Progress Towards the Development of the nEDM@SNS Experiment

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PSI 2022 – 19 October 2022

Overview of nEDM@SNS

Experiment under construction at the Spallation Neutron Source at Oak Ridge National Laboratory

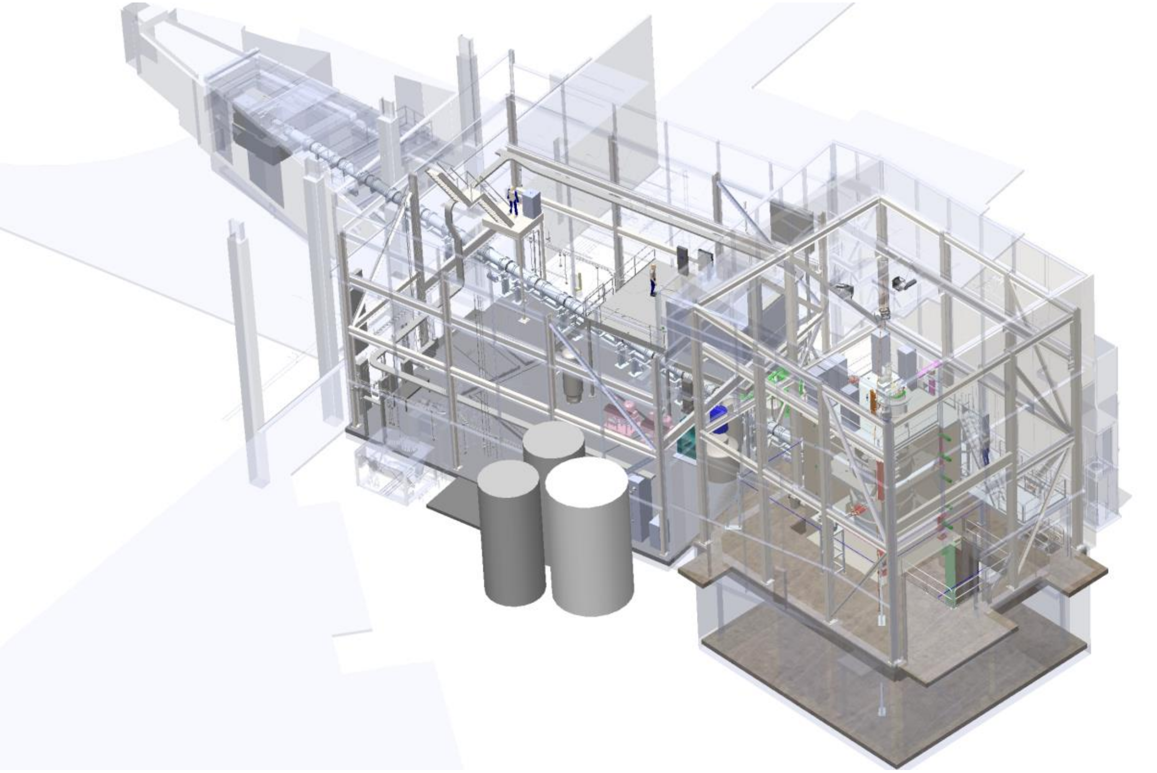
- Based on the pioneering concept of R. Golub and S. K. Lamoreaux, Phys. Rept. 237, 1 (1994)

0.5 K Superfluid ^{4}He Environment

- In-situ UCN production (8.9 Å cold beam)
- Dilute mixture of polarized ^{3}He as co-magnetometer and spin analyzer
- Large electric field breakdown strength

Projected 90% CL Sensitivity

- "Free Precession": 5.7×10^{-28} e-cm
- "Dressed Spin": 2.9×10^{-28} e-cm



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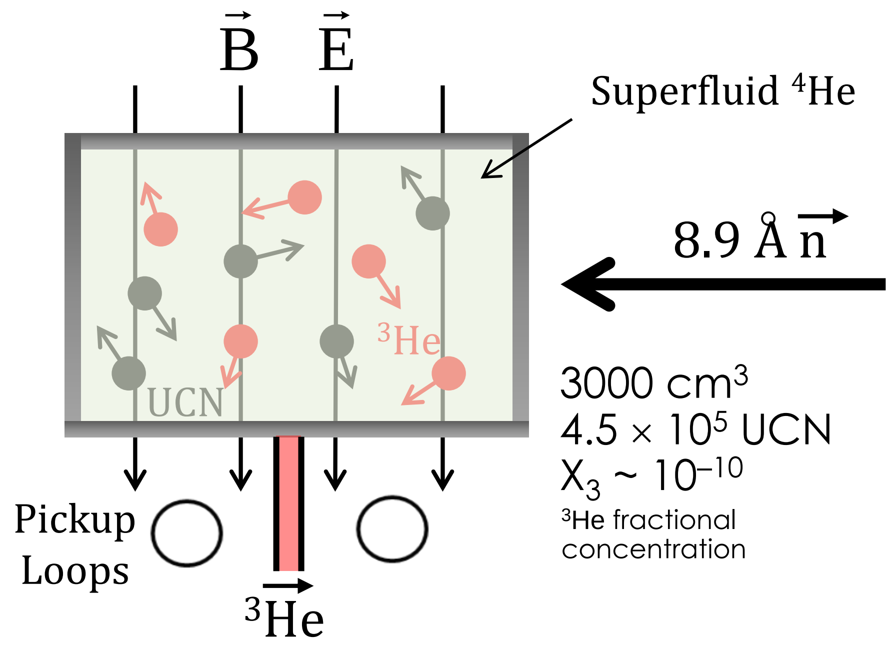
Review of Concept: "Free Precession"

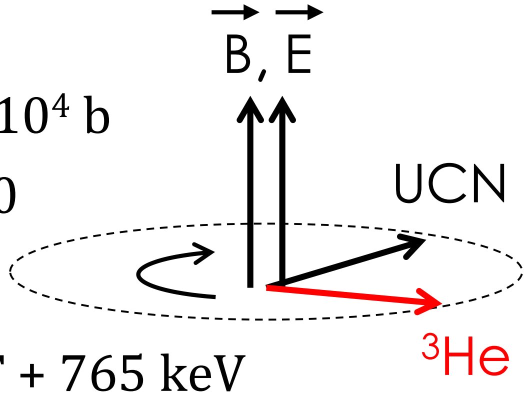
- Transfer polarized ^{3}He to measurement cells
- Illuminate measurement cells with polarized 8.9 Å beam to produce polarized UCN
- Apply $\pi/2$ pulse to rotate ^{3}He and UCN spins
- Measure precession frequencies via scintillation light and SQUID pickup loops
- Remove (de)polarized ^{3}He from measurement cells

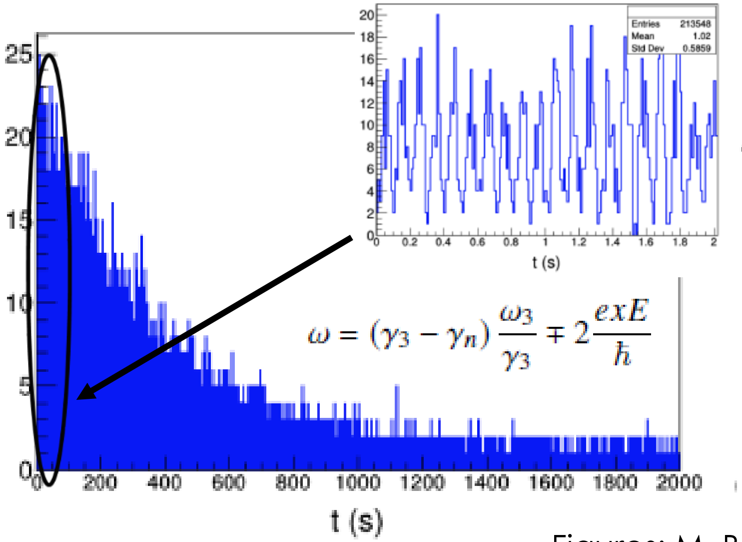


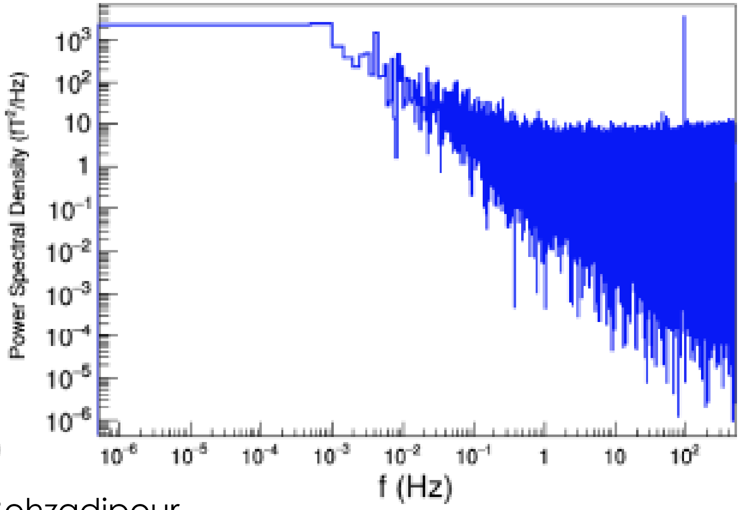
$\sigma(n\uparrow{}^3\text{He}\downarrow) \sim 10^4$ b

$\sigma(n\uparrow{}^3\text{He}\uparrow) \sim 0$

$n + {}^3\text{He} \rightarrow p + \text{T} + 765\ \text{keV}$







Figures: M. Behzadipour

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Review of Concept: “Dressed Spin”

Transfer polarized ^{3}He to measurement cells

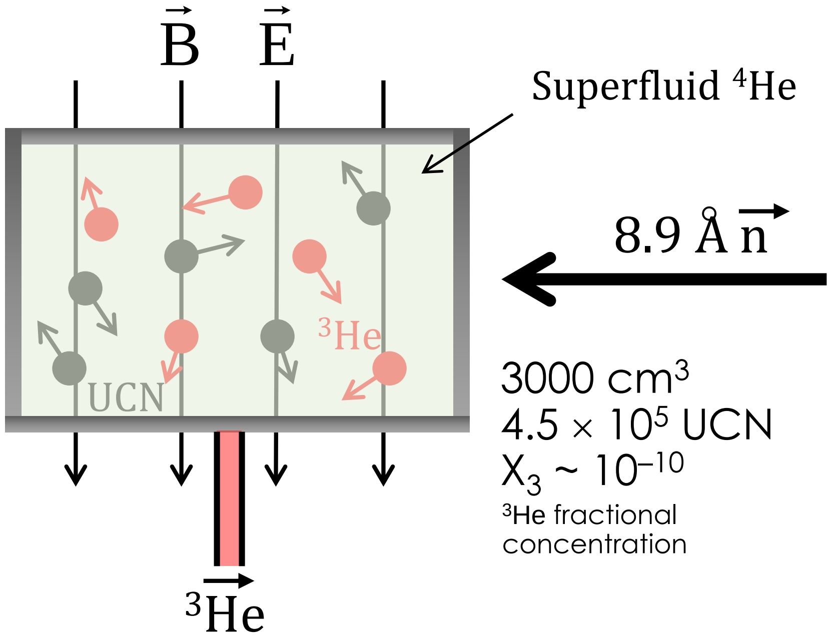
Illuminate measurement cells with polarized 8.9 Å beam to produce polarized UCN

Apply $\pi/2$ pulse to rotate ^{3}He and UCN spins

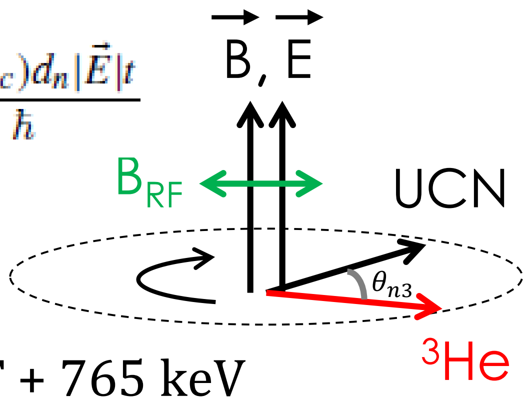
Apply perpendicular B_{RF} field

Control of spins

Remove (de)polarized ^{3}He from measurement cells



$$\theta_{n3}(t) = \pm\phi_0 + \frac{2J_0(x_c)d_n|\vec{E}|t}{\hbar}$$



$$n + {}^3\text{He} \rightarrow p + \text{T} + 765\ \text{keV}$$

Apply a perpendicular B_{RF} field to “dress” the ^{3}He and UCN spins

$$\mu^{\text{eff}} = \mu J_0(\mu B_{RF}/\omega_{RF})$$

Precess at same rate at “critical dressing”. Control of initial angle and thus scintillation rate (sensitivity).

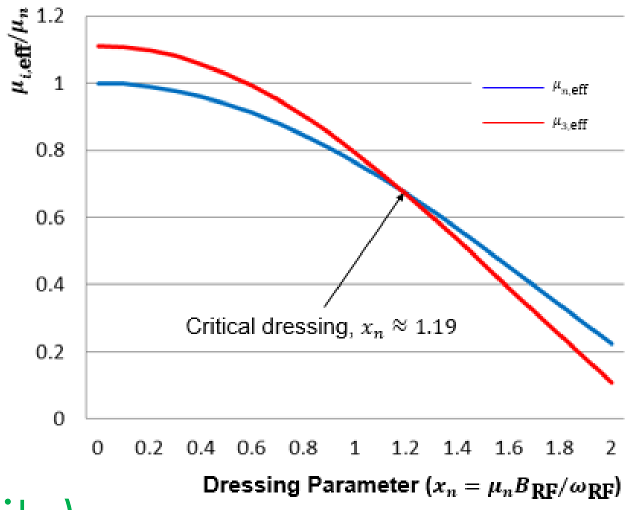


Figure: V. Cianciolo

Sensitivity Projection: Physics Parameters

Stated sensitivity projections based on these physics parameters:

Table 1. Experimental design goals for the key parameters that influence the statistical uncertainty.

Quantity	Definition	Value
P_{UCN}	UCN production rate	0.31 UCN/cc/s
N_0	Number of UCNs in each cell at t=0	4.5×10^5
V_{cell}	Measurement cell volume	3000 cc
τ_β	β-decay lifetime	880 s
τ_3	UCN-^{3}He absorption time	500 s
τ_{cell}	UCN-wall absorption time	2000 s
$\lvert E\rvert$	Electric field	75 kV/cm
T_m	Measurement time	1000 s
T_f	Cold neutron fill time	1000 s
T_d	Dead time between cycles	400 s
P_3	^{3}He initial polarization	0.98
P_n	UCN initial polarization	0.98
τ_P	^{3}He & UCN depolarization time	20,000 s
ε_3	Detection efficiency for UCN-^{3}He capture	0.93
ε_β	Detection efficiency for β-decay	0.5
$\dot N_B$	Non β-decay background rate	5 Hz
	Operating Pressure	2 atm

Free Precession: $\sigma_d \sim \dfrac{\sqrt{2}\hbar}{4|\vec{E}|\tau P_{He3} P_n \sqrt{mN}}$

90% CL ~ 5.7 × 10^{-28} e-cm (300 live days)

Sinusoidal Scintillation Rate

Dressed Spin:

$$\sigma_d^{tot} = \frac{\hbar\bar{\tau}_3}{(2J_0|E|N_0\epsilon_3\sin\phi_0)\left\{\int_0^T \frac{P^2t^2e^{-\Gamma t}\,dt}{\dot{N}_B e^{\Gamma t} + N_0\left[\frac{\epsilon_\beta}{\tau_\beta} + \frac{\epsilon_3}{\bar{\tau}_3}(1-P\cos\phi_0)\right]}\right\}^{\frac{1}{2}}}.$$

90% CL ~ 2.9 × 10^{-28} e-cm (300 live days)

Can Optimize the Scintillation Rate

	Cycle Step	t_{start} (s)	Δt (s)	
1	Heat flush ^{3}He to MC	0	100	Measurement Cell
2	Neutron loading	100	1000	
3	Precession measurement	1100	1000	
4	Heat flush ^{3}He to SV	2100	300	Sequestration Volume
5	Dump/refill SV			
6	Injection volume ^{3}He fill			

Complete sensitivity details in:
M.W. Ahmed et al., JINST 14, P11017 (2019)

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Sensitivity Projection: Management and Current Status

Description of Scope	KPP	NPP	UPP
Magnetic Field Gradient $\langle \partial B_i/\partial x_j \rangle_{vol}$ [μG/cm] [A]	0.5	0.25	0.1
Magnetic Shielding Factor at 0.01 Hz [A]	1×10^4	5×10^4	7.5×10^4
UCN Wall Loss Time [B]	100	1000	2000
⟨Photoelectrons⟩ per n-^{3}He Capture [C]	6	20	20
SQUID Noise [fT / √Hz] [D]	20	10	1
Electric Field [kV/cm] [E]	10	40	75
^{3}He ABS Flux [s^{-1}] | Signal-to-Noise Ratio [F]	1×10^{14} | 20	1×10^{14} | 50	1×10^{14} | 100
^{3}He Injection Volume Temperature [mK] [G]	350	320	300
8.9 Å Neutron Flux [n/Å/cm^2/s/MW] [H]	2×10^6	6×10^6	6×10^6
8.9 Å Neutron Polarization [%] [H]	80	90	98
Estimated Sensitivity [10^{-28} e-cm] [I]	30	11	3

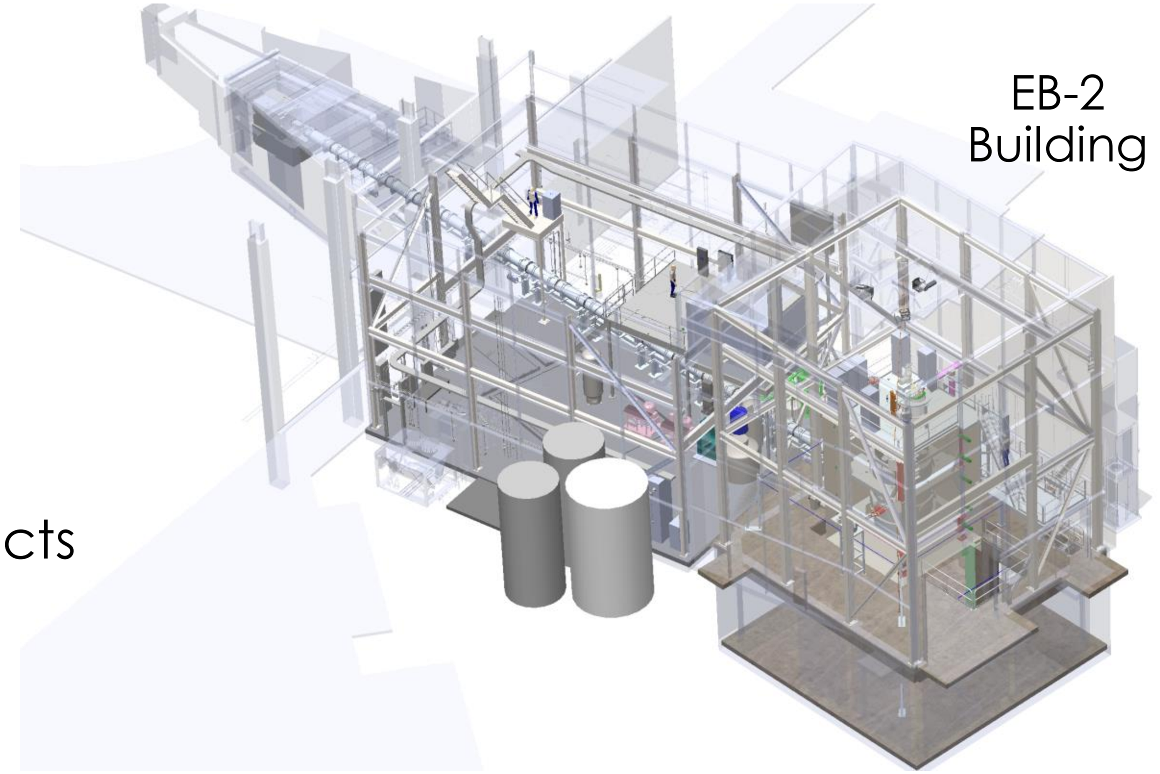
Present Values *

0.1 μG/cm
5×10^4
800 – 1800 s
17
1.6 fT/√Hz
75 kV/cm
1×10^{14} | 20
120 mK
6×10^6 n/A/cm^2/s/MW
87%
6×10^{-28} e-cm

*** Best estimates based on work to date (i.e., not all measured under experiment's final operating conditions)**

KPP: Key Performance Parameter
NPP: Nominal Performance Parameter
UPP: Ultimate Performance Parameter

Experiment Timeline



EB-2
Building

Rigorous project management process in place with hands-on oversight by the funding agencies (DOE and NSF) and review panels

Most recent bottom-up schedule update projects completion of the project in late-2027 (i.e., apparatus commissioned, all performance parameters on previous slide demonstrated)

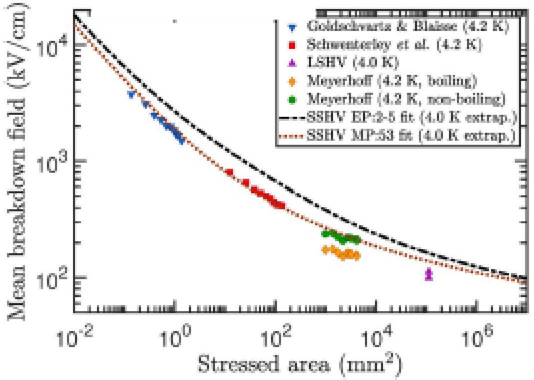
However, this schedule assumed construction of the EB-2 Building starting in 2023

We are now planning, in close communication with the funding agencies, for construction of the EB-2 Building to start in 2024. We are currently evaluating the impact of this delay to the EB-2 construction on the overall schedule for project completion.

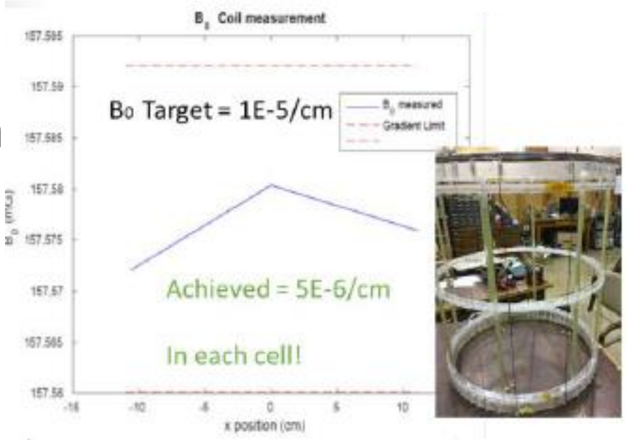
Previous Major R&D Progress: Pre-2021

1/5-Scale High Voltage System Achieved 85 kV/cm with PMMA Electrodes with Copper Implantation

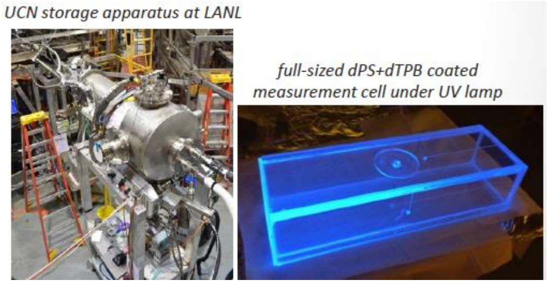
High Voltage Studies Revealed Key (Area) Scaling Laws



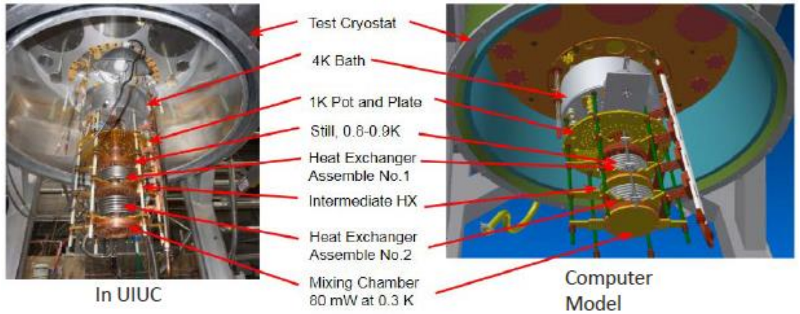
1/3-Scale Magnet System Demonstrated Field Gradient Requirements



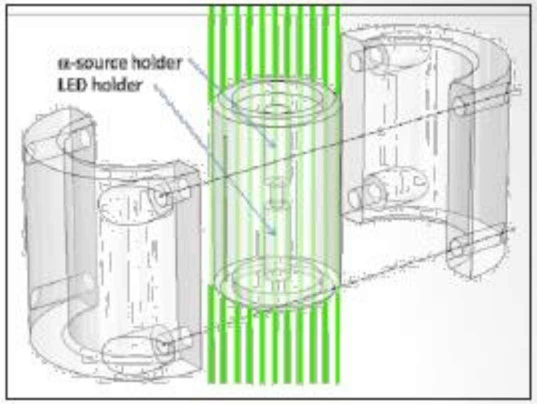
Measured 1800 s UCN Wall Loss Time in Cryogenic Environment



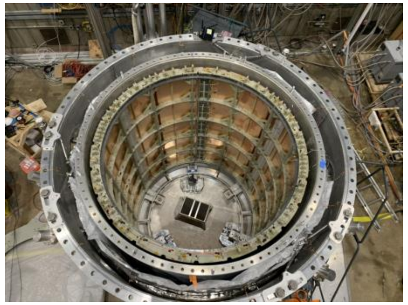
^{3}He System Constructed Full-Scale Non-Magnetic Dilution Refrigerator

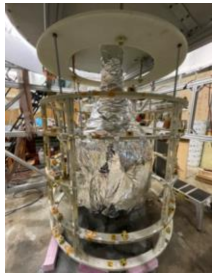


Light Collection Prototype Extrapolates to 17 PE in Final Apparatus



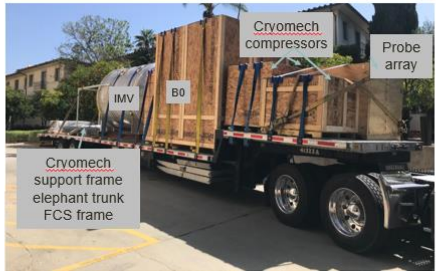
Recent Technical Highlights: Magnetic Fields

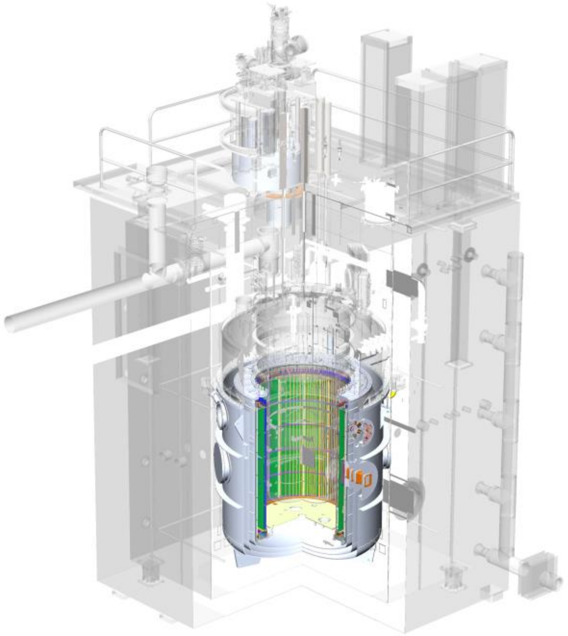




Shipment #1: Out: 5/18/22, In: 5/25/22

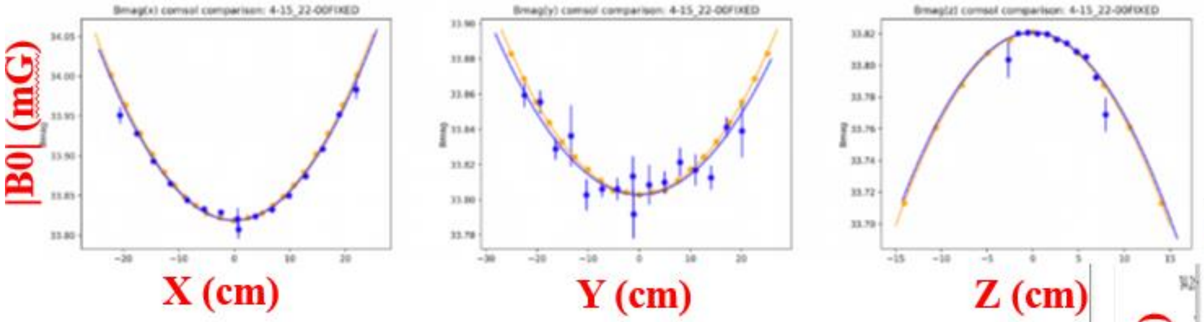
Shipment #2: Out: 6/15/22, In: 6/20/22





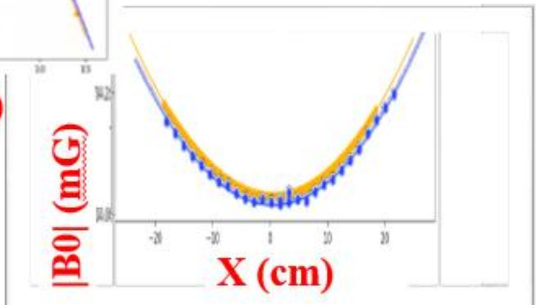
Final Testing at Caltech

- Field Measurements at Low Temperature
- Compare Probe Array Reconstructions with Map
- Measure Magnet System Temperature Distribution



3-axis fluxgate (blue) vs. COMSOL Theory Calc.
Note: no Pb Shield yet

For these figures:
x: along B_0
y: along beam
z: vertical



3-axis fluxgate (blue) vs. Cryoprobe Array

Full-Scale Magnetic Field Performing to Design

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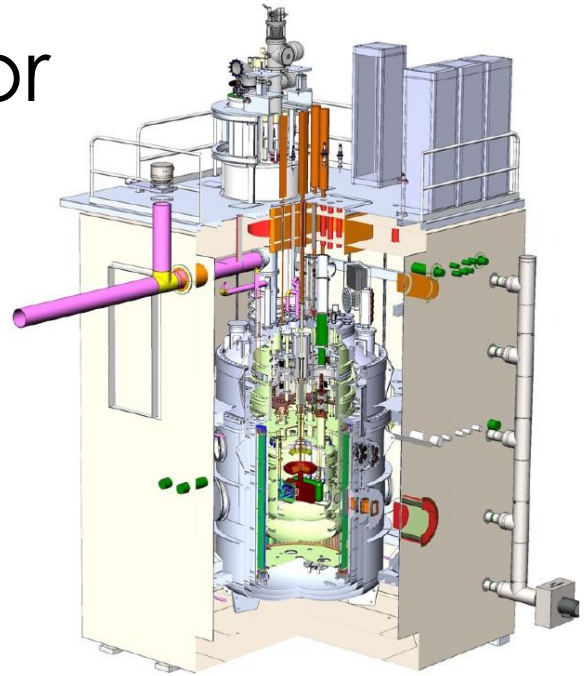
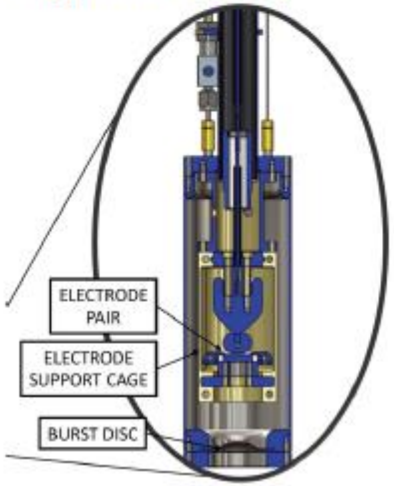
Slide Content: B. Filippone et al.

Recent Technical Highlights: Central Detector

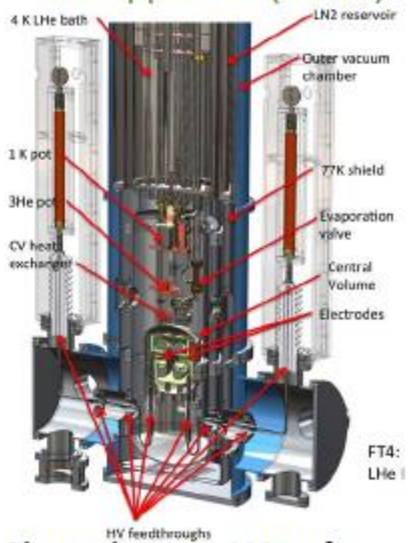


Small Scale High Voltage Test Apparatus (SSHV)



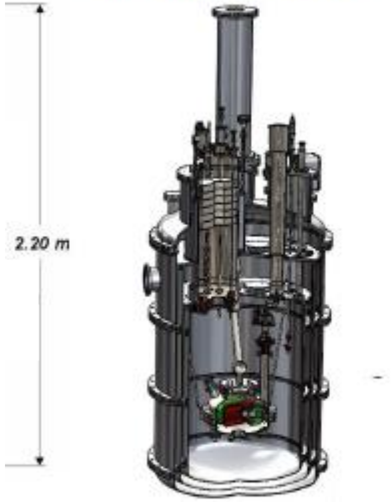
Electrode size: ~1 cm²
HV: 40 kV

Medium Scale High Voltage Test Apparatus (MSHV)

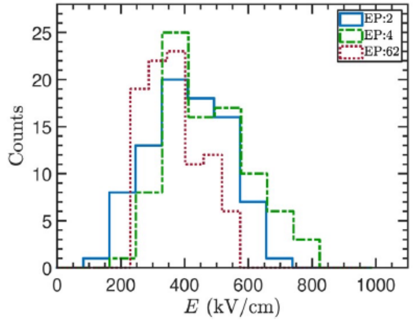


Electrode size: ~100 cm²
HV: 50 kV + 50 kV = 100 kV

Half Scale High Voltage Test Apparatus (HSHV)



Electrode size: ~1000 cm²
HV: 200 kV



Breakdown field distribution data taken with small electrodes (~1 cm²)

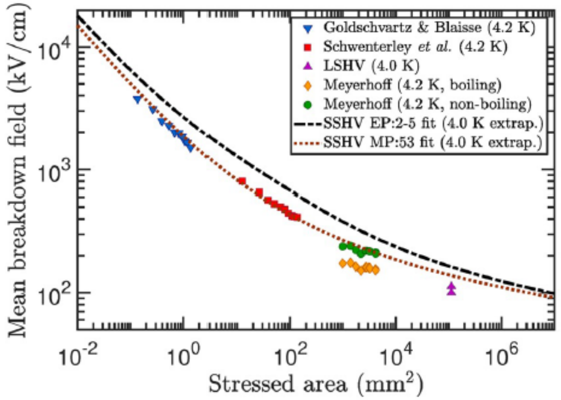
From the data on the distribution, one can determine the cumulative distribution function.

$$P_b(E) = 1 - e^{-SW(E)}$$

W: probability of breakdown
S: area of the electrode

Area scaling naturally follows from the cumulative distribution function.

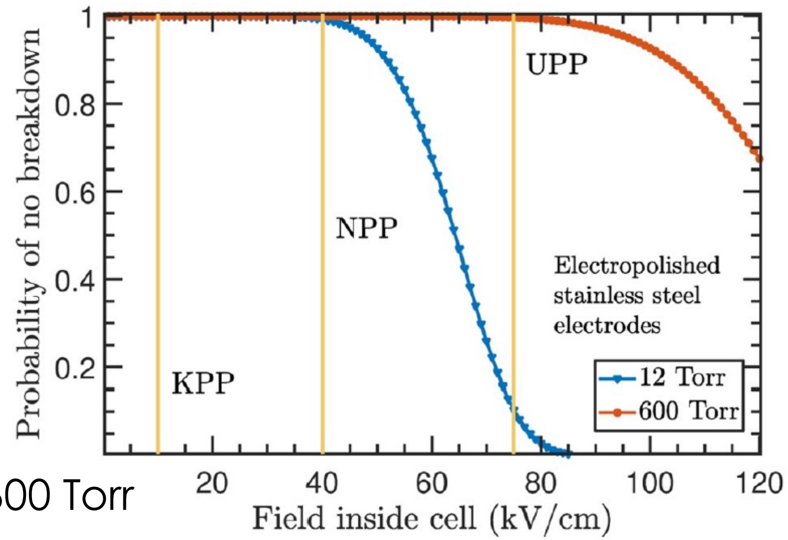
$$\hat{P}_b(E;n) = 1 - e^{-nS\hat{W}(E)}$$



Our prediction agrees well with data

N.S. Phan et al.,
J. Appl. Phys. 129, 083301 (2021)
Slide Content: T. Ito et al.

Recent Technical Highlights: Central Detector



600 Torr

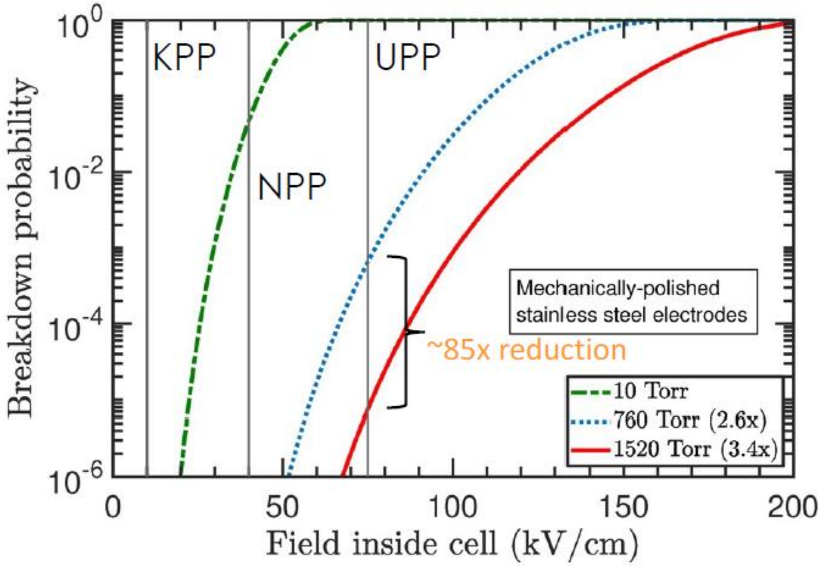
We can now predict the breakdown field distribution for electrodes with arbitrary surface field distribution.

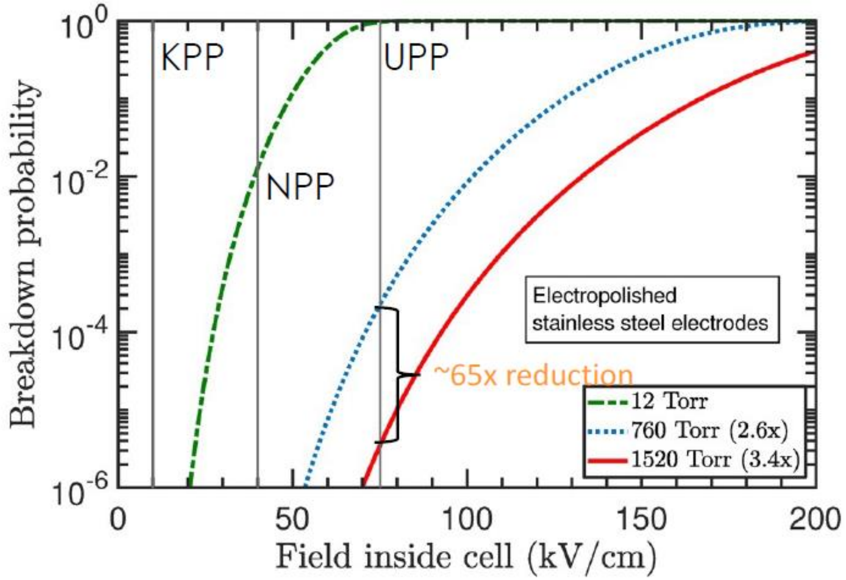
$$P_s = \prod_{E_i} e^{-S(E_i)W(E_i)}$$

The plot on the left assumes that the electrode surface for SNS nEDM is similar to that for electropolished stainless steel. The pressure dependence is taken from our data on mechanically polished electrodes. This plot is for the MC Electrodes and Cavallo combined.

Probability of Breakdown at 75 kV/cm Predicted to be Very Small; Further Mitigated by Operating at a Nominal Pressure of 2 Atm

N.S. Phan et al., J. Appl. Phys. 129, 083301 (2021)
Slide Content: T. Ito et al.





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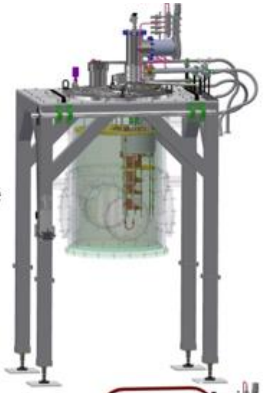
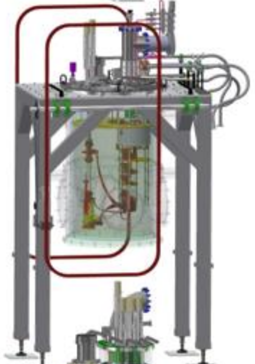
Recent Technical Highlights: ^{3}He Services

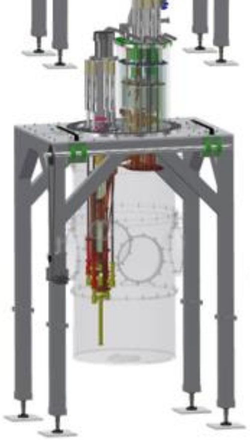
1. Completion and commissioning of the DR – essentially complete



2. Fabricate/assemble/test injection system components – the current phase
   - Use test-stand vacuum system and top flange.
   - Includes *in situ* "High field" wall depolarization testing.
   - Holding field coils, MEOP ^{3}He polarization.



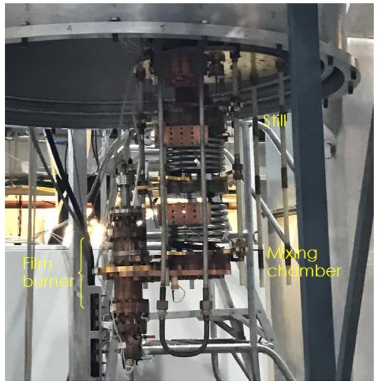
3. Fabricate/assemble/test purification system components
   - Requires ORNL top flange, "extended" DR vacuum can.

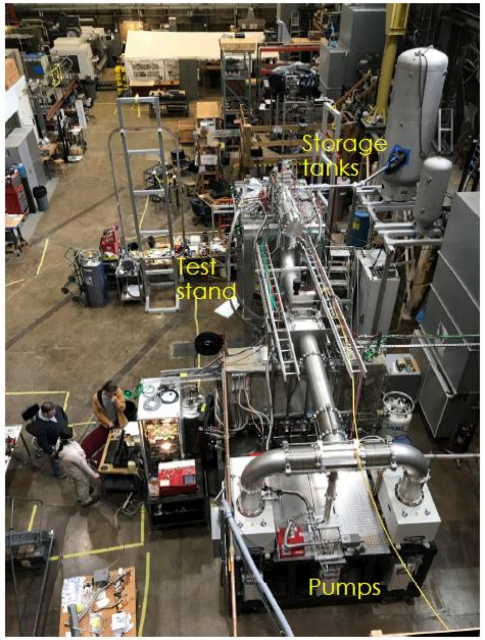


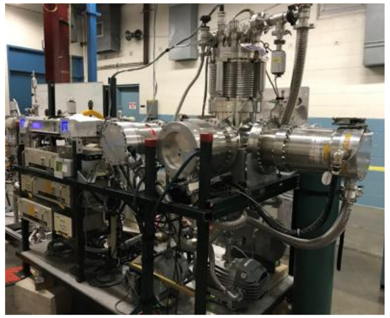
4. High-field polarization transport
   - ABS and support.
   - Holding field coils,
   - "Real beam line" including ABS interface.
   - Check heat flush transport to test volume.

5. Low-Field Polarization Testing at ORNL
   - Segmented vacuum chamber, SQUID polarization measurement, spin-transport coils

Dilution Refrigerator and Test Stand at Illinois







Atomic Beam Source

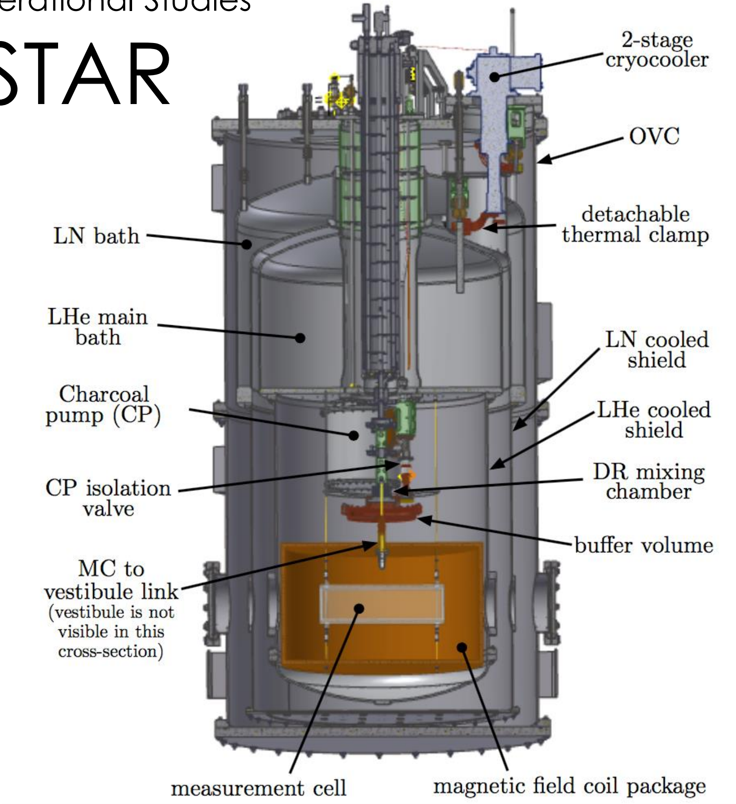
<u>Recent Progress</u>:
- Film burner constructed
- Heat flush with Nuclepore filter ready to be installed
- Injection volume complete
- Interim (MEOP*) source of polarized ^{3}He for depolarization testing in injection volume

Slide Content: D. Beck, S. Williamson, et al.

* Metastability Exchange Optical Pumping

* Systematic and Operational Studies

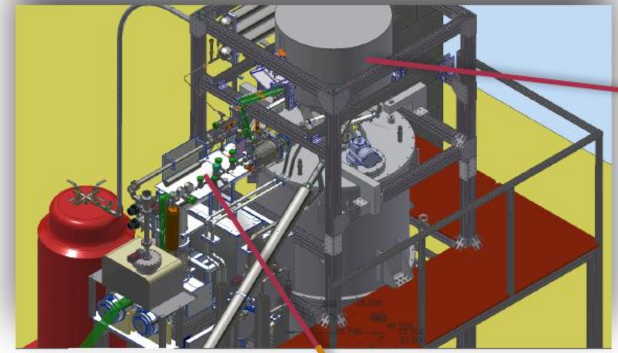
Recent Technical Highlights: SOS* at PULSTAR

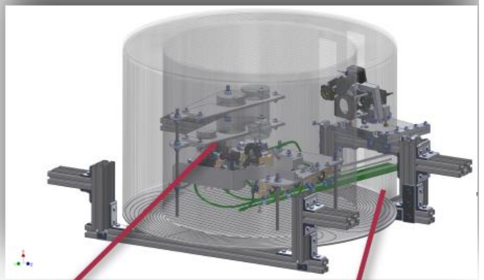


"Mini" nEDM@SNS with one measurement cell, no E field

Small size, rapid thermal cycling

Develop spin manipulation techniques, characterize geometric phase, validate measurement cells

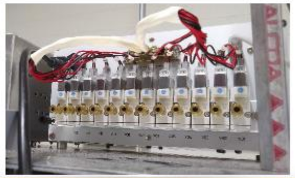




Trolley for MEOP assembly installation on top of cryostat

Gas Handling System

He3 diluting manifold



Control box for pneumatic actuation

MEOP coil cylindrical part

Significant Technical Progress on SOS; Please See Poster by Tom Rao

OAK RIDGE National Laboratory nEDM@SNS

Slide Content: E. Korobkina et al.

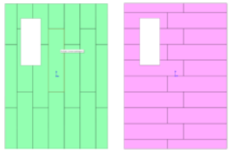
Recent Technical Highlights: Magnetic Shield Enclosure

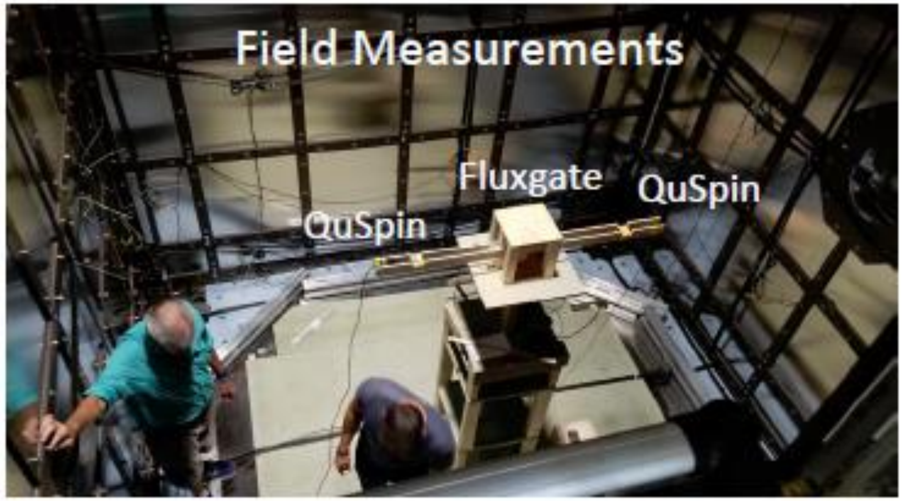
External Coils for Shielding Factor Measurement

Interior: 4.1 m x 4.1 m x 6.1 m

Two 3.0-mm layers of μ-metal separated by 40 cm

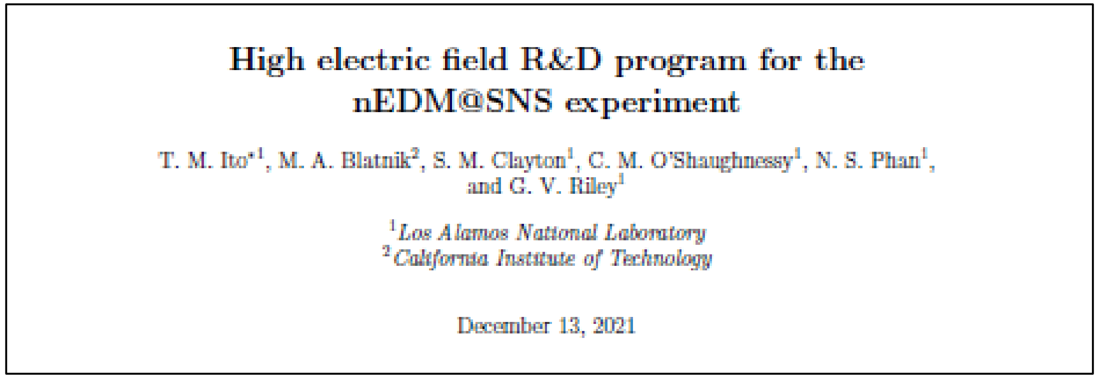
Layers composed of 0.745 m x 0.3 m x 1 mm sheets tiled to minimize gaps





Within 1 m^3 "Target Volume" centered on location of measurement cells, specifications of $|B| < 10$ nT and $dB_i/dx_j < 2$ nT/m largely achieved

Forward Looking: Strategy for Some Technical Challenges



High electric field R&D program for the nEDM@SNS experiment

T. M. Ito*[1], M. A. Blatnik[2], S. M. Clayton[1], C. M. O'Shaughnessy[1], N. S. Phan[1], and G. V. Riley[1]

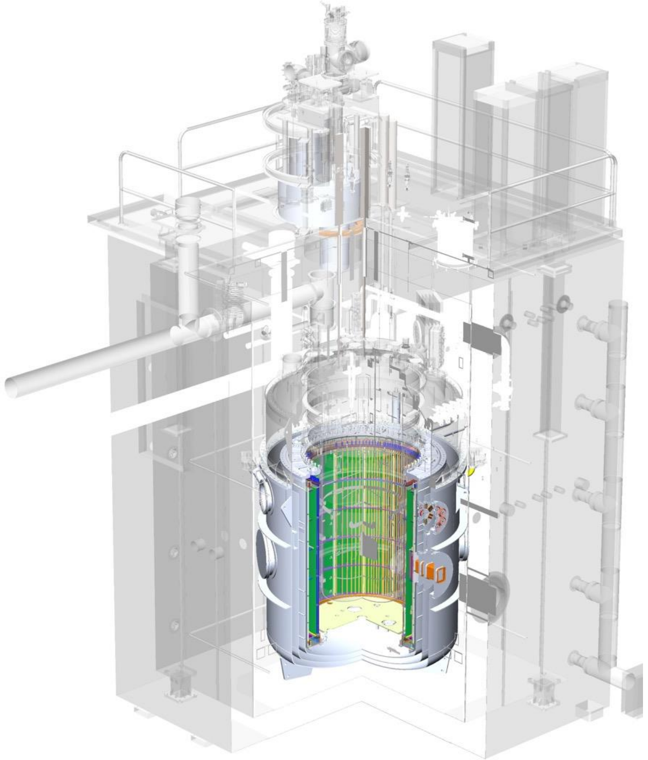
[1]Los Alamos National Laboratory
[2]California Institute of Technology

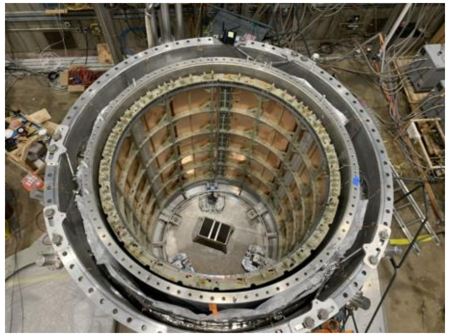
December 13, 2021

Scaling Laws for PMMA-Coated Electrodes

Long-Time Testing of PMMA-Coated Electrodes to Establish Mean Time to Failure

Test Full-Scale Cavallo High-Voltage Amplification System in Liquid Helium at Voltages Required for Final Apparatus





“Polarization/Transmission” Test

First beam for nEDM@SNS !

Polarized cold neutrons sent through cryogenic magnets system to verify transmission and polarization

Please See Poster by Kavish Imam

Collaboration

Collaboration
Meeting, July 2022

EB-1
Building

20 US institutions, Simon-Fraser (Canada) and U. Nacional Autónoma de México
67 Voting members of collaboration = significant fraction of research effort on nEDM@SNS
17 current graduate students, 10 current postdocs

Acknowledgments and Summary

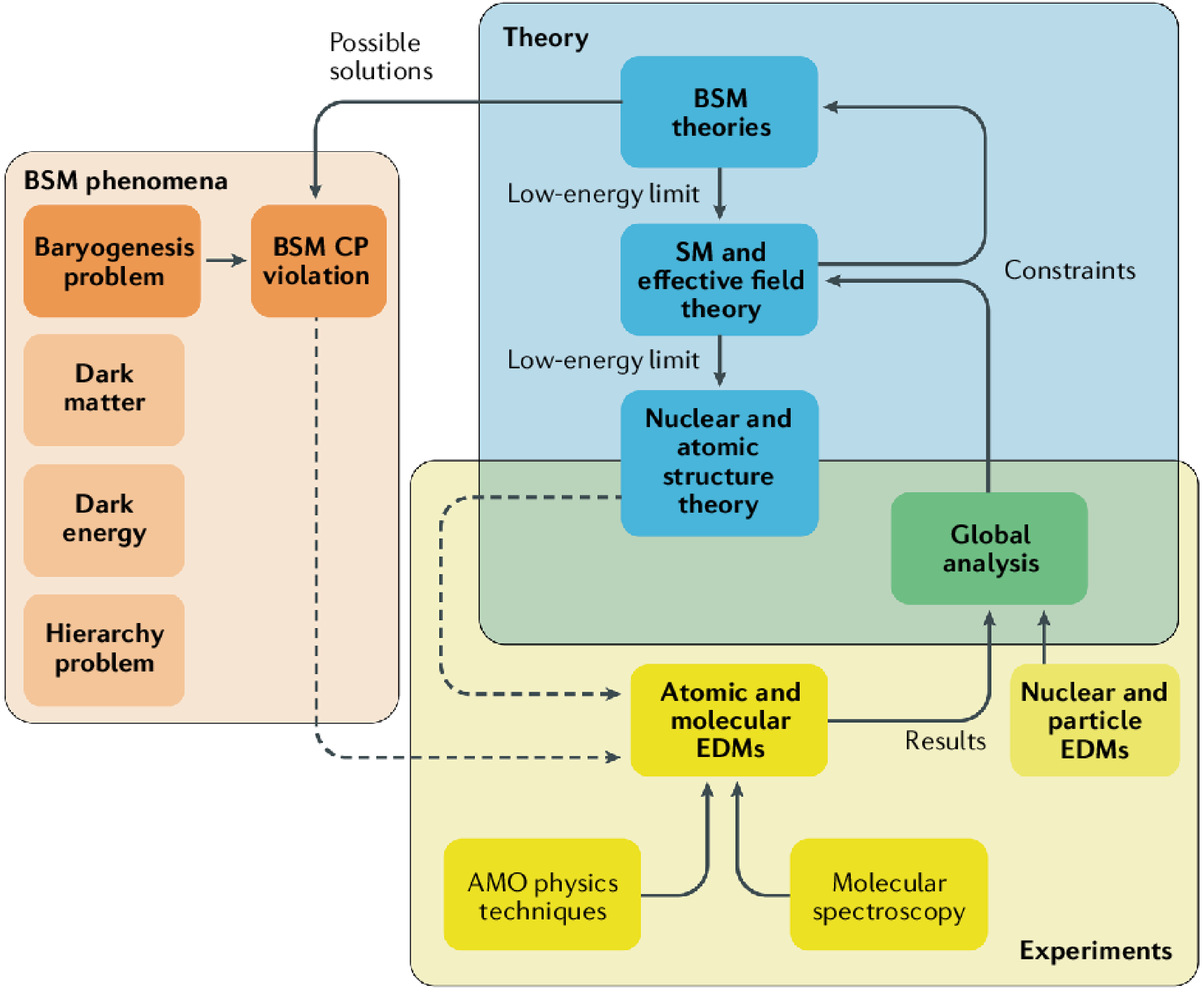
We are grateful to the funding agencies for their continued commitment to the nEDM@SNS experiment. We thank the many review panels for their expert guidance.

The collaboration is working hand-in-hand with the funding agencies to deliver the experiment on schedule.

Strategies for addressing technical challenges have been vetted by expert review panels.

The next several years will be very exciting for nEDM@SNS !

Conclusion: For nEDM@SNS, Our Continued Excitement !



William Cairncross, Jun Ye
Nature Rev. Phys., Volume 1, pg 510–521 (2019)

Oak Ridge National Laboratory