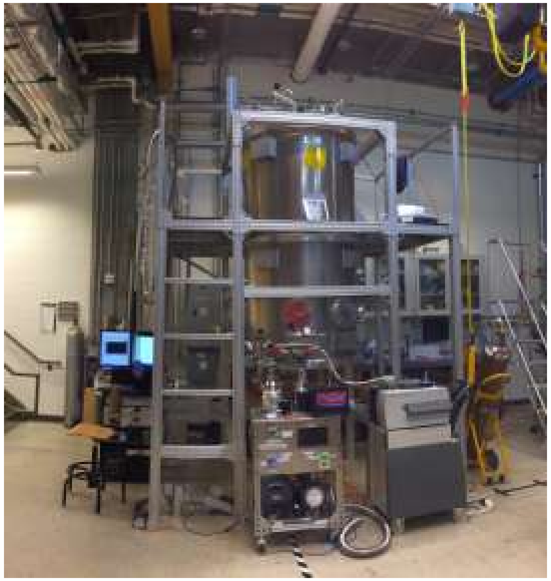
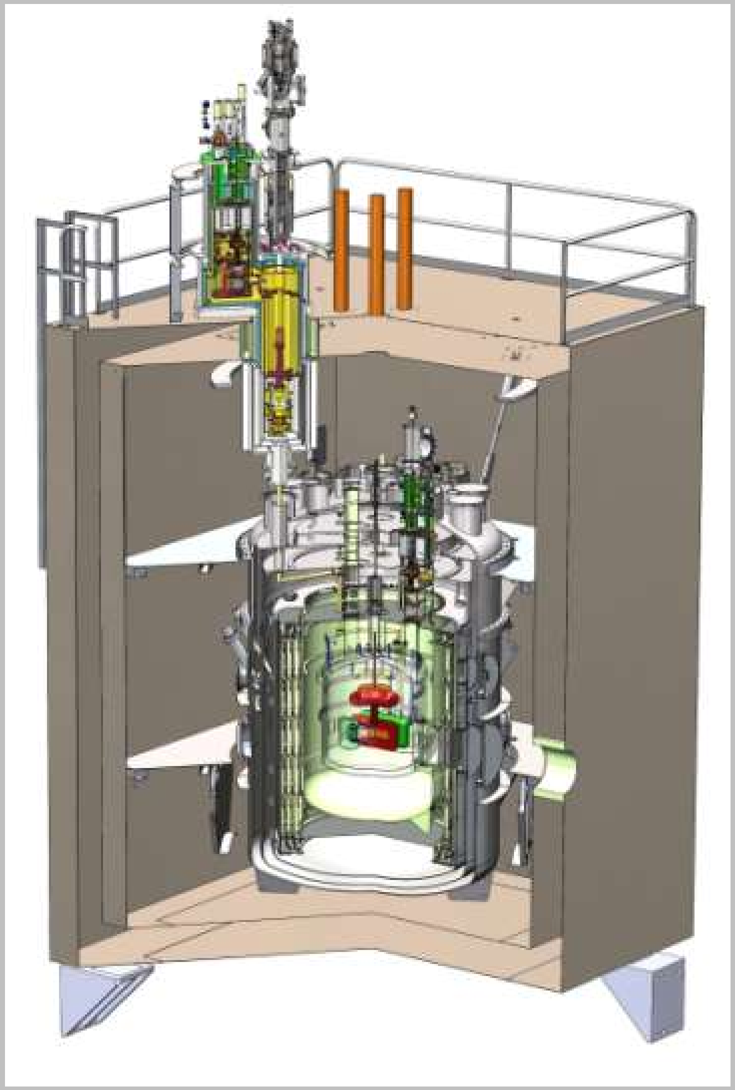
Systematic and Operational Studies apparatus SOS@PULSTAR

E. Korobkina
on behave of EDM@SNS
collaboration



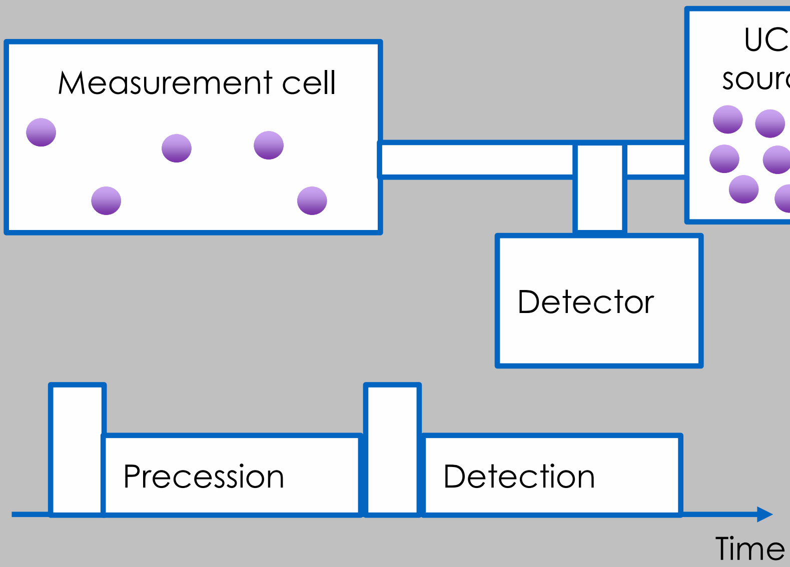
nEDM at SNS apparatus's subsystems



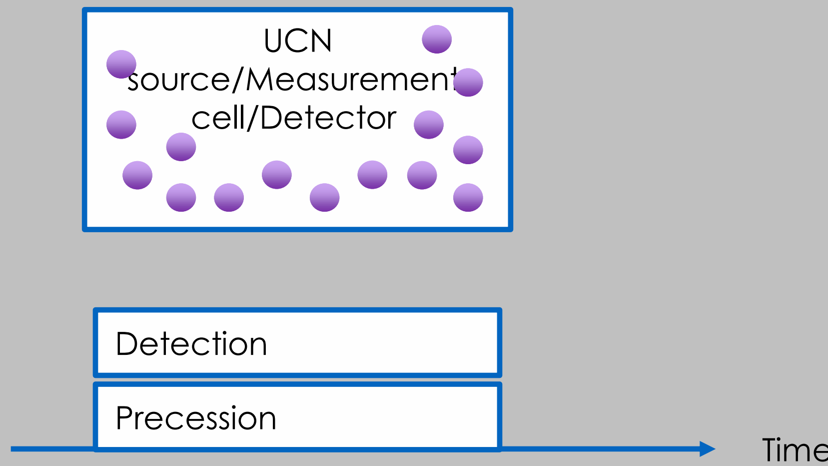
- **nEDM@SNS project will be measuring neutron EDM in cryogenic environment**
- **Cryogenic setup allows to reach ultimate statistical and systematic uncertainties down to 10^{-28} range**
- **The apparatus itself is split into modular subsystems:**
  - **central detector**
  - **magnetic package**
  - **He-3 services**
  - **neutron guide**
- **A separate subsystem of the project is a smaller cryogenic setup called Systematic and Operational Studies at PULSTAR reactor (SOS@PULSTAR).**

Motivation for SOS apparatus

- **Traditional nEDM technique:**



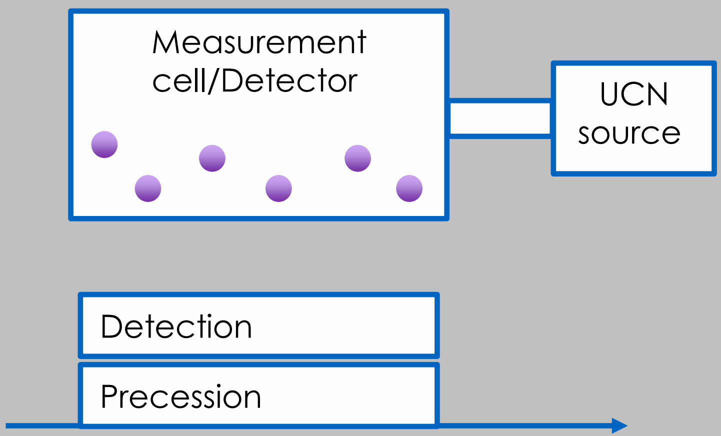
- **nEDM@SNS technique:**



- **This unique feature provides independent information on potential unknown systematic u**
- ***Requires novel techniques for which detailed studies are required to optimize statistical s***
- ***The studies don't require electric field, only magnetic system for spin gymnastic***

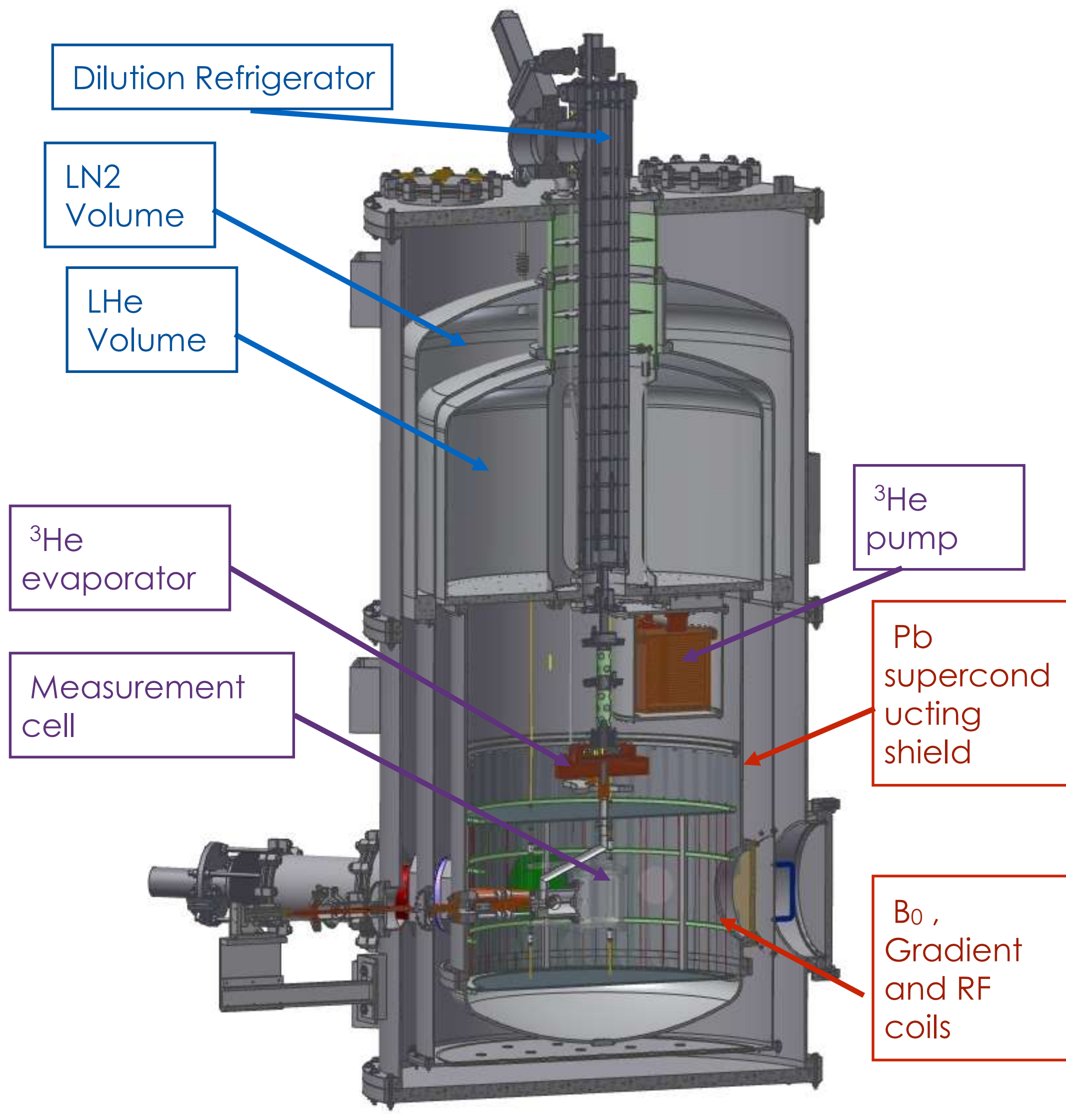
Motivation for SOS apparatus

Technical overview



Main design objectives :

- UCN and He-3 simultaneous storage in liquid helium at temperatures 0.4-0.5K
- spin manipulations and spin detection of He-3 and neutrons in homogenous magnetic field with T2 >500sec
- neutron storage >100 sec
- ability to remove depolarized He-3

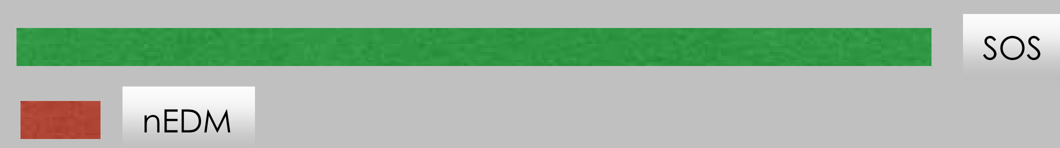


Summary of design difference

	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		
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		
magnetic field gradients	< 100 nG/cm or $< 3\times10^{-6}$ cm^{-1} for $T_{\text{gradient},^3\text{He}} > 10,000$ sec	< 500 nG/cm or $< 1.5\times10^{-5}$ cm^{-1} for $T_{\text{gradient},^3\text{He}} > 400$ sec
measurement cycle rate		

- **Cool down:** 2 weeks (~ 4-5 times shorter than nEDM).

- **Cycle time:** ~ 2-3 hours (~ 10 times longer then nEDM).



Our scientific program

- Three key studies related to nEDM@SNS project:
  - geometric phase related studies
  - spin manipulation
  - characterization of experimental cells

- Precise measurement of the neutron to shielded helion gyromagnetic ratio γ_3/γ_n

  - The ratio can be determined to ~ 0.1 ppm level with 1-2 months of running

  - Combining with the CODATA 2014 recommended value for of 13 ppb, the precision of the value can thus be improved by a factor of ~ 2.5.

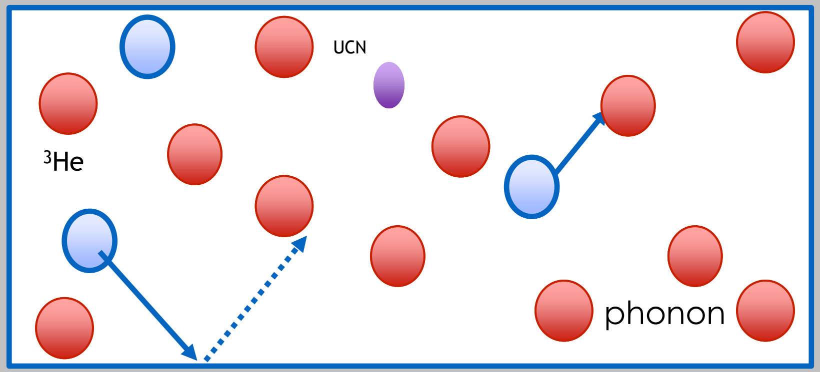
Key measurements

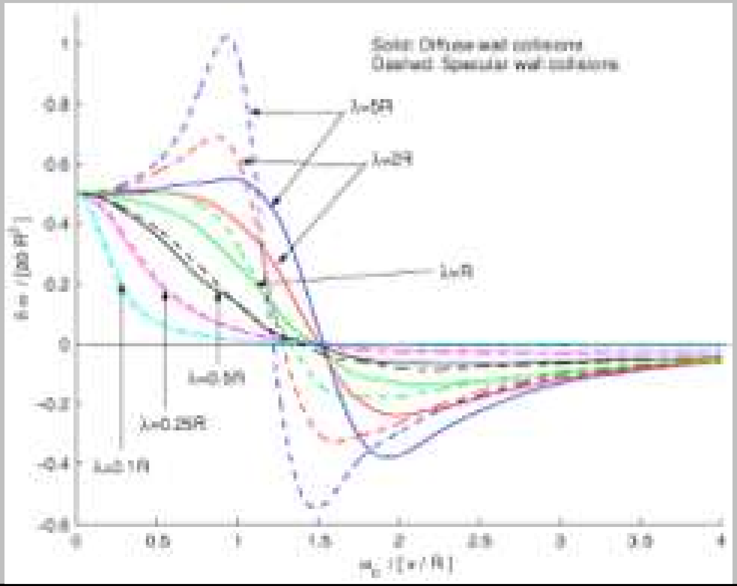
- **Geometric phase study:**
  - -Characterization of the main nEDM systematic effect caused by the frequency shift due to interaction of the motional (E × v/c) magnetic field with stray field gradients

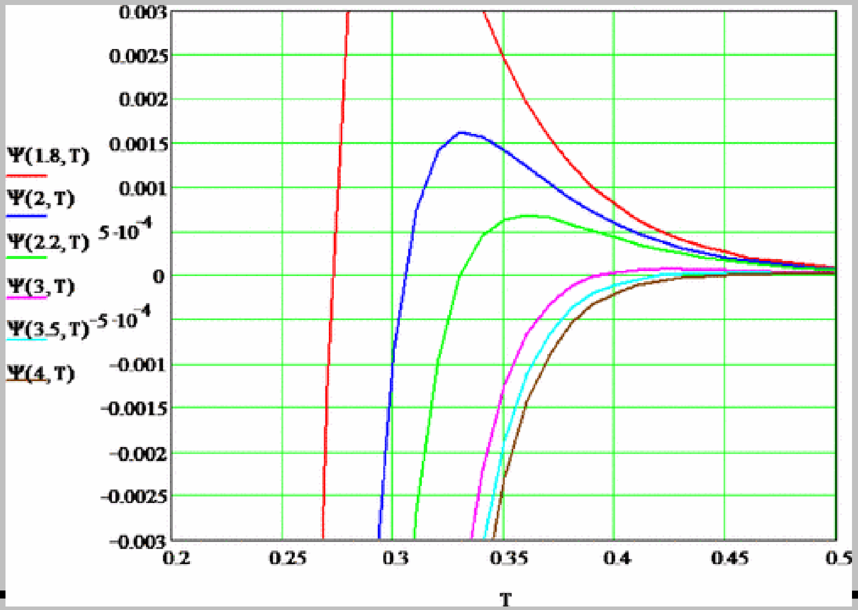
- **Spin manipulation:**
  - -Development of operational procedures required to demonstrate sufficient control of the ^{3}He and neutron spins (for both, free spin precession and spin dressing)

- **Test of measurement cells:**
  - -UCN and ^{3}He friendliness (storage and polarization times) of FINAL cells

Geometric phase effect study







Geometric phase studies

- **Theoretical studies of the Geometrical phase effect :**
  - Swank, C.M.; Petukhov, A.K.; Golub, R., “Random walks with thermalizing collisions in bounded regions: Physical applications valid from the ballistic to diffusive regimes”, Physical Review A, **93**, n 6, p 062703 (15 pp.), June 2016.
  - Golub, R.; Kaufman, C.; Müller, G.; Steyerl, A., “Geometric phases in electric dipole searches with trapped spin-1/2 particles in general fields and measurement cells of arbitrary shape with smooth or rough walls,” Physical Review A, **92**, n 6, p 062123 (18 pp.), Dec. 2015.
  - Pignol, G.; Guigue, M.; Petukhov, A.; Golub, R., “Frequency shifts and relaxation rates for spin-1/2 particles moving in electromagnetic fields”, Physical Review A (Atomic, Molecular, and Optical Physics), **92**, n 5, p 053407 (8 pp.), Nov. 2015.
  - A. Steyerl, C. Kaufman, G. Müller, S. S. Malik, A. M. Desai and R. Golub, "Calculation of geometric phases in electric dipole searches with trapped spin-1/2 particles based on direct solution of the schrödinger equation.," *Phys. Rev. A,* vol. 89:052129, 2014.
  - C. Swank, A. Petukhov and R. Golub, "Correlation functions for restricted brownian motion from the ballistic through to the diffusive regimes," *Physics Letters A,* vol. 376(34):2319, 2012.
  - G. Pignol, S. Roccia, “Electric-dipol-moment-searches: Re-examination of frequency shifts for particles in traps”; Physical Review A, 84(4):042105(5), 2012
  - C. M. Swank, PhD thesis, North Carolina State University, Raleigh, NC, 2012
  - S.M. Clayton, “Spin relaxation and linear-in-electric-field frequency shift in an arbitrary time-independent magnetic field”, Journal of Magnetic resonance, 211(1):89-95, 2011
  - A. L. Barabanov, R. Golub and S. K. Lamoreaux, "Electric dipole moment searches: Effect of linear electric field frequency shifts induced in confined gases," *Phys. Rev. A,* vol. 74:052115, 2006.
  - S. K. Lamoreaux and R. Golub, "Detailed discussion of a linear electric field frequency shift induced in confined gases by a magnetic field gradient: Implications for neutron electric-dipole-moment experiments," *Phys. Rev. A,* vol. 71:032104, 2005
  - J. M. Pendlebury et al., "Geometric-phase-induced false electric dipole moment signals for particles in traps," *Physical Review A,* vol. 70:032102, 2004

Geometric phase studies

Geometric phase can be calculated using motional correlation

$$\delta\omega = \frac{\gamma^2 E}{c^2}\left[\omega_0 \mathrm{Im}\left(S_{B_x x}(\omega_0)\right) + \omega_0 \mathrm{Im}\left(S_{B_y y}(\omega_0)\right) + < x B_x > + < y B_y >\right]$$

There are 3 ways to measure Correlation function:

- via. spin relaxation time T1

$$\frac{1}{T_{1,gradient}} = \frac{\gamma^2}{2}\left(G_x^2 \mathrm{Re}\left[S_{xx}(\omega_0)\right] + G_y^2 \mathrm{Re}\left[S_{yy}(\omega_0)\right]\right)$$

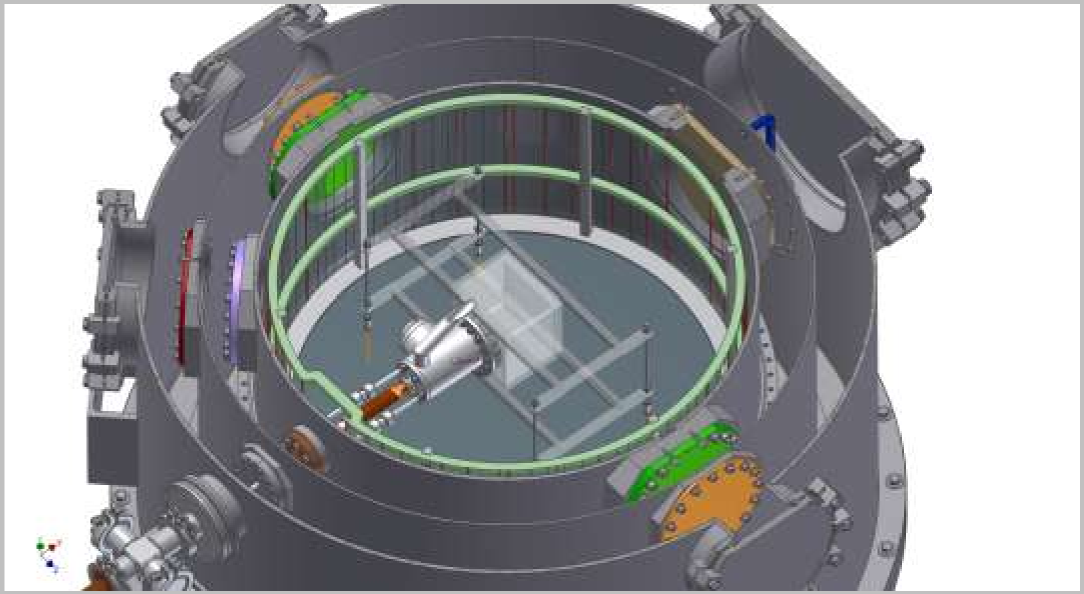
- via. spin relaxation time T2

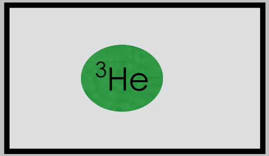
$$\frac{1}{T_{2,rf\ gradient}} = \frac{\gamma^2 G_{xr}^2}{2} \mathrm{Re}\left[S_{xx}(\omega_{eff})\right]$$

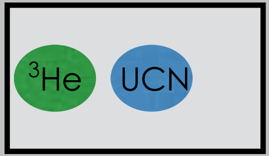
- B^2 frequency shift.

$$\delta\omega_{B^2} = \frac{\gamma^2}{2}\left(G_x^2 \mathrm{Im}\left[S_{xx}(\omega_0)\right] + G_y^2 \mathrm{Im}\left[S_{yy}(\omega_0)\right]\right)$$

Key measurements: correlation function







- To compensate for only 80% of He-3 polarization : use higher He-3 concentrations $x_{pol\ 3} \sim 10^{-8}$ to 10^{-7}.

Note that for $x < 10^{-7}$ the mean-free-path of the ^{3}He remains essentially unchanged since it is still in the regime where scattering with phonons in the superfluid helium dominates.

Key measurements

- **Correlation function:**
  -Characterization of the main nEDM systematic effect caused by the frequency shift due to interaction of the motional ($E \times v/c$) magnetic field with stray field gradients

- **Spin manipulation:**
  -Development of operational procedures required to demonstrate sufficient control of the ^3He and neutron spins (for both, free spin precession and spin dressing)

- **Test of measurement cells:**
  -UCN and ^3He friendliness (storage and polarization times) of FINAL cells

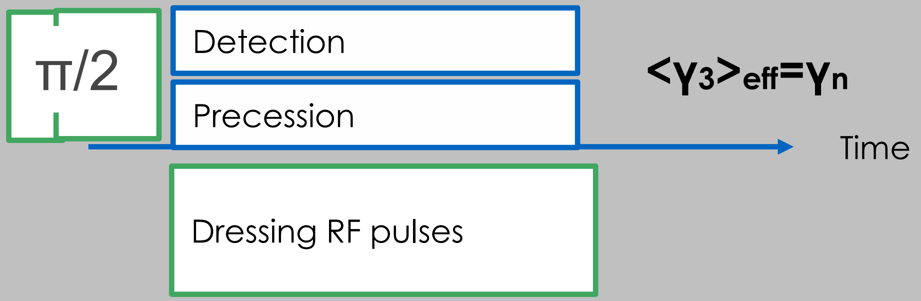
Spin manipulation

- **free precession**:

$\gamma_3 = 1.1\gamma_n$

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

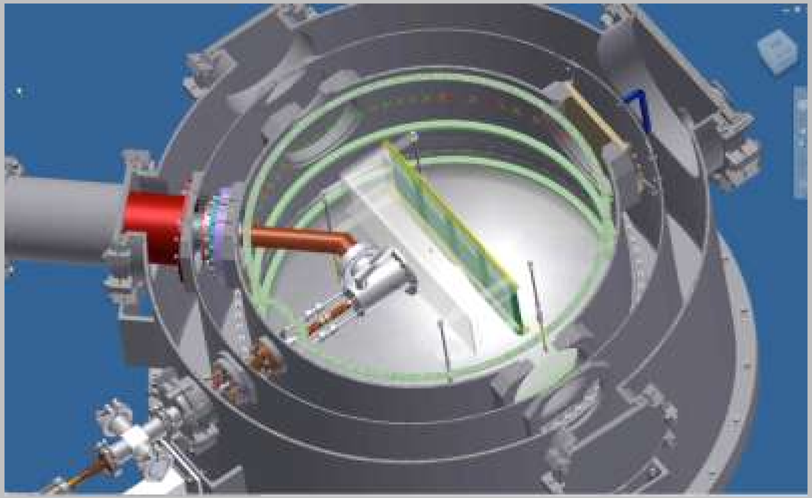
- **critical dressing:**



$\langle\gamma_3\rangle_{eff} = \gamma_n$

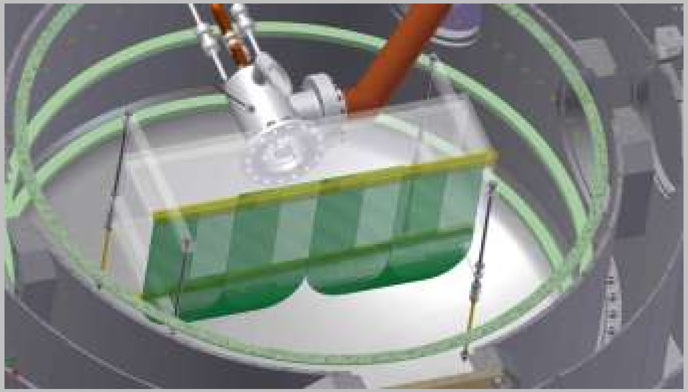
- Spin dressing have beed done separately with neutrons or He-3, never with two species together
- Need scanning of large parameter space

Spin manipulation



- **Free precession : use SQUID and light scintillation detectors**
  - to achieve the 0.06° precision goal : repeated measurements of φ_0 and use of an intermediate $x_{pol\,3} \sim 10^{-9}$.
  - rough estimate of the required measurement time about a month for one parameter scan

- **Critical dressing: use light scintillation technique**



- Light collection system is designed at Oak Ridge (the same as nEDM@SNS)
- Serpentine fiber arrangement to reduce heat leak into the cell

Key measurements

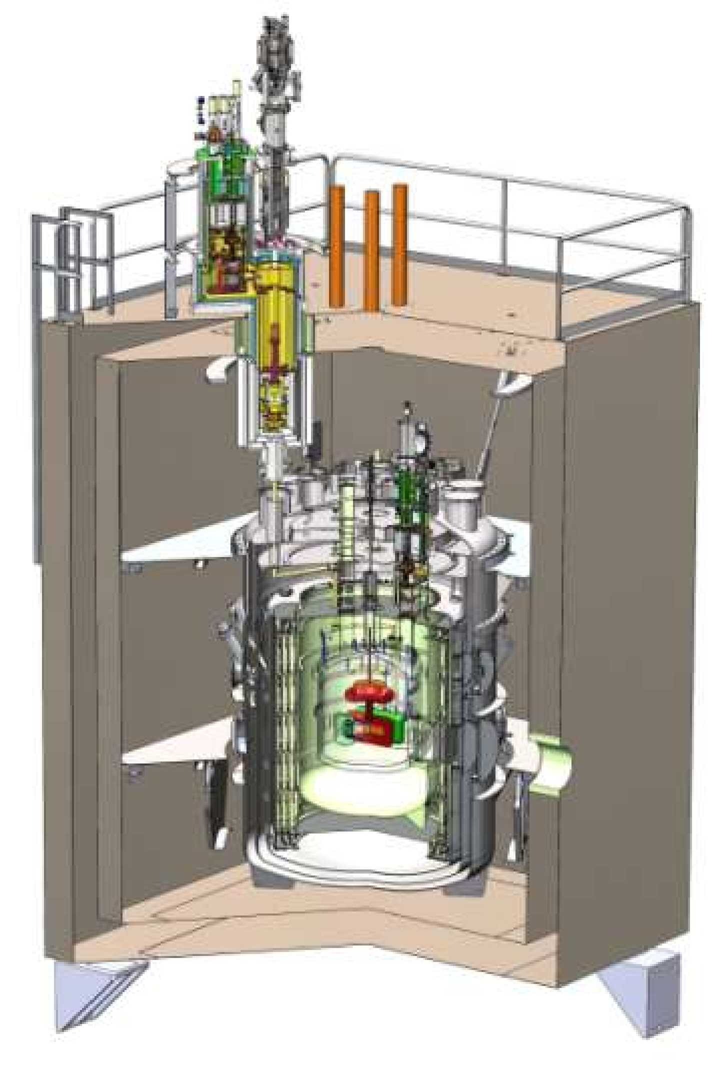
- **Correlation function:**
  -Characterization of the main nEDM systematic effect caused by the frequency shift due to interaction of the motional (E × v/c) magnetic field with stray field gradients

- **Spin manipulation:**
  -Development of operational procedures required to demonstrate sufficient control of the ^{3}He and neutron spins (for both, free spin precession and spin dressing)

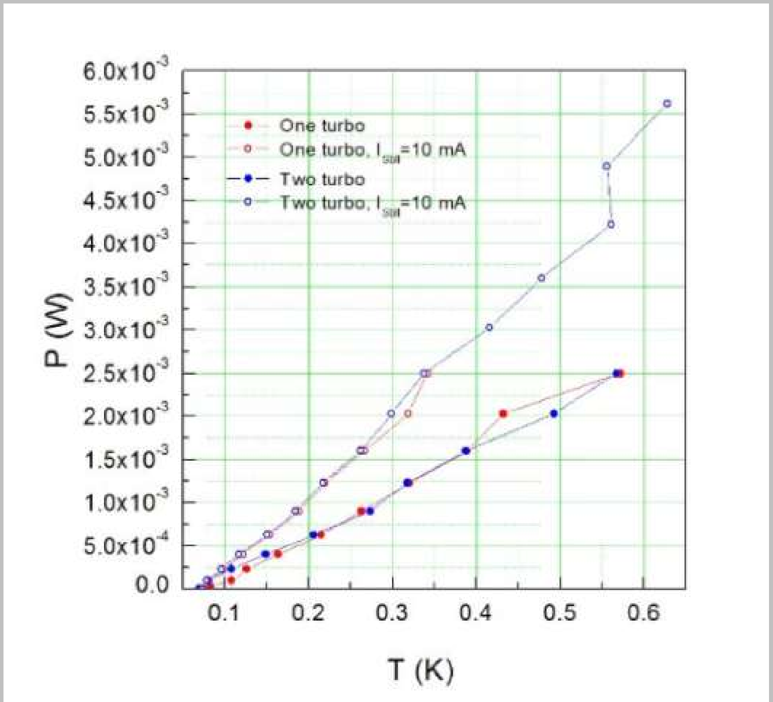
- **Test of measurement cells:**
  -UCN and ^{3}He friendliness (storage and polarization times) of FINAL cells

Cell characterization

- Full-sized measurement cells at conditions close to operating:
  - UCN storage time
  - UCN&He-3 Depolarization properties
  - He-3 Correlation function

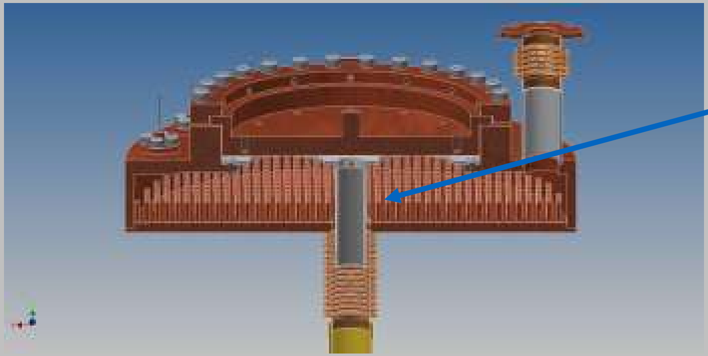


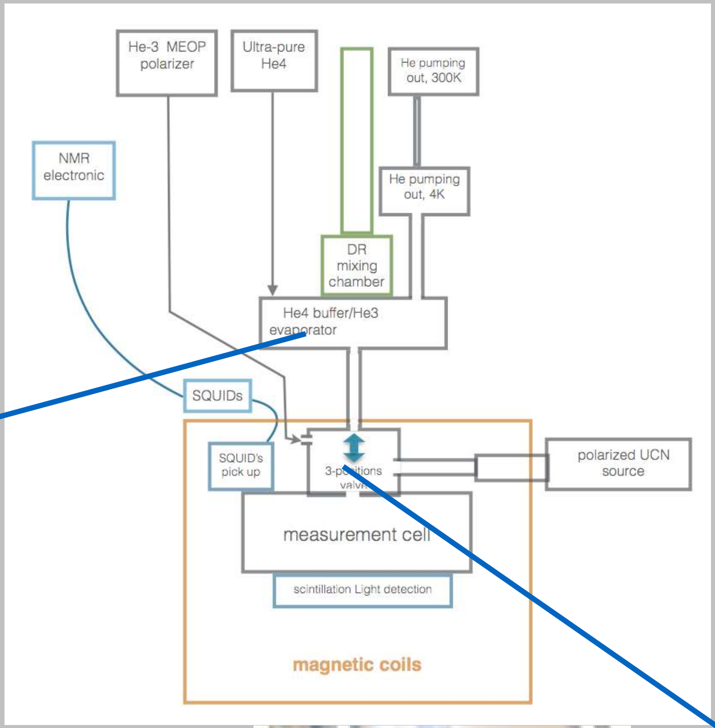
SOS apparatus commissioning status: non-magnetic cryostat and Dilution Refrigerator

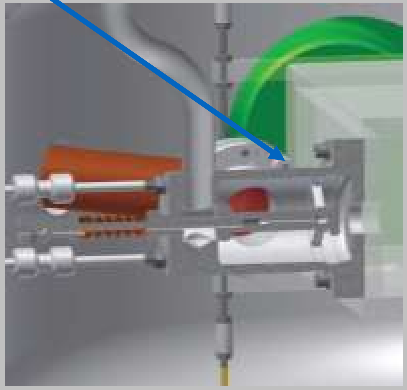


Temperature of the mixing chamber vs heater power

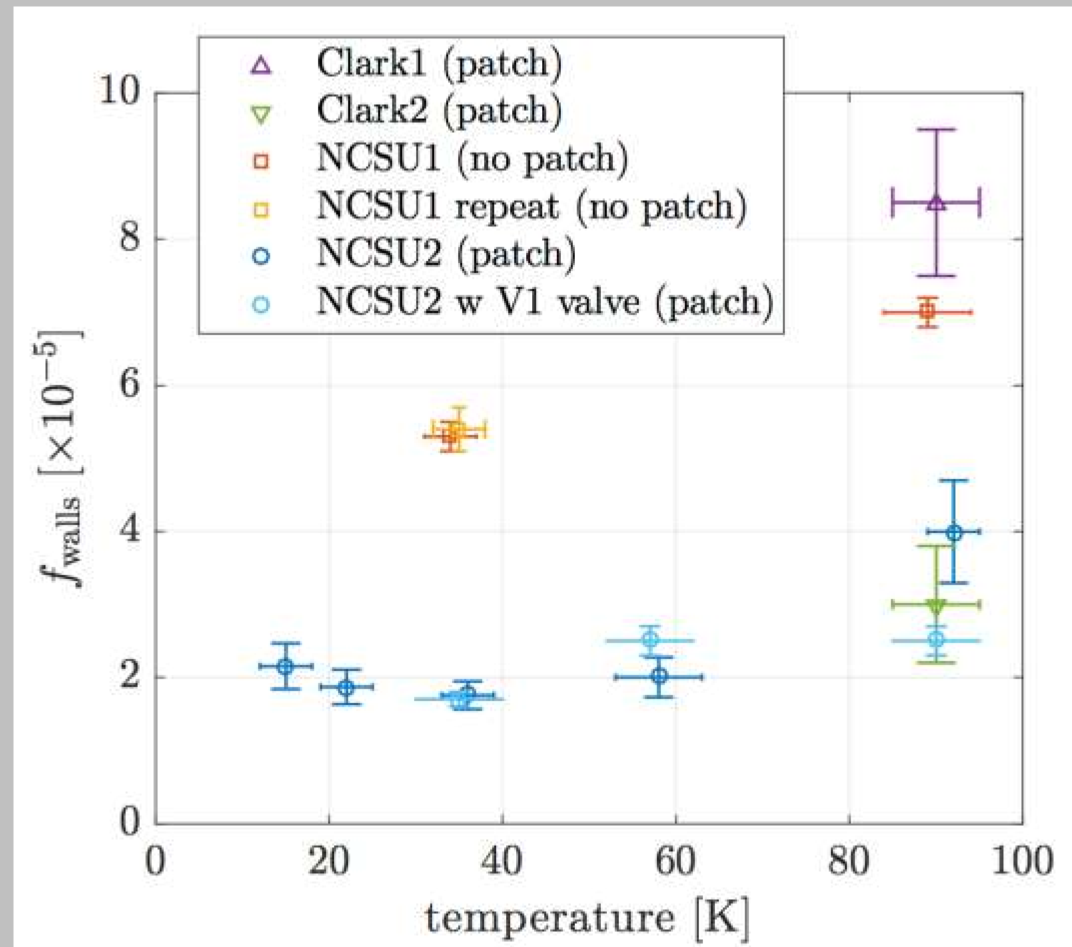
SOS apparatus commissioning status: He-4 system



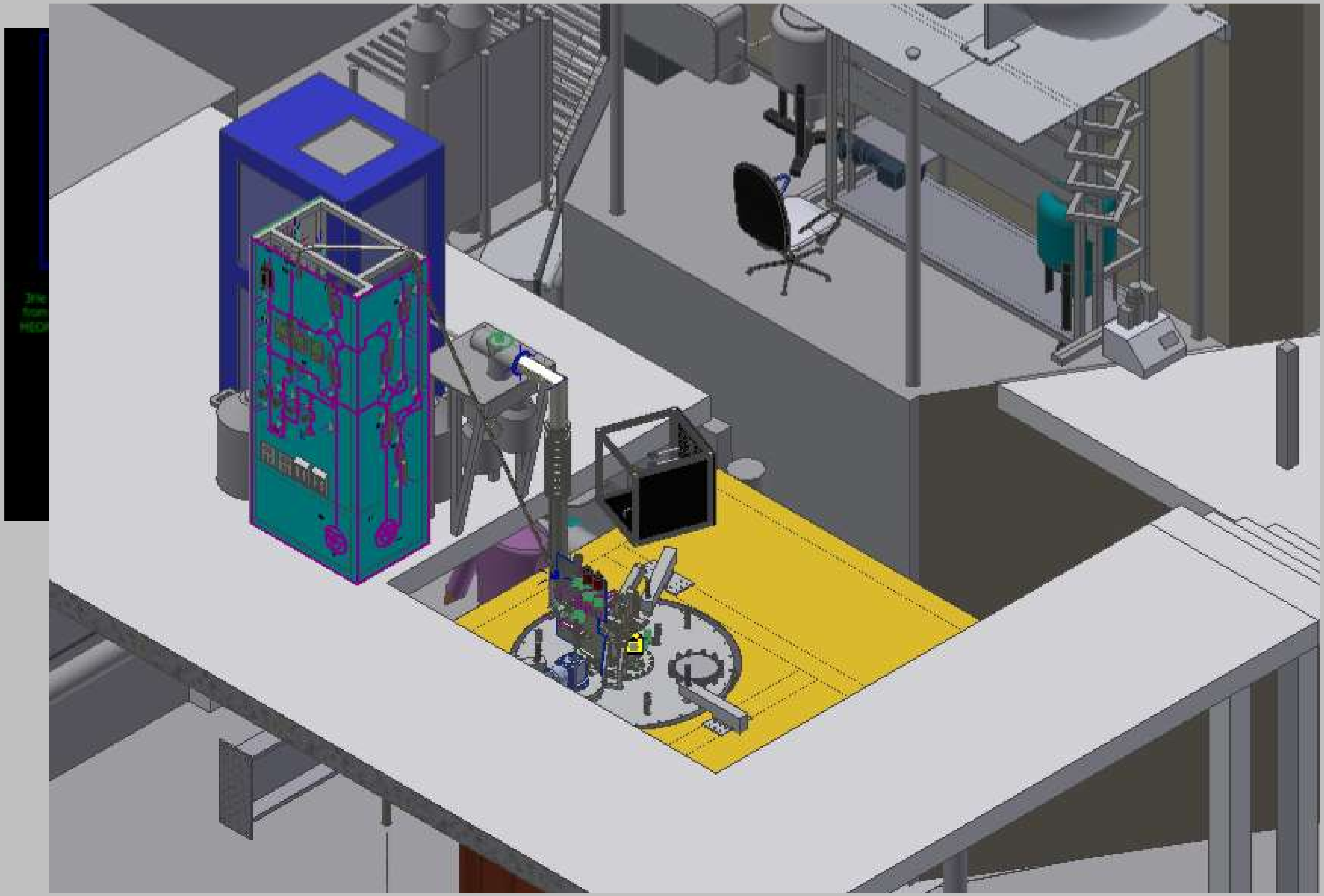




SOS apparatus commissioning status: measurement cell

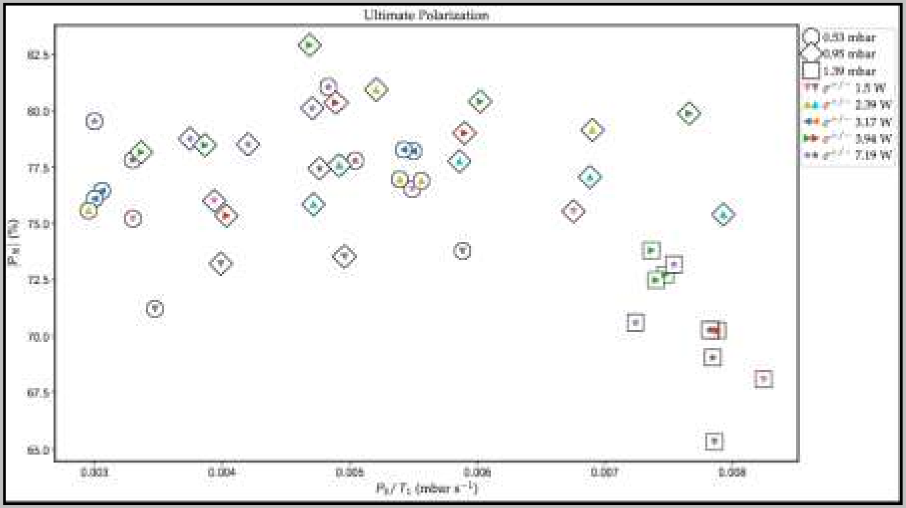


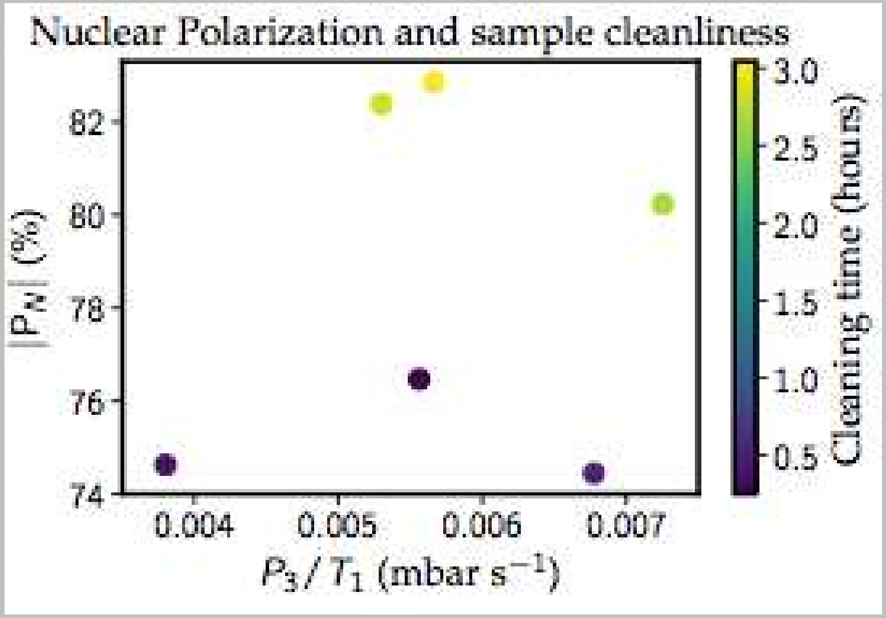
SOS apparatus commissioning status: He-4 system

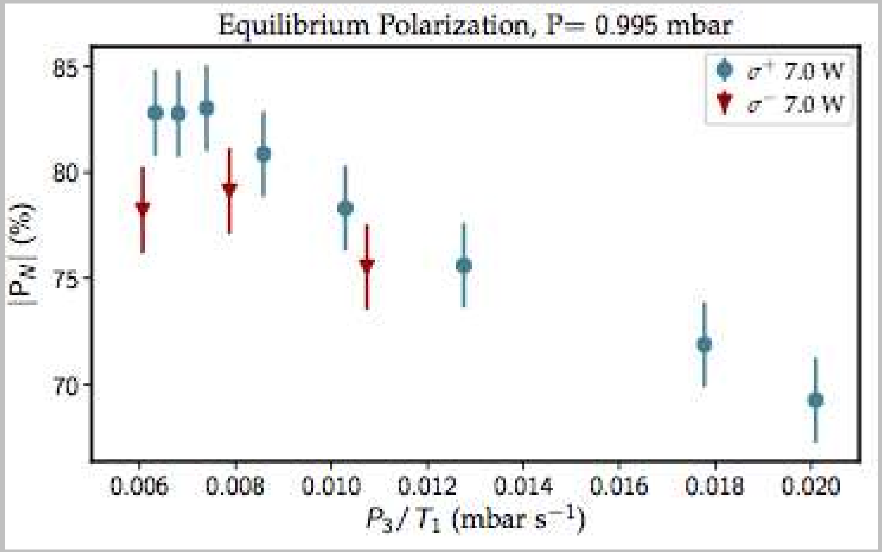


SOS apparatus commissioning status: He-3 polarization

- We have working, optimized MEOP set-up
- We can polarize He-3 within 20 min from cold start.
- We can polarize He-3 within hour after re-filling the cell.



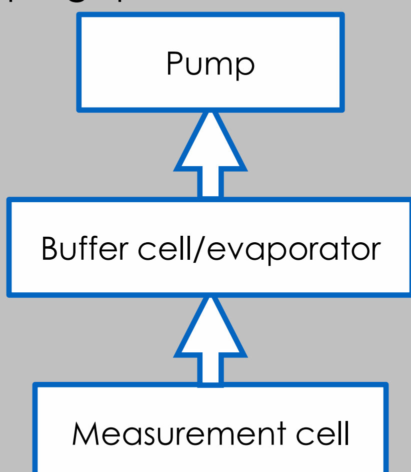




SOS apparatus commissioning status: He-3 removal

- He-3 will be moved to buffer cell/evaporator by phonon wind
- Our COMSOL model shows that with 1 mW of heat power the concentration can be done within 20 min

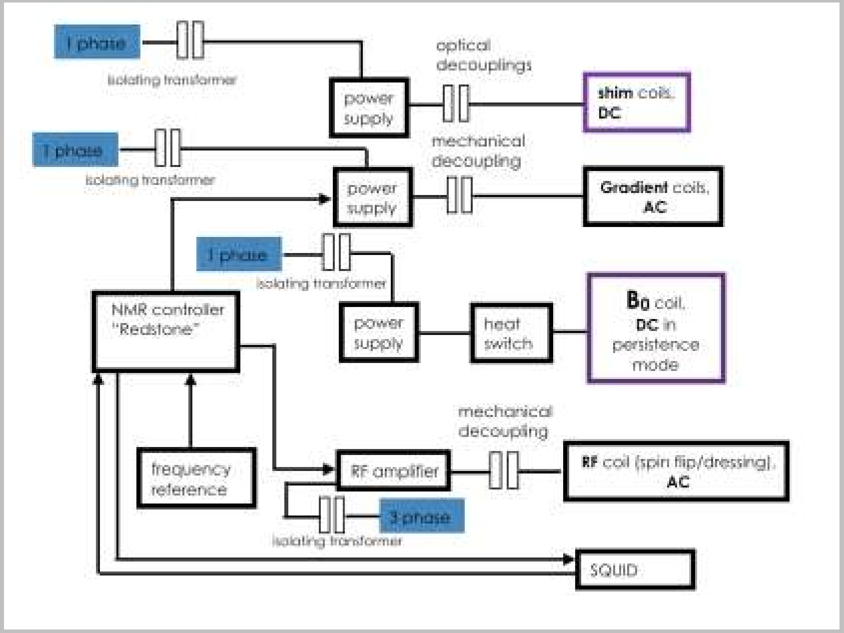
- From evaporator He-3 will be pumped by a Charcoal Pump thermally linked to 4K
- the pumping time is estimated to be 2-3 hours
- Pump capacity has been measured at least 100 STP liters of He
- The pumping speed will be measured soon

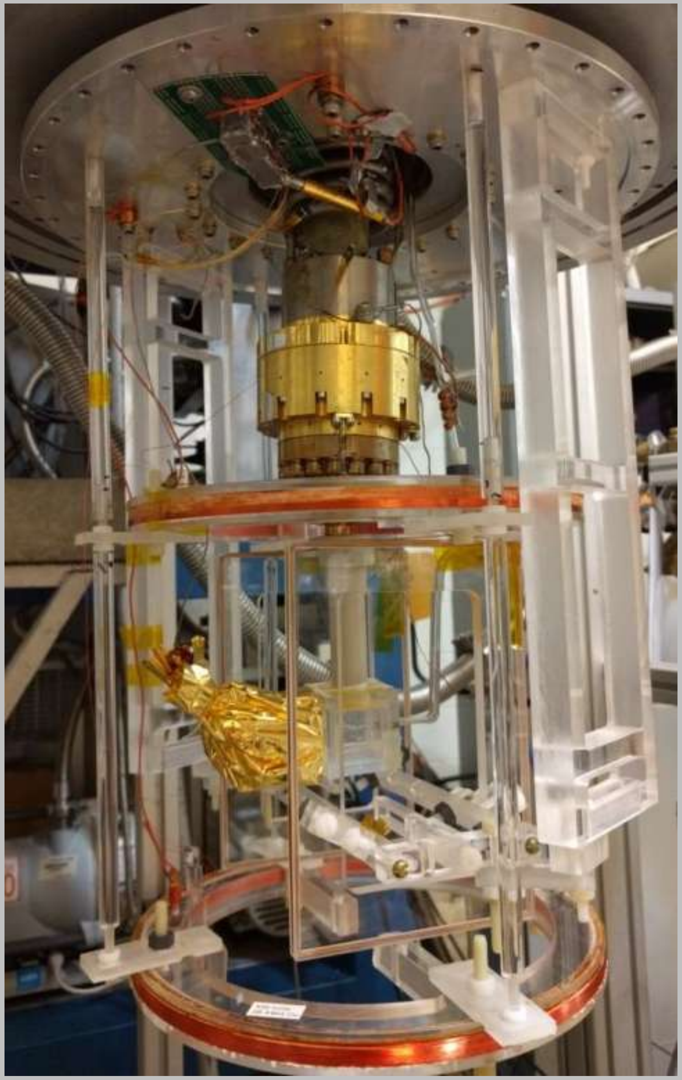


Pump capacity at is least 100 STP liters of He

SOS apparatus commissioning status: SQUID and NMR electronic

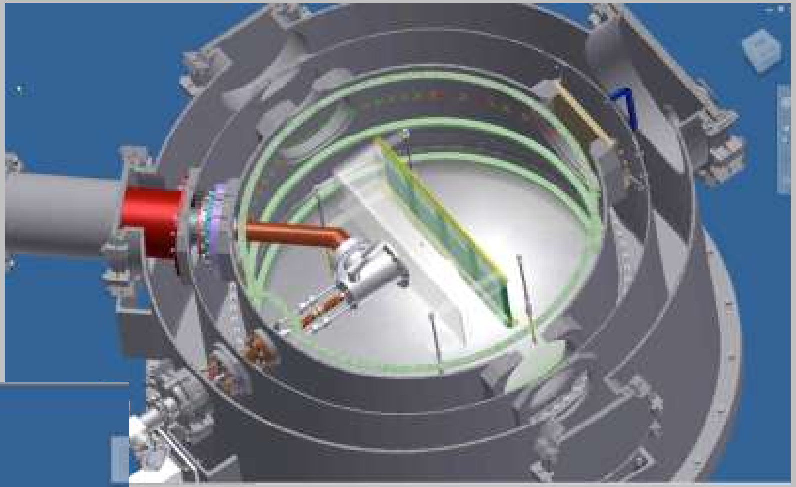
- We have a smaller Blue cryostat with SQUID installed to develop operational technique and noise suppression
- Main goal: to test effect of optical decoupling and power isolating transformer on SQUID noise
- After this cool down, we plan to move SQUID to the new dewar

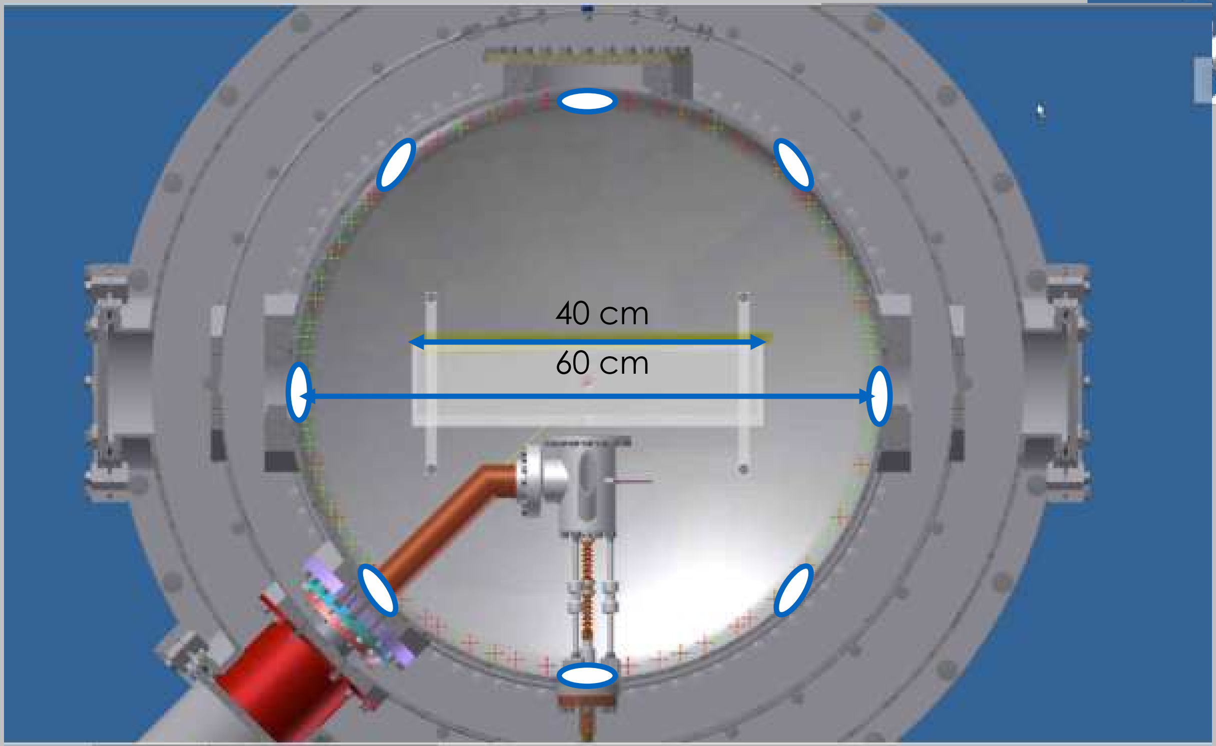




Magnetic coils design: internal coils

- Main challenge - compact coils with several side penetrations, 30 mG field
- Relatively large homogeneous field region with T_2 >500 sec

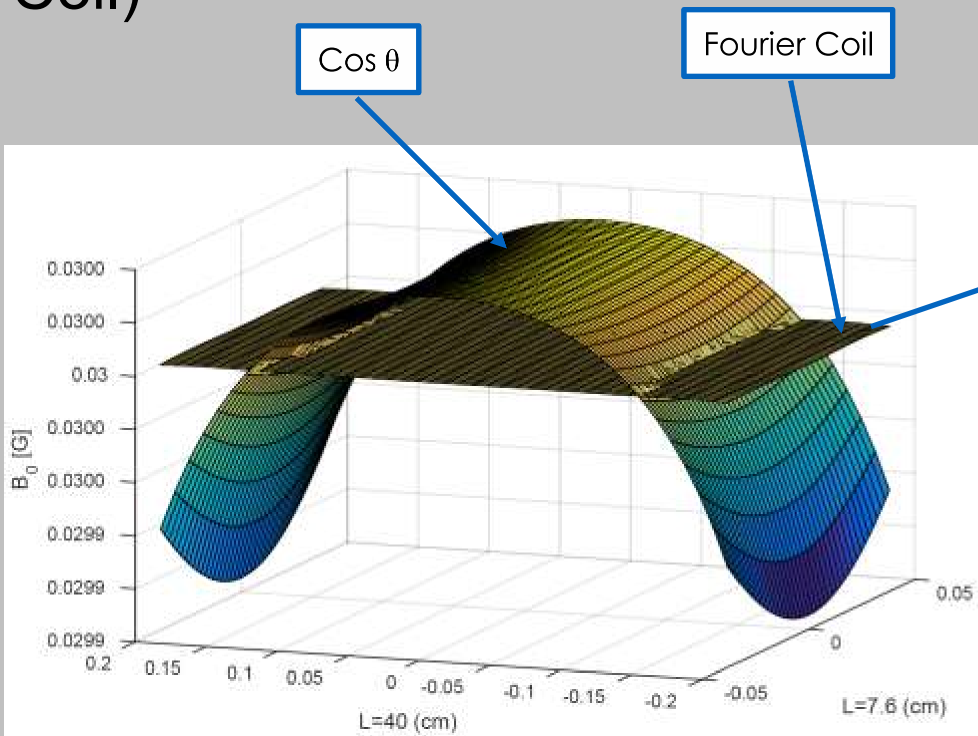


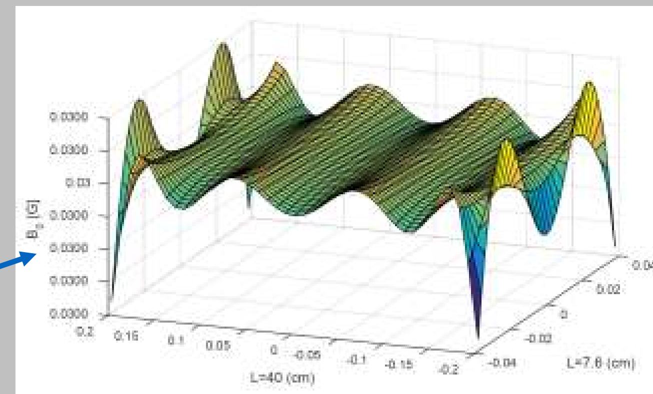


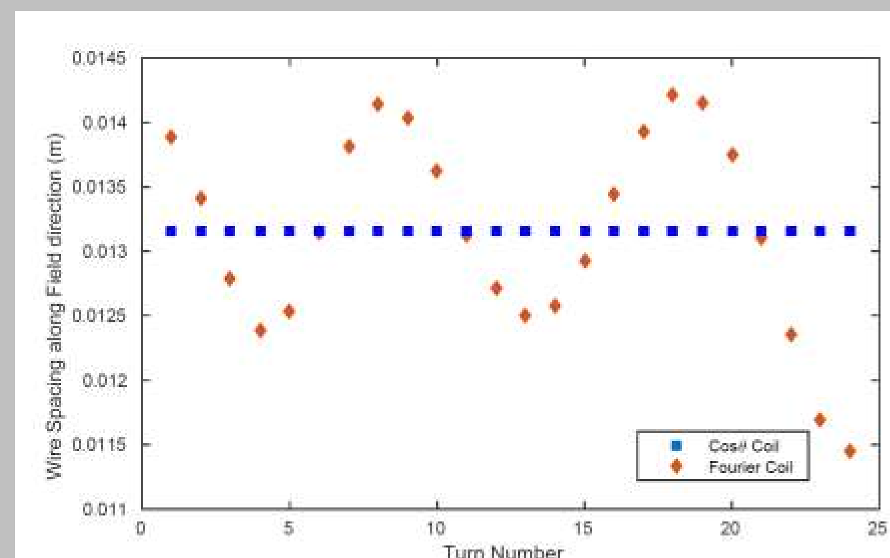
- B_0 , Gradient and RF coils
- Present design T2 about 2000 s

Magnetic coils design: external coils and shield

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



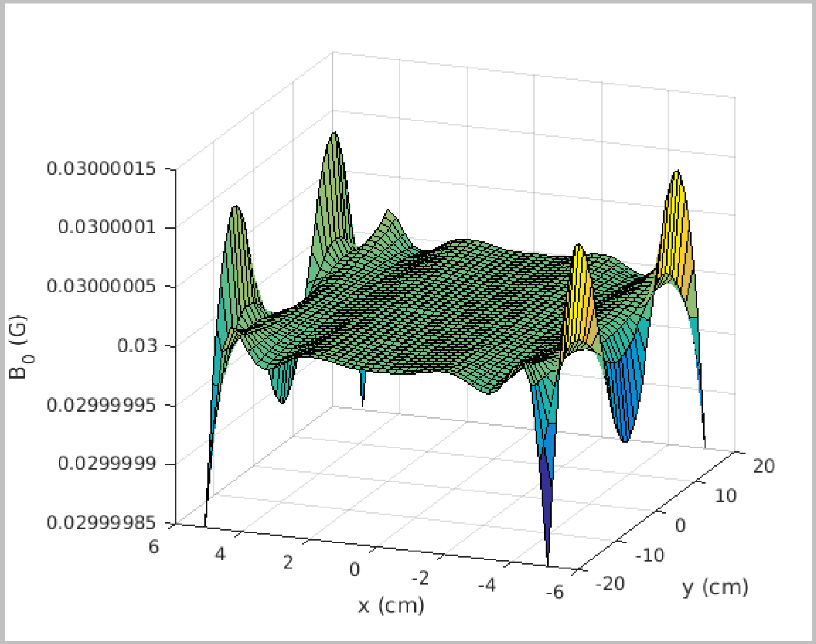




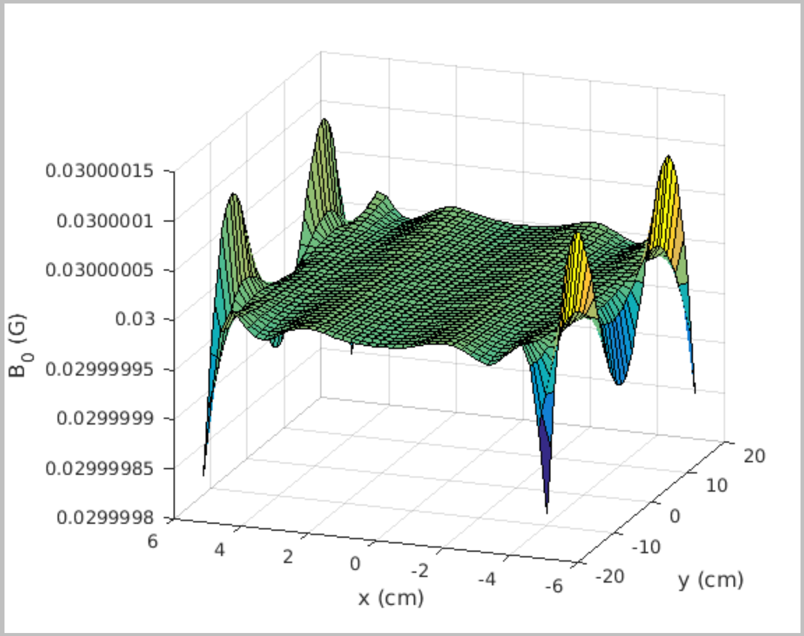
(credit C.M. Swank, Caltech)

Magnetic coils design: external coils and shield

Fourier minimization without conditional density



Fourier minimization with conditional density



T_2 is 4 times longer

(credit C.M. Swank, Caltech)

Summary

- **Systematic and Operational Study apparatus will allow us to do spin manipulations/studies with both, polarized ultra-cold neutrons and He-3 atoms, dissolved in LHe at 300-600 mK.**
- **SOS@PULSTAR experimental program:**
  - **Correlation function - first experimental studies**
  - **Spin manipulation: first spin dressing simultaneously of both, neutron and ^{3}He**
  - **UCN storage Cell characterization**
  - **Measure γ_3/γ_n. ratio at ppm level**
- **At present apparatus is under step-by-step design and commissioning of components:**
  - **MEOP fully operational, produces 80% ^{3}He polarisation**
  - **Development completed: Kapton bellow, Kapton seal on PEEK flanges, UCN/Vacuum window 10 mkm thick**
  - **Developed new methods to design compact magnetic coils (D) with homogeneous magnetic field region T_2 > 2000 sec for D/2 diameter inside the coil**

nEDM@SNS collaboration

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