NC STATE UNIVERSITY

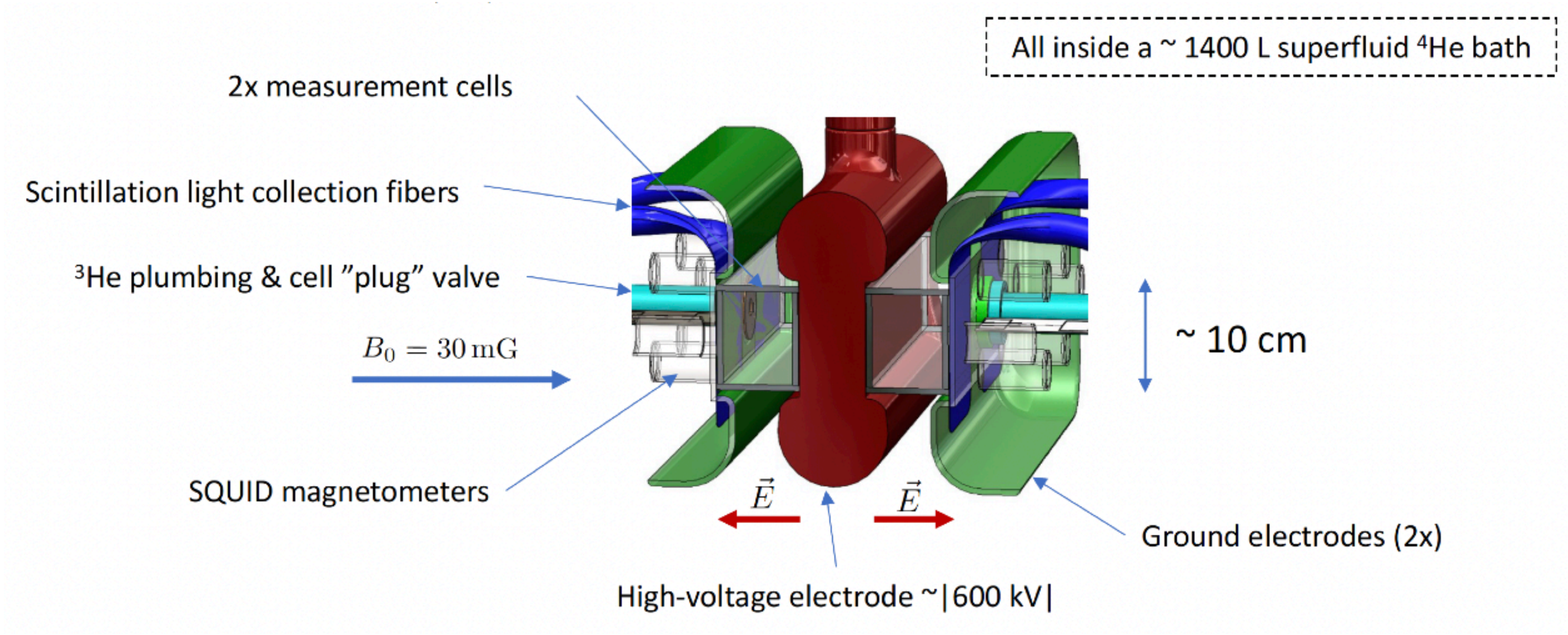
nEDMSF - a New Cryogenic Search for the Neutron Electric Dipole Moment

neutron EDM with SuperFluid ^{4}He (and ^{3}He)

Paul Huffman
for the nEDMSF Collaboration

Thanks to Kent Leung (Montclair St) for slides

nEDMSF: UCNs + superfluid ^{4}He + polarized ^{3}He

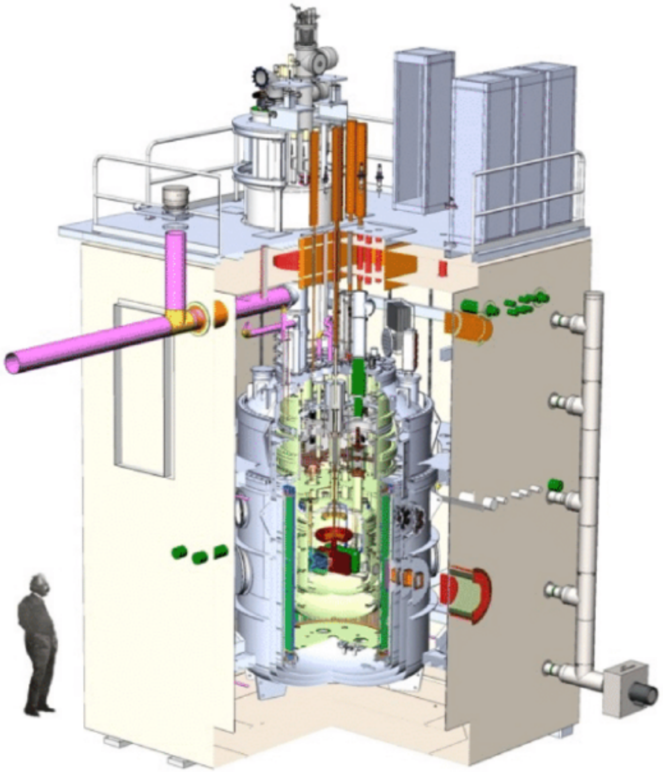


- Two cell setup with E-field relative to B-field opposite in each cell.
- > 95 % polarized ^{3}He loaded into cell (dissolved in isotopically-pure superfluid ^{4}He at 0.4 K).
- ^{3}He serves as a comagnetometer and UCN spin analyzer

Golub/Lamoreaux

nEDMSF's Approach

- Funding for the "legacy" nEDM@SNS was cancelled by US Department of Energy (Office of Science) in Nov. 2023
    - Idea proposed in 1995 (Golub/Lamoreaux)
    - Collaboration was formed in early 2000's
    - LANL -> SNS/ORNL
    - About half the apparatus was been constructed
    - Cancellation letter noted that the experiment had overcome "a number of impressive technical challenges ... and in some cases developing new technical solutions that have value on their own"
    - but … a "low state of technical readiness for critical subsystems" remained



NC STATE UNIVERSITY

nEDMSF's Approach

- Based on the investment to date, we are investigating partnering with European collaborators to build up the measurement technique in a **staged approach**.
  - **New international nEDMSF collaboration formed**
  - Neutron sources: **Institut Laue - Langevin (France) & European Spallation Source (Sweden)**
  - Incorporate what we learn AND new ideas into subsequent steps

Institut Laue-Langevin

European Spallation Source

NC STATE UNIVERSITY

European Support

We […] suggest an **evolution of the project's achievements towards a larger international collaboration** for a cryogenic neutron EDM measurement **hosted at the best possible neutron source in the world.**

[…] the **U.S. contribution to the new collaboration** would therefore be, in first order, the **in-kind transfer of equipment as well as operational support for the U.S. groups to participate**. […] the **US would remain the major player within the collaboration** with corresponding weight in key decisions regarding project evolution.

We […] give our **strongest support for the future nEDMSF project** […]. Beam time proposals of this collaboration were recently **evaluated by ILL's scientific subcommittee and the scientific excellence was clearly recognized**. The subcommittee highlighted the **strategical importance of this future-of-the-field-defining experiment** and **recommended ILL to support this program**. The critical importance of such a global nEDM program is also **endorsed by nuclear and particle physics communities** within the **NUPECC Long range plan and the European Strategy for Particle Physics.**

Ken Andersen ILL Director	Jacques Jestin ILL Science Director	Helmut Schober ESS Director	Giovanna Fragneto ESS Science Director

Staged Approach

- Proof-of-principle tests for 3 key techniques
  - Phase 1 (Institut Laue-Langevin's PF1B cold neutron beam)
    - Ultracold Neutron production in superfluid & detection of $n + {}^3He$ capture light in a (legacy) measurement cell (largely existing apparatus)
  - Phase 2 (Institut Laue-Langevin's PF1B cold neutron beam)
    - UCN production, detection of capture light & polarization (largely existing apparatus)
  - Phase 3
    - Superfluid HV test with Cavallo multiplier, realistic electrodes, measurement cell (significant existing apparatus)

NC STATE UNIVERSITY

International Collaboration for Phase I experiments at the Institut Laue-Langevin

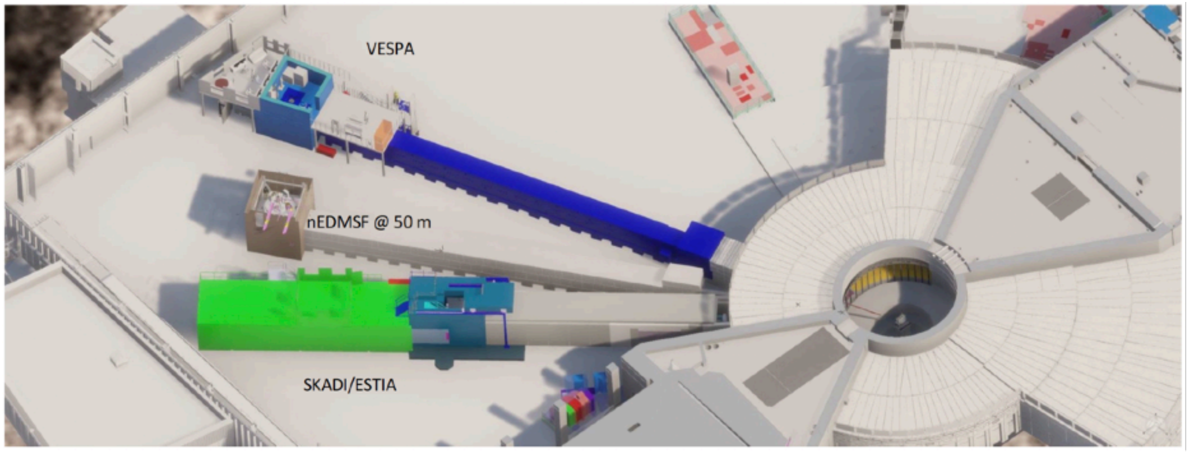
1	Brad Filippone	*Caltech*	**16**	Weijun Yao	*Oak Ridge National Laboratory*
2	Skyler Degenkolb	*Heidelberg University*	**17**	Maurits van der Grinten	*Rutherford Appleton Laboratory*
3	Hanno Filter	*Institut Laue Langevin*	**18**	David Milstead	*Stockholm University*
4	Tobias Jenke	*Institut Laue Langevin*	**19**	Peter Fierlinger	*Technical University of Munich*
5	Michael Jentschel	*Institut Laue Langevin*	**20**	Robert Georgi	*Technical University of Munich/FRM II*
6	Oliver Zimmer	*Institut Laue Langevin*	**21**	Thomas Neulinger	*Technical University of Munich/FRM II*
7	Benoit Clément	*Laboratoire de Physique Subatomique & Cosmologie*	**22**	Florian Piegsa	*University of Bern*
8	Kent Leung	*Montclair State University*	**23**	Doug Beck	*University of Illinois at Urbana-Champaign*
9	Robert Golub	*North Carolina State University*	**24**	Chen-Yu Liu	*University of Illinois at Urbana-Champaign*
10	Paul Huffman	*North Carolina State University*	**25**	Chris Crawford	*University of Kentucky*
11	Ekaterina Korobkina	*North Carolina State University*	**26**	Wolfgang Korsch	*University of Kentucky*
12	Vince Cianciolo	*Oak Ridge National Laboratory*	**27**	Brad Plaster	*University of Kentucky*
13	Paul Mueller	*Oak Ridge National Laboratory*	**28**	Valentina Santoro	*University of Lund*
14	John Ramsey	*Oak Ridge National Laboratory*	**29**	Clark Griffith	*University of Sussex*
15	Andy Saunders	*Oak Ridge National Laboratory*	**30**	Steve Lamoreaux	*Yale University*

Staged Approach II

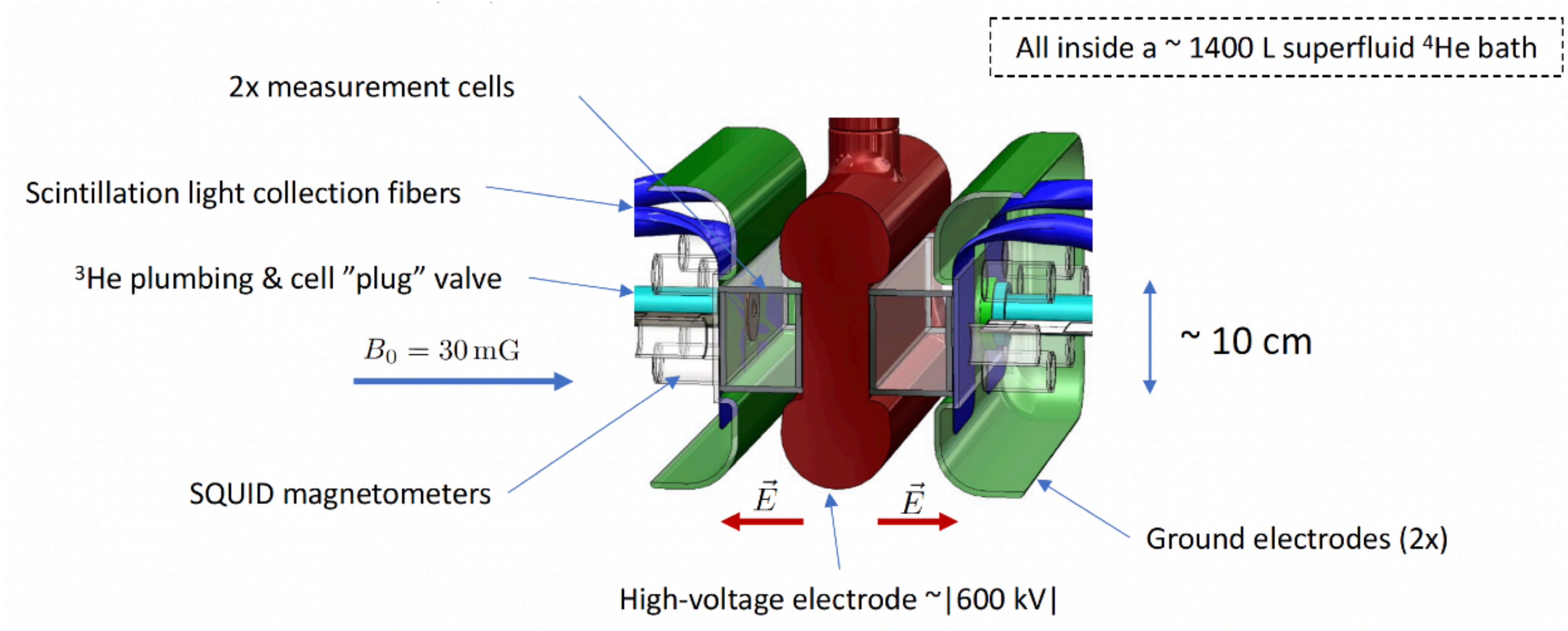
- Three major areas requiring further development
  - High voltage
    - Complete development of HV delivery, robust electrode material
    - LN_2 testing of Cavallo multiplier at LANL ongoing
  - Composite vessels
    - Vessel holding ~1400 L of superfluid helium in AC magnetic field (spin dressing)
    - Have started working with Rutherford Appleton Laboratory/Sussex to continue existing development
  - Helium-3 services
    - Completion of system to add polarized ^{3}He, then remove it after measurement
- Many opportunities for new contributions!

Staged Approach III

- The physical scale of a superfluid experiment is difficult to accommodate at ILL
- Have started working with ESS collaborators on a possible beamline design
- Published ANNI beamline design has ~10 x flux of at SNS*
    - Engineering on beamline @ ESS started (March 2025)
    - Expect higher cold neutron flux (at 1 meV) c.f. SNS



nEDMSF: UCNs + superfluid ^{4}He + polarized ^{3}He

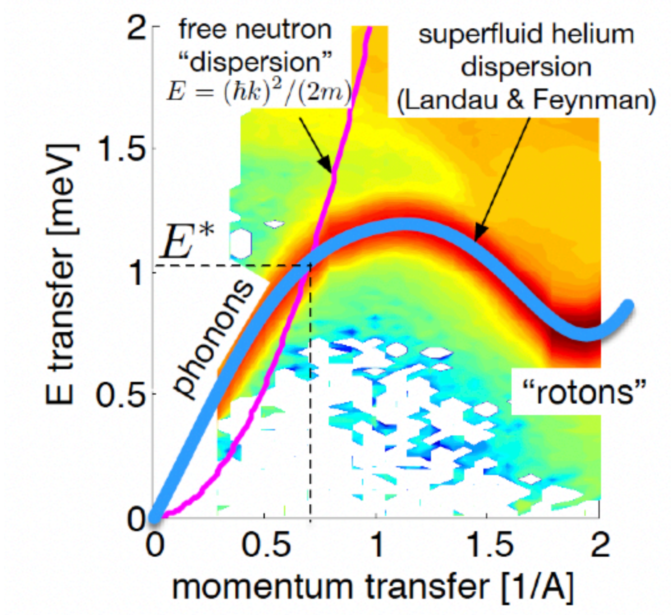


- Two cell setup with E-field relative to B-field opposite in each cell.
- > 95 % polarized ^{3}He loaded into cell (dissolved in isotopically-pure superfluid ^{4}He at 0.4 K).
- ^{3}He serves as a comagnetometer and UCN spin analyzer

Golub/Lamoreaux

Roles of the Superfluid ^{4}He

- Cold neutrons (1 meV, 12 K) scatter off phonons in superfluid ^{4}He to become UCNs (< 160 neV, “2 mK”)



Andersen et al. J. Phys. Condens. Matter (1994)

Roles of the Superfluid ^{4}He

- "Super-thermal" because UCNs ($\lesssim$ 2 mK) remain out of thermal equilibrium with the helium.
  - Dominant UCN loss is two-phonon scattering:

$$\tau_{\mathrm{up,2-phonon}} = (100\,\mathrm{s\,K}^7)\,T^{-7}$$

Golub & Pendlebury, Physics Letters A (1977)

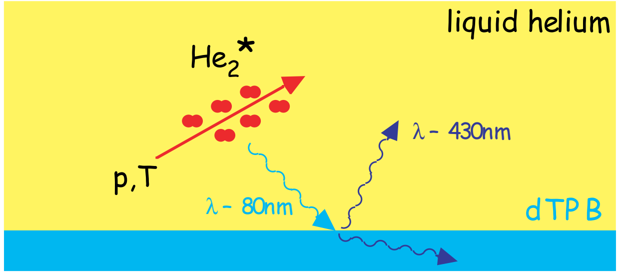
  - At T = 0.4 K, up-scattering (or "thermalization") $\tau_{\mathrm{up}} \approx$ 20 hr.
- Neutron absorption by ^{4}He is zero in isotopically pure ^{4}He.

NC STATE UNIVERSITY

Roles of the Superfluid ^{4}He

- Superfluid ^{4}He scintillates at ~ 80 nm (EUV) which is used to detect n-^{3}He capture events

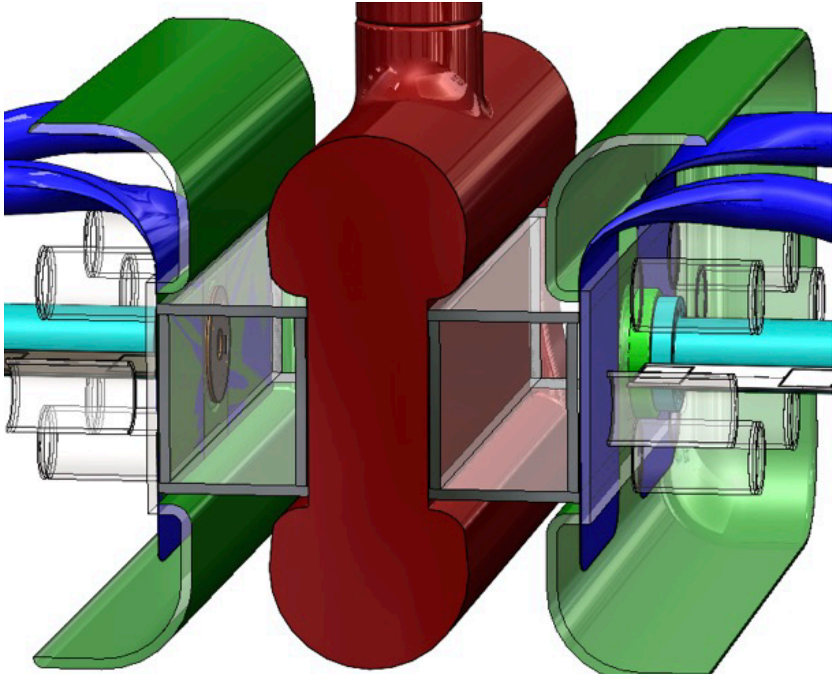
$$n + {}^3He \rightarrow p + T$$



- ^{3}He atoms scatter off phonons
  - mean-free-path ~ $T^{7.5}$
  - important for key “false EDM” systematic control

NC STATE UNIVERSITY

How Does the Experiment Work?

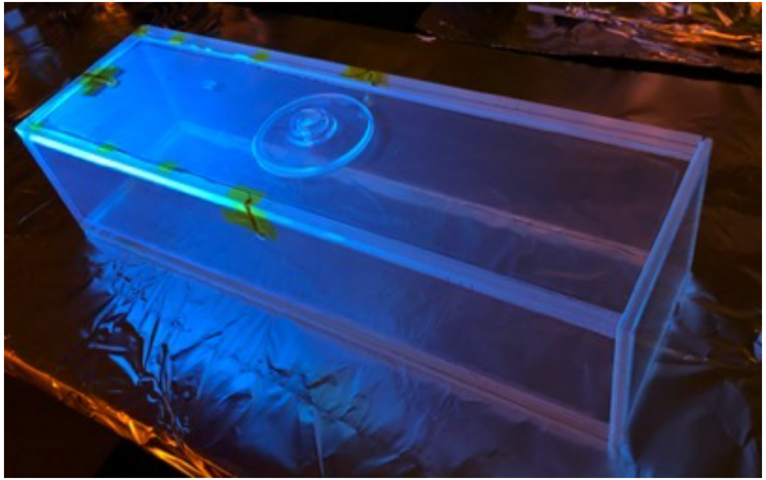


- Load two measurement cells with polarized ^3He and polarized UCN
- Strong E field, weak B field
- Rotate spins and perform a precession measurement
- Two different techniques for measuring the EDM

Measurement Cells

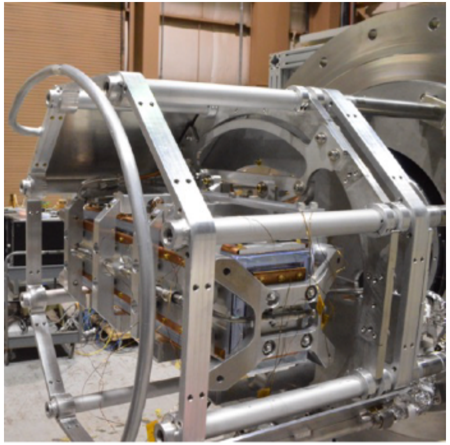
- ID: 7.5 cm (W), 10 cm (H), 40 cm (D) rel. to beam.
- Inner walls: deuterated PS + d-TPB (for fluorescent properties to detect 80 nm scintillation light).
- Neutron wall potential = 170 neV
- Goal wall loss τ_{cell} = 2,000 s

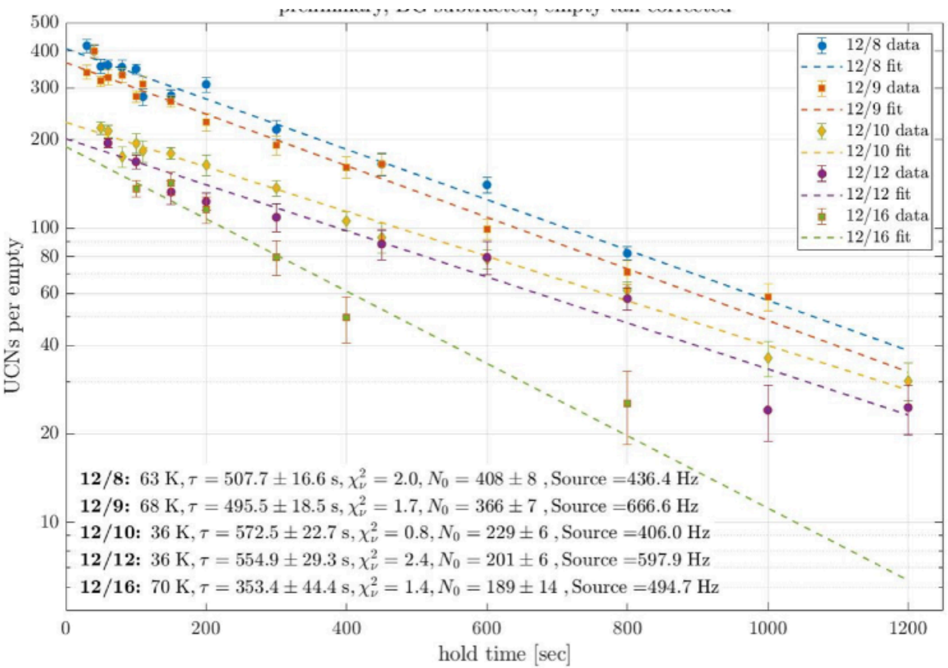
$$\tau_{\beta+cell} = \left(\tau_{\beta}^{-1} + \tau_{cell}^{-1}\right)^{-1} = 610\,\mathrm{s}$$



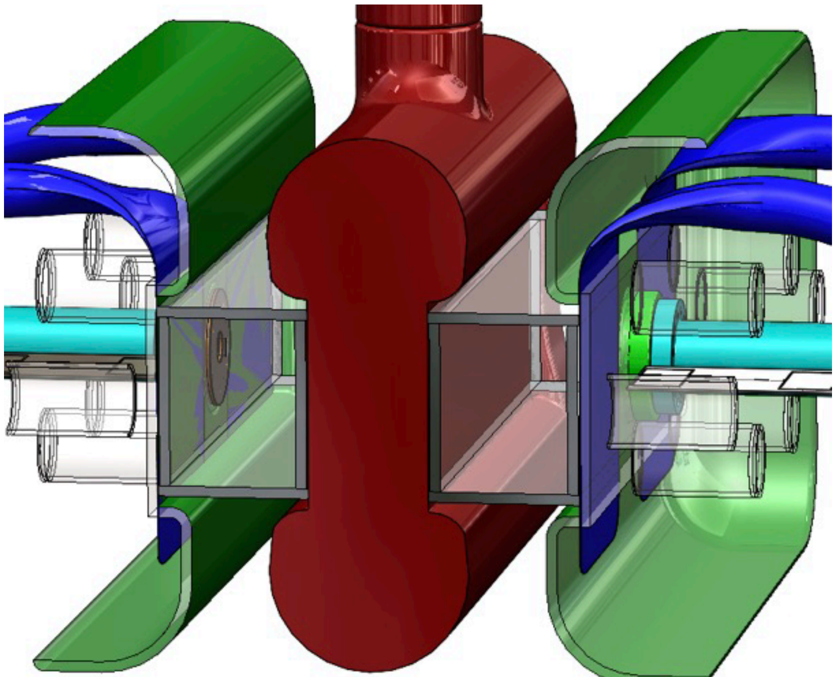
Measurement Cells

- Last cell tested at LANL UCN source had $\tau_{\beta+\mathrm{cell}}$ of 570 ± 20 s.
  (Single exponential decay only observed)





How Does the Experiment Work?

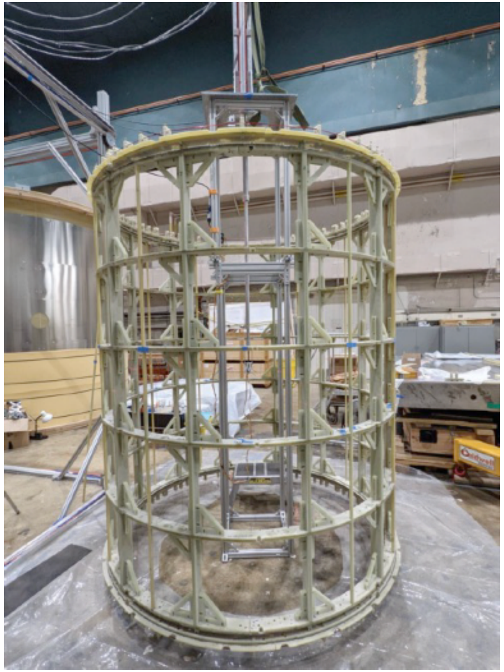


- Load two measurement cells with polarized ^3He and polarized UCN
- Strong E field, weak B field, in a well controlled environment.
- Rotate spins and perform a precession measurement
- Two different techniques for measuring the EDM

NC STATE UNIVERSITY

Magnetic Field System

- B_0 system complete and tested at 4K
- Magnetic shield house complete
- Spin-dressing coils designed, not constructed

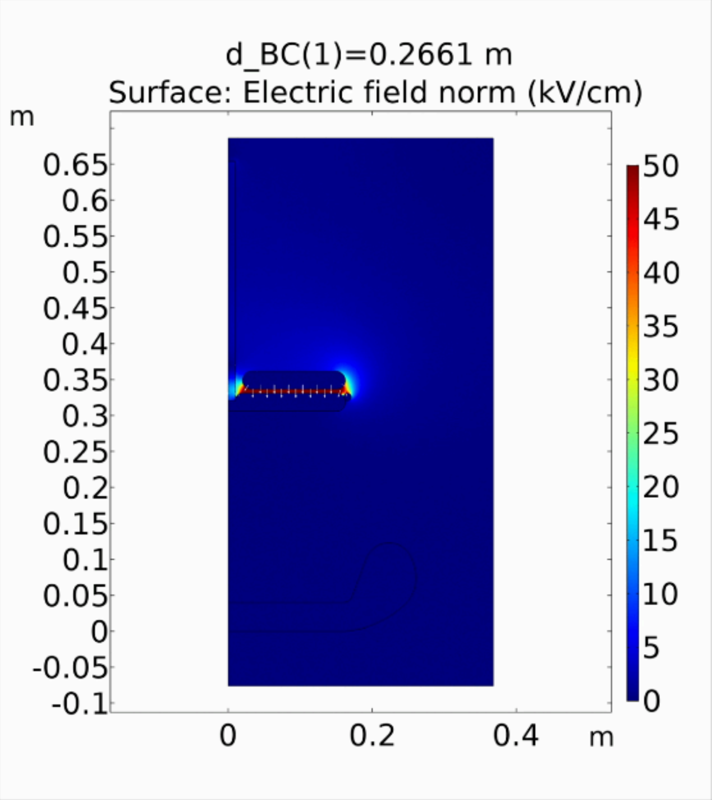


B_0 Coils

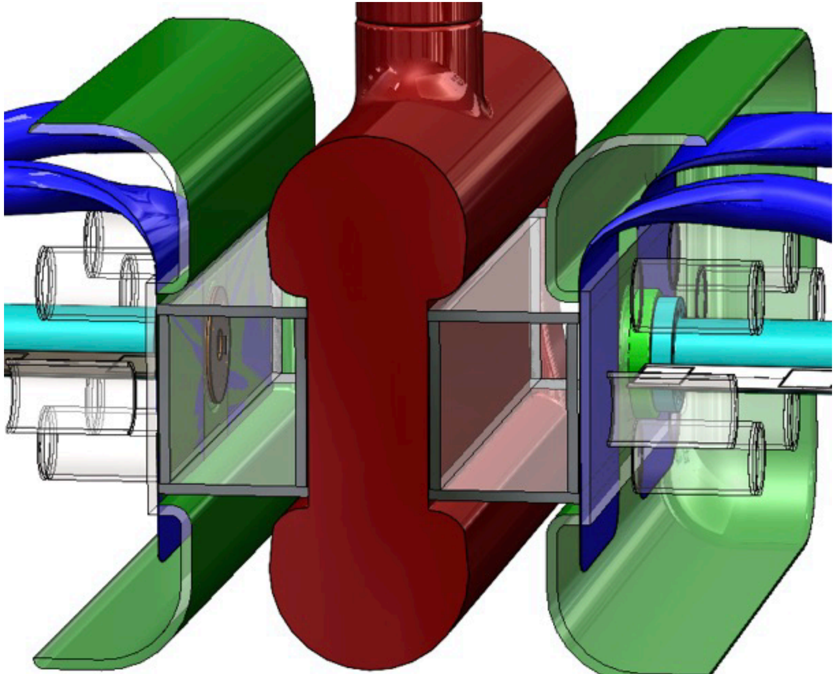
Magnetic Shield House

Electric Field System

- High-voltage ~|600 kV|
- A direct feedthrough is not practical (large vacuum/cryogenic feedthroughs will breach Faraday cage shielding the SQUIDs)
- Use Cavallo technique that utilizes induction and a moving electrode to attain the desired electric field using a 50 kV feedthrough.



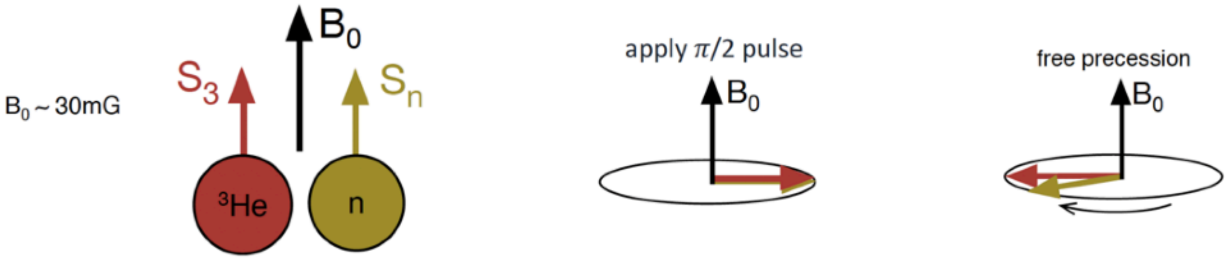
How Does the Experiment Work?



- Load two measurement cells with polarized ^3He and polarized UCN
- Strong E field, weak B field, in a well controlled environment.
- Rotate spins and perform a precession measurement
- Two different techniques for measuring the EDM

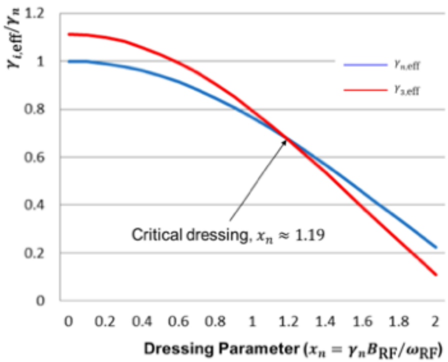
Two Measurement Techniques

- Free Precession



- Dressed Spin

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

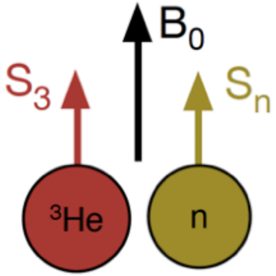


Free Precession

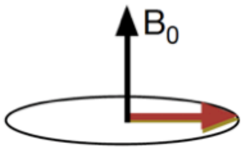
$^{3}He + n \rightarrow t + p$

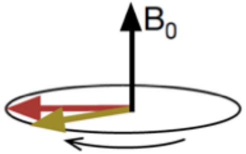
σ(parallel) < 10^2 b

σ(opposite) ~ 10^4 b



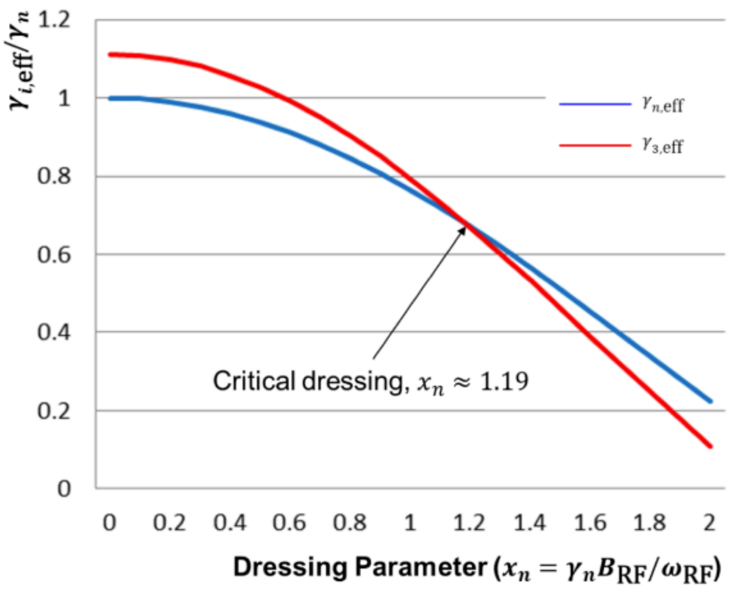
- $1 - \vec{p}_3 \cdot \vec{p}_n = 1 - p_3 p_n \cos[(\gamma_n - \gamma_3)B_0 + 2dE]\, t$
- Detect ^{3}He precession rate with SQUIDS.
- $|\gamma_n - \gamma_3| = |\gamma_3|/10$ – Sensitivity to magnetic fields is reduced by an order of magnitude!
- Fractional concentration needed:
  $x = {}^3He/{}^4He \sim 10^{-10}$ ($n_3 \approx 2 \times 10^{12}$ cm^{-3})





Dressed Spin

- Spins of UCN and ^{3}He precess in a plane perpendicular to the holding field
- Oscillating magnetic field perpendicular to holding field causes an oscillation in the spin direction relative to this plane and thus modifying the precession frequency
- UCN and ^{3}He precession frequencies can be made identical, so-called "critical dressing".
- Increases the statistical precision by ~x2 and reduces certain systematic effects.



$$\boxed{\gamma^{\mathrm{eff}} = \gamma J_0(\gamma\, B_{\mathrm{RF}}/\omega_{\mathrm{RF}})}$$

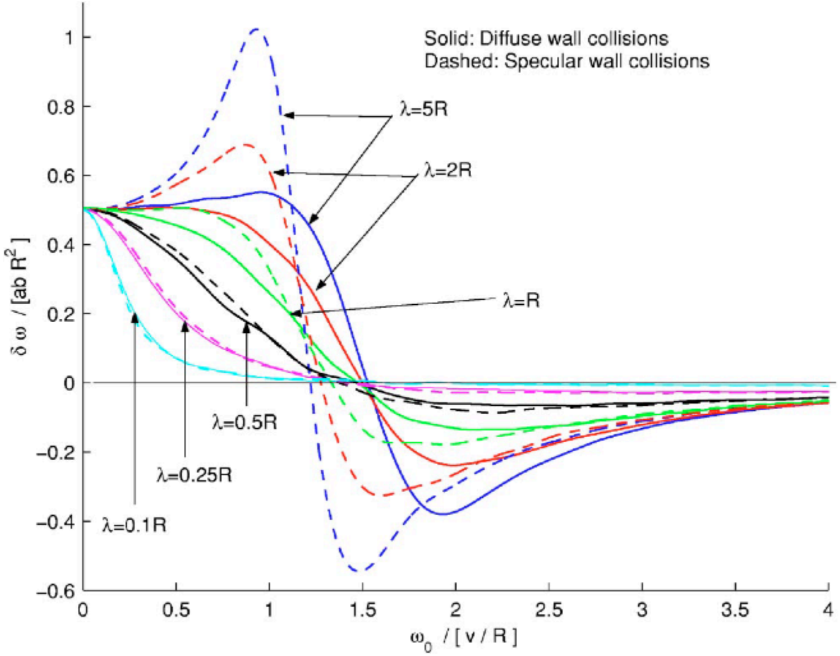
NC STATE UNIVERSITY

Systematics

- From interaction between the motional field and magnetic field gradients ("geometric-phase *v* x *E* induced false EDM")
- Can change ^{3}He-phonon scattering mean-free-path by changes in superfluid temperature:

$$\lambda_{3\mathrm{He}} \approx 0.077\,\mathrm{cm} \times \left(\frac{0.45\,\mathrm{K}}{T}\right)^{15/2}$$

- Can tune temperature to make false EDM zero by scanning *T* !



NC STATE UNIVERSITY

Statistical Sensitivity

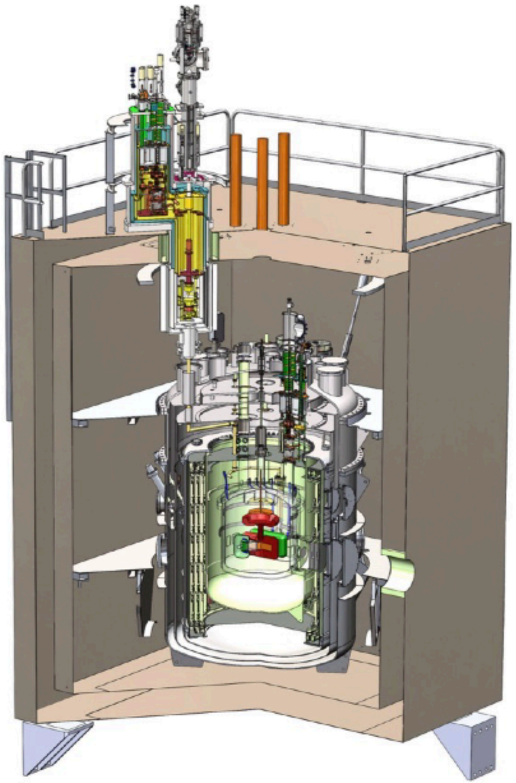
$$\sigma(d_n) \sim \frac{\hbar}{2\alpha E T \sqrt{N}}$$

$E =$ electric field	75 kV/cm in superfluid ^{4}He @ ~ 2 atm pressure vs ~ 10 kV/cm in vacuum
$\alpha =$ polarization contrast	(UCN & ^{3}He polarization ~ 98%)
$T =$ precession time	(we can use 1000 s vs. ~ 200 s for room temp. experiments)
$N =$ no. detected neutrons	2-3x improvement on running/close-to-running 10^{-27} e.cm experiments. We have high-density in small cells which reduces systematics (see later)

Predicted sensitivity: 300 live days of data (e.g. 3 years running) $\sigma(d_n) = 1.7 \times 10^{-28}\ e{\cdot}\mathrm{cm}$

Conclusions

- The cryogenic UCN + ^{3}He + superfluid scheme offers many advantages to reach 10^{-28} e•cm sensitivity
- We are exploring a reformulation of the experiment with our European colleagues using a staged approach
- Significant amount of show-stoppers have been solved and a many key components of the apparatus exists



NC STATE
UNIVERSITY

NC STATE UNIVERSITY

Legacy Experiment Apparatus

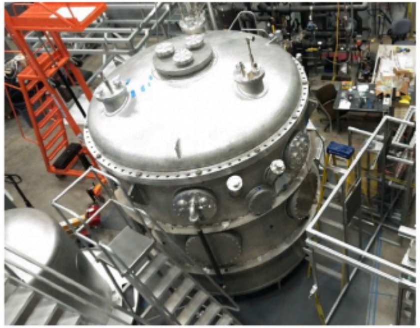
Main subsystems

1. Superconducting magnet and shield: B_0 = 1-3 μT + flip, trim & *dressing* coils (Caltech, UK, ORNL, …)
   - Large (5 x 5 x 7 m^3) magnetically shielded enclosure
2. Central detector system: acrylic measurement cells, HV, light collection, SQUIDS (LANL, ORNL, Caltech, Montclair, …)
   - Dilution refrigerator I: ~75 mW @ 250 mK
3. Polarized ^{3}He system: atomic beam source, injection, purification (UIUC, MIT, …)
   - Dilution refrigerator II: ~75 mW @ 250 mK
4. Cryostat vessels: aluminum, composite (ORNL, …)
5. Neutron transport (UK, ORNL, …)
6. DAQ, slow controls (ORNL, …)
7. Simulation (ORNL, UK, Caltech, Montclair…)
8. Systematics and operational systems apparatus (NCSU, Caltech, Montclair …)

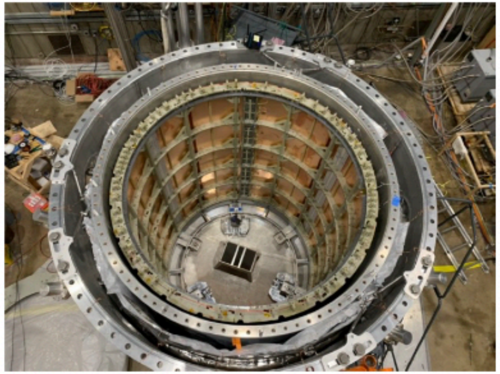
NC STATE UNIVERSITY

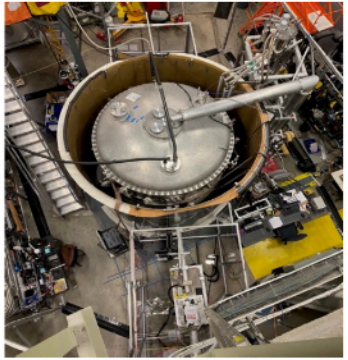
Hardware Status: Magnet System


B_0 cosθ coil


Magnet system closed for cold test at ORNL


Completed magnetic shielded room at Imedco: Hägendorf, CH


Completed B_0 coil, sc shield, vacuum chamber at ORNL

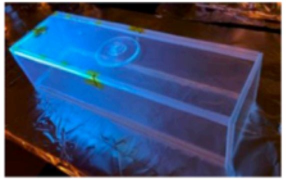

Magnet system in cold beam test at ORNL (summer '23, '24)

NC STATE UNIVERSITY

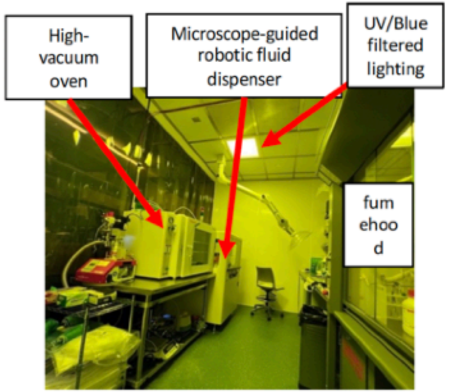
Hardware Status: Central Detector System

Completed cryostat top flange, tail for CDS testing

Half-scale HV test (T=0.4 K)



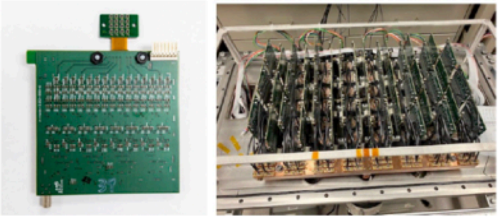
Measurement cell



Small scale HV
N. S. Phan, et al *J. Appl. Phys.* 129, 083301 (2021)

OVC composite vessel

Full-size stainless Cavallo electrodes

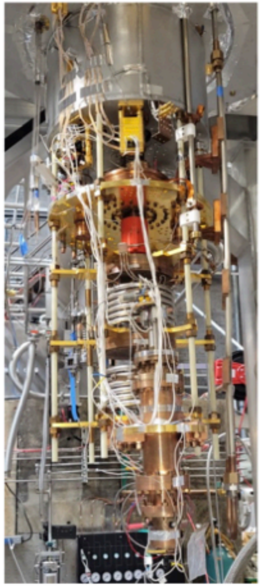


SiPM light collection

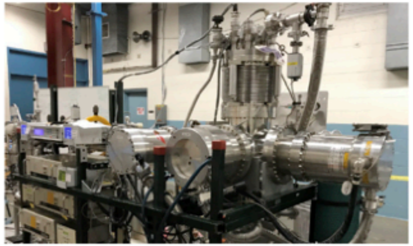
- To do: final electrode material choice & full-sized multilayered cells with thin windows

Hardware Status: Polarized ^{3}He System

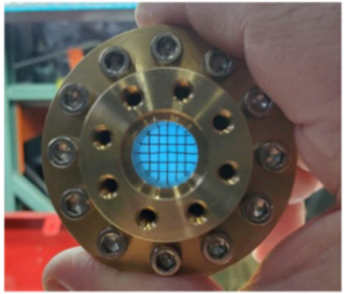
Dilution refrigerator/test cryostat



Dilution refrigerator + film burner
(75 mW at 250 mK)



Atomic beam source



Nuclepore filter: magnetic particles

- To do: injection system commissioning