SOS@PULSTAR test bed for nEDM@SNS

E. Korobkina on behalf of nEDM@SNS collaboration, North Carolina State University, Raleigh, NC

nEDM @SNS experimental strategy

The nEDM@SNS apparatus is designed to implement the nEDM measurement strategy laid out by Golub and Lamoreaux more than two decades ago. While technically rather challenging, at present this strategy is the only one with potential to reach both statistical and systematic uncertainties of nEDM value in 10^{-28} range.

Key points of nEDM@SNS experimental strategy

Cryogenic environment: the main challenge for nEDM experiments at present level of accuracy is requirement of an extremely precise magnetic environment. This includes the uniform DC holding field (called B0) for spin precession and other AC fields (up to 3 kHz) for spin manipulation. The nominal B0 field must have coherence times due to transverse relaxation (T2) greater than 10^4 s. In addition, frequency shifts linear in E that arise due to field gradients must be below 2 x 10^{-28} e-cm for both 3He and neutrons. These goals require uniform gradients in B0 to be < 3 ppm/cm, and uniform gradients in transverse fields to be < 1.5 ppm/cm. Furthermore, we require ambient environmental noise to be reduced to less than 1 part in 10^4 and drifts to be stable to better than 1 part in 10^7
Working at cryogenic temperatures naturally allows us to use *superconducting* shield and coils, the only way to satisfy this stringent field conditions.
Furthermore, cryogenic allows to use LHe instead of vacuum. There are several advantages to use LHe instead of working in vacuum:

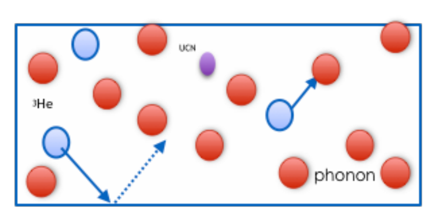
Higher electric field *E* because LHe is better electric isolator then vacuum

Longer observable time τ : LHe has the same zero absorption for neutrons as vacuum. In addition, at operating temperatures below 0.5K the dominant cause of UCN losses at room temperature , upscattering, becomes negligible. Therefore, with a measurement cell made from low adsorbing deuterated material storage time can be as long as 500-1000 sec range.

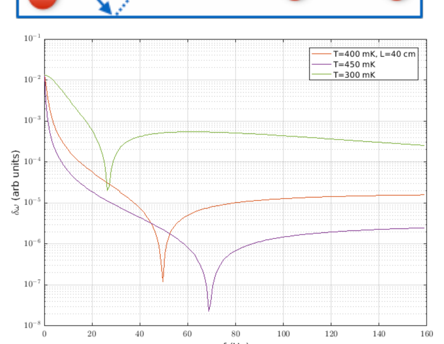
Higher counting rate ***N***: LHe is one of the best materials for production of storable neutrons, called Ultra-Cold Neutrons(UCN) from cold neutrons. Cold neutrons can be delivered directly through the walls to the measurement cell, producing UCN on site and avoiding usual significant transport losses from an external UCN source.

In addition to increasing the statistical figure of merit, LHe environment allows significantly increase control of systematic.

He-3 co-magnetometer: LHe naturally allows to use polarized He-3 as co-magnetometer (with optional SQUID readout). It was first proposed by Ramsey in 1984, but practical issues prevented its use in experiments till now. Since we need relatively small He-3 concentration (about 10^{-10}), this amount can be produced by Atomic Beam Source with polarization 99% to ensure highest possible sensitivity.



Full Control of Geometric Phase effect: The main advantage of using He-3 diluted in LHe is that this combination allows full control of Geometric Phase Effect of He-3. Indeed, since this effect is caused by correlated motion and the correlation can be destroyed by increasing collisions with buffer gas, LHe provides a perfect substitute for a buffer gas , i.e. phonon gas, which density is strongly dependent on temperature. Lowering T down to about 0.3K the Geo-effect can be maximized to check field gradients. Operating at about 0.45K we can minimize it.



C. M. Swank, A. K. Petukhov, and R. Golub, Phys. Rev. A 93 , 062703 (2016).

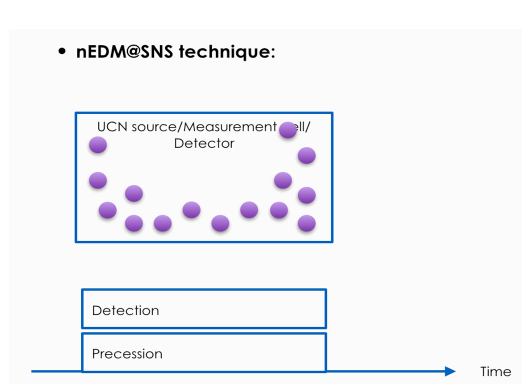
Two new independent techniques of nEDM detection:

• LHe environment with diluted He-3 allows to detect precession frequency of neutrons via scintillations, produced when neutron is captured by polarized He-3: (i) LHe is scintillator; (2) He-3 absorption cross section is strongly spin dependent. Therefore, first way of detecting nEDM is to use standard free precession technique, where spin rotation of neutrons is detected via scintillations, while He-3 spin precession is detected by SQUID. The new thing is that precession and detection are not separated in time and space. It will be done directly in the measurement cell during 500 sec of the precession cycle.

•The Larmor precession of neutron is slightly off it's value for He-3 in the free precession mode. Second way of detecting nEDM is to "dress" spins using RF field to equalize both frequencies. There are three advantages: (1) it allows to increase statistic (because of decreased neutron absorption rate); (2) the limits for the uniformity of the spin dressing field are reduced by roughly a factor 15, or < 45 ppm/cm; (3) compare to the free precession this technique has different systematic and no use of SQUIDs.

assuming a total live time of 300 days (which we expect to achieve after three years of calendar running), we obtain a statistical sensitivity from the free precession measurement of

$$\sigma_d^{TOT} = 3.3 \times 10^{-28} e - cm$$

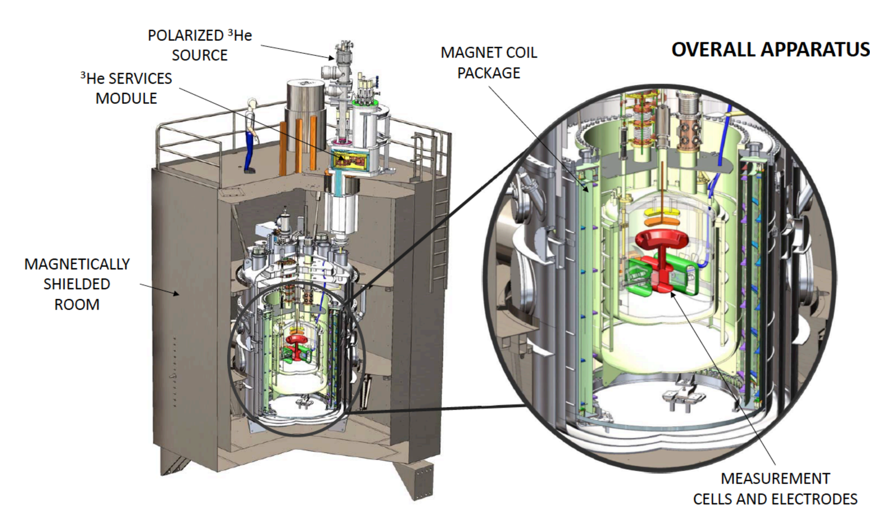


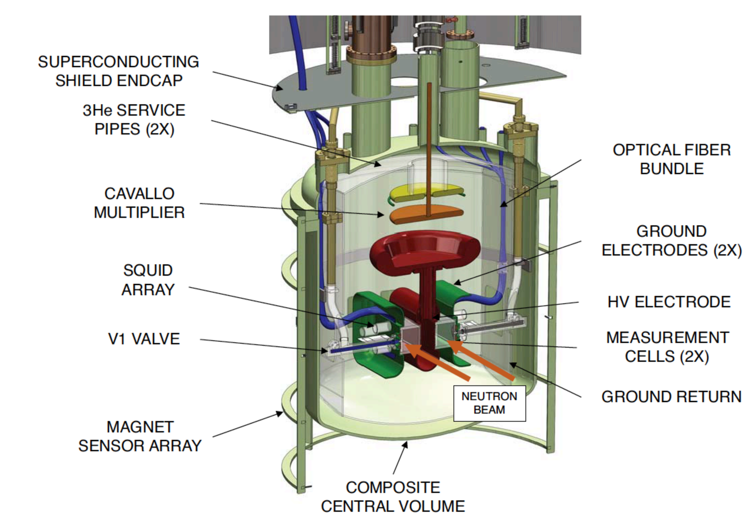
assuming the same a total live time of 300 days, we obtain a statistical sensitivity for Critical Spin Dressing mode of

$$\sigma_d^{TOT} = 2.1 \times 10^{-28} e - cm$$

nEDM@SNS apparatus

The high voltage electrode is shown in red and is connected to the lower plate of the voltage amplifying system. The two ground electrodes are shown in green. The polarized neutron beam (0.89 nm) is parallel to the electrodes and enters through a series of windows in the various magnetic and thermal shields. The magnetic fields are produced by a set of cylindrical coils coaxial to the vertical direction and conceived as a module, which can be removed as a whole from the apparatus. Optical fibers, which carry the scintillating light signal to the silicon photo-multipliers are located only on the electrode ground side of the measurement cells. The system for handling the 3He is shown above the main cryostat. 3He atoms, polarized by passing an atomic beam through a strong magnetic field gradient produced by permanent magnets, are incident on a surface of liquid 4He (injection module) to which they are attracted by a relatively strong binding energy of 2.8 K. They are then transported by phonons (heat flush technique) to the two measurement cells. After each measurement cycle, partially depolarized 3He are removed from the measurement cells and concentrated and recycled by means of heat flush and evaporation. The high voltage is fed in from the top of the main apparatus and used to charge a capacitor. The charge can be transferred from this capacitor to the electrodes, multiple times in such a way that the voltage on the electrodes can be built up to be several times greater than the input voltage, somewhat similar to a van der Graaff generator (Cavallo multiplier). Most of the apparatus is contained within a room temperature magnetic field enclosure (based on two layers of mu-metal) to reduce the ambient field and minimized magnetic gradients.

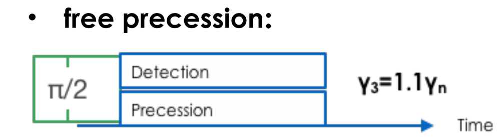




SOS@PULSTAR: NMR test bed for the new experimental technique of spin manipulations

The nEDM@SNS apparatus is optimized for data taking, but has 2-3 month turn around. To accelerate our learning curve of the new techniques we have designed and are at present commissioning a smaller apparatus, which allow us to perform NMR studies with polarized He-3 and storable neutrons. We call it Systematic and Operational Study apparatus at PULSTAR reactor UCN source, where we expecting to see first neutrons next year.

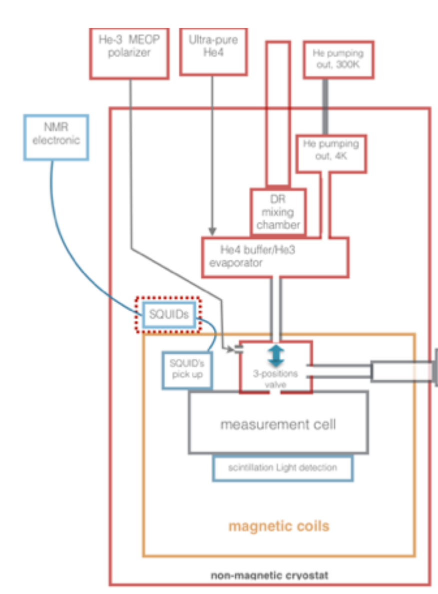
• **free precession:**

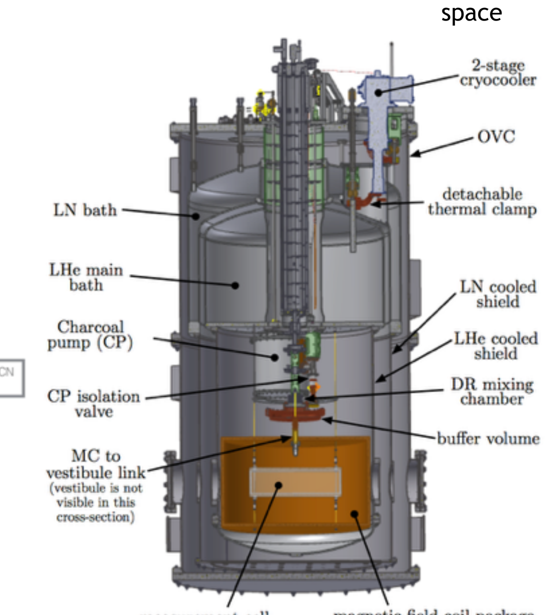


need to reproducibly set initial phase to 1 mrad (or 0.06°) for each measurement
pseudomagnetic frequency shift: size proportional to the tipping angle

• **critical dressing:**

Spin dressing have been done separately with neutrons or He-3, never with two species together. Need scanning of large parameter space





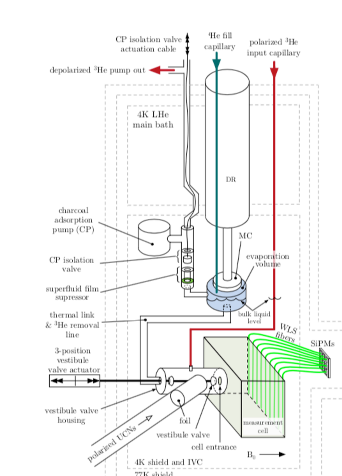
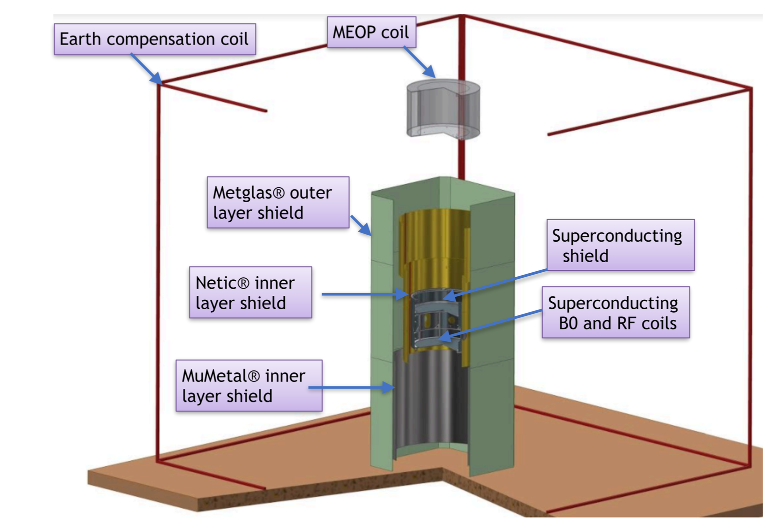


FIG. 2. Schematic of the SOS apparatus. The magnetic coil package and the SQUID magnetometers with their pick-up coils are not shown. CAD drawings of the apparatus are shown in Figs. 3 and 4.

	nEDM@SNS	*SOS apparatus*
measurement cell	2× cells	1× full-sized cell, designed so can be installed in nEDM
high voltage	direct-feed and then Cavallo	none
0.4 K superfluid He	∼ 1000 L	∼ 5 L
ultracold neutrons	UCN production inside of cell with the FNPB cold neutron beam	UCNs fed in from external UCN source (PULSTAR UCN source or LANL UCN source)
polarized ^{3}He	ABS system: $x_3 \sim 10^{-10}$ and $P_3 \sim 98\%$)	MEOP system: x_3 can reach 10^{-7} with $P_3 \sim 70\%$
magnetic field gradients	< 100 nG/cm or < 3×10^{-6} cm^{-1} for $T_{\text{gradient},^3\text{He}} > 10,000$ sec	< 500 nG/cm or < 1.5×10^{-5} cm^{-1} for $T_{\text{gradient},^3\text{He}} > 400$ sec
measurement cycle rate	30×/day (dead time = 400 s, 24 hours/day)	3×/day (dead time = 2 hrs, 9 hours/day)

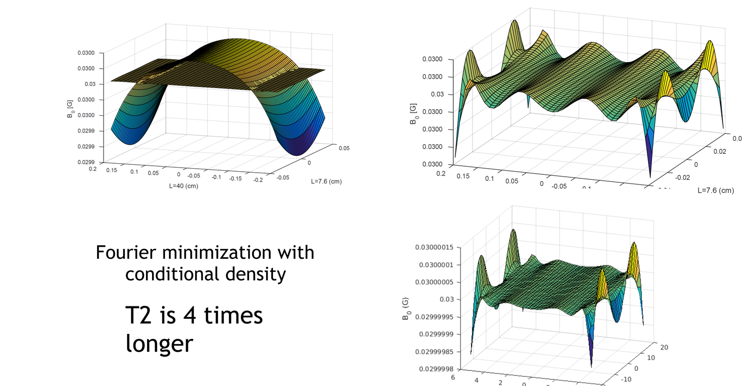
SOS@PULSTAR apparatus

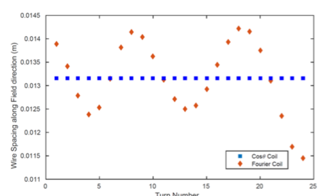
Magnetic system



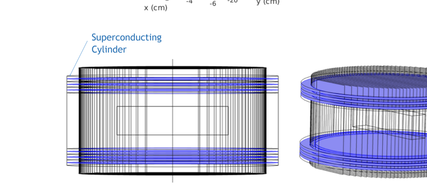
Calculated T2 for B0 is around 5000s, T2 for Spin dressing is 7000s

Field from Fourier Coefficient Minimization (Fourier Coil) vs Cos θ



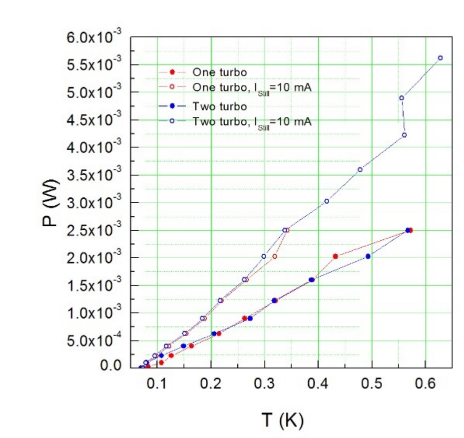


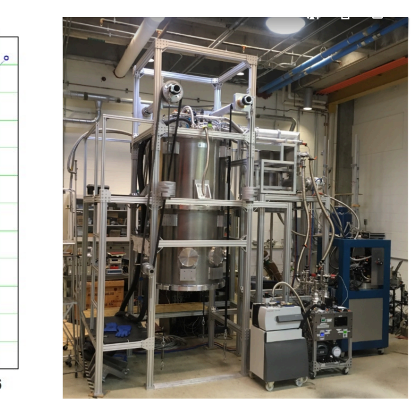
Wire spacing shows high order corrections

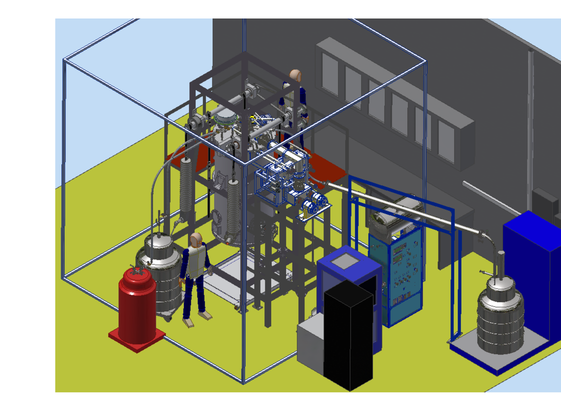


Gradient Coils for T_1 are wrapped on the same (but fewer) positions.

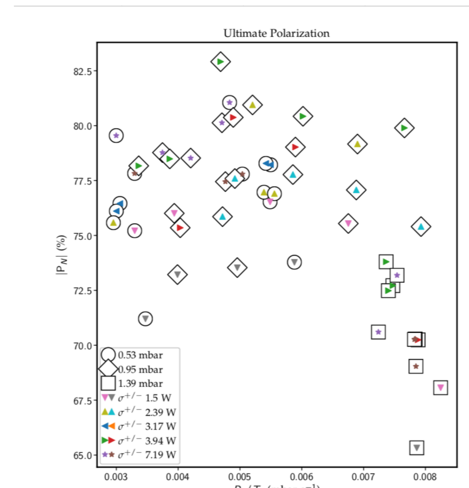
Dilution refrigerator and cryocooler with non-magnetic cryostat



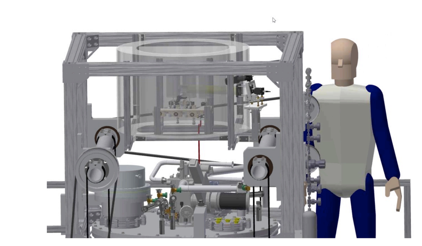


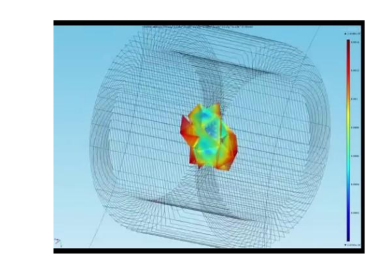


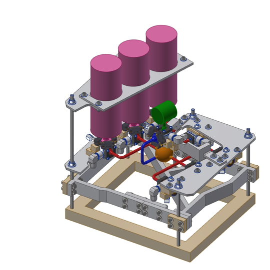
Polarized 3He source: MEOP and diluting manifold

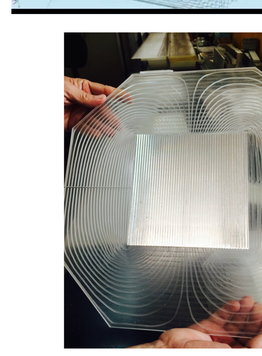


Ultimate polarization achieved in bench top setup as a function of laser power, sample pressure, and discharge intensity. P_N is calculated with Lorenzon's f_p, so all points should be further decorated with a ±2% error bar.









UCN source