (via CPT)

How to measure an EDM?

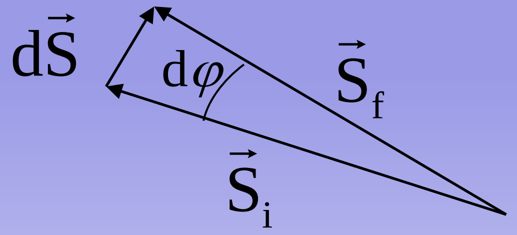
Recall magnetic moment in B field:

$$\hat{\mathbf{H}} = \vec{\boldsymbol{\mu}} \cdot \vec{\mathbf{B}}; \qquad \vec{\boldsymbol{\mu}} = 2\left(\frac{\boldsymbol{\mu}_N}{\hbar}\right)\vec{\mathbf{S}} \quad ;\textbf{for spin } \frac{1}{2}$$

$$\vec{\boldsymbol{\tau}} = \frac{d\vec{\mathbf{S}}}{dt} = \vec{\boldsymbol{\mu}} \times \vec{\mathbf{B}} \Rightarrow 2\left(\frac{\boldsymbol{\mu}_N}{\hbar}\right)\left|\vec{\mathbf{S}}\right|\left|\vec{\mathbf{B}}\right|; \quad \textbf{if } \vec{\mathbf{S}} \perp \vec{\mathbf{B}}$$

Classical Picture:

- If the spin is not aligned with B there will be a precession due to the torque
- Precession frequency ω given by



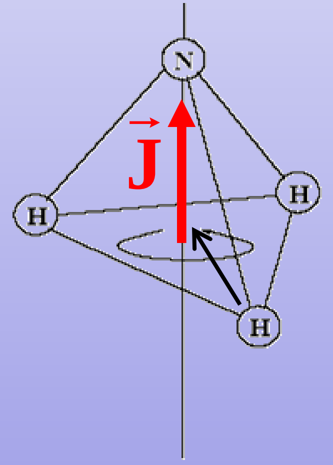
Gyromagnetic Ratio

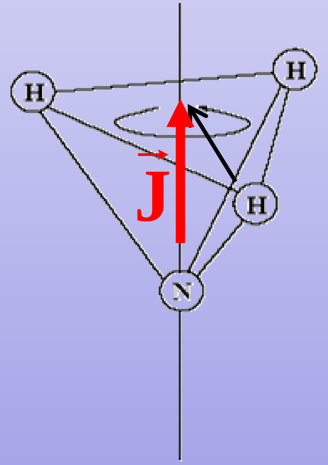
$$\omega = \frac{d\varphi}{dt} = \frac{1}{S}\frac{dS}{dt} = \frac{2\mu_N B}{\hbar} = \gamma B$$

$$or \quad \frac{2d_N E}{\hbar} \quad \text{for a } \vec{d}_N \text{ in } \vec{E}$$

But some molecules have HUGE EDMs!

H_2O: $d = 0.4 \times 10^{-8}$ e-cm
NaCl: $d = 1.8 \times 10^{-8}$ e-cm
NH_3: $d = 0.3 \times 10^{-8}$ e-cm





But NH_3 EDM is not T-odd

$$\vec{d} \neq d\frac{\vec{J}}{J}$$

$$\left(\text{both } \vec{d} = +d\frac{\vec{J}}{J} \quad \text{and} \quad \vec{d} = -d\frac{\vec{J}}{J} \text{ exist!}\right)$$

Ground state is actually a superposition

If neutron/electron had a degenerate state, then their EDM would not violate T or CP.
But they don't!