^{3}He Polarization and Injection System for the nEDM@SNS SOS apparatus

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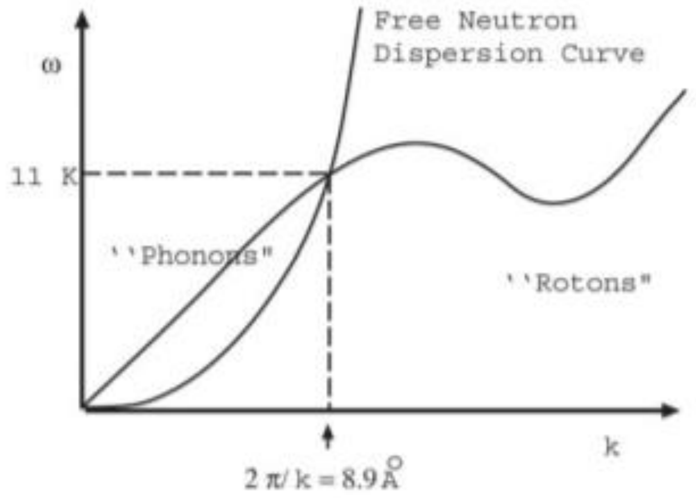
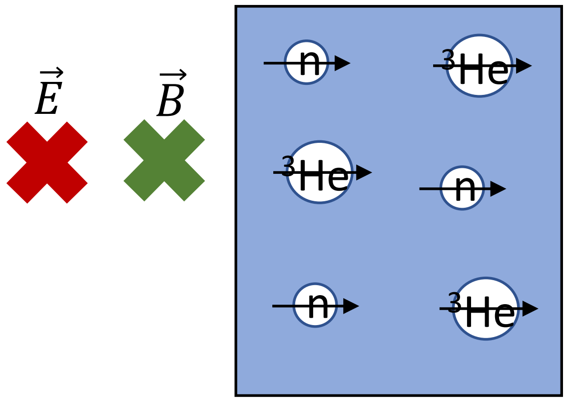
nEDM@SNS

- Will be located at Spallation Neutron Source (SNS) at Oak Ridge National Labs
- UCN production from 8.9 Å neutron beam (from SNS) incident on superfluid filled measurement cell
- Neutrons precess in // E and B field
  - Flip E ⇒ $\Delta\nu = \mp \frac{4|d_n|E_0}{h}$
- Measure precession frequency using scintillation light from
  - $\vec{n} + \overrightarrow{^3He} = p + t + 765$ keV
  - ^{3}He concentration of 10^{-10}
- Expected sensitivity of ~10^{-28} e cm
- Approximately 100 times more precise than current upper bound
- The Geometric Phase Effect is a source of systematic error for this experiment



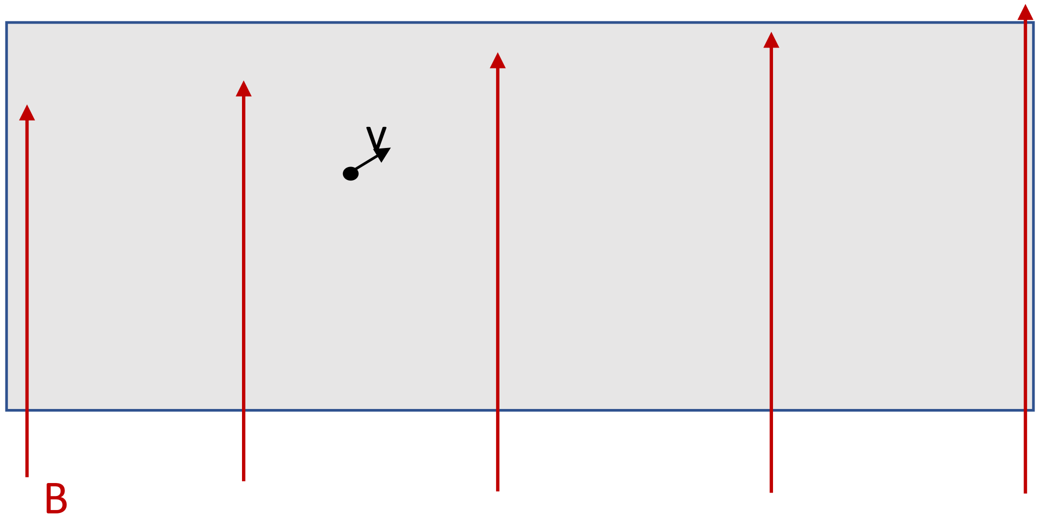
S K Lamoreaux and R Golub 2009
J. Phys. G: Nucl. Part. Phys. **36** 104002



Superfluid filled measurement cell

Geometric Phase Effect

- Without an electric field, magnetic field gradients result in a decay of the precession signal (T_2) and shift in the Larmor precession which are related to ∇B^2
- If an electric field is added $\vec{v} \times \vec{E}$ motional field combined with magnetic gradients results in additional linear in E frequency shift
- This frequency shift will show up as a false EDM in the nEDM@SNS experiment
- Systematic and Operational Studies (SOS) apparatus will be used to experimentally measure the trajectory correlation functions that describe the frequency shift



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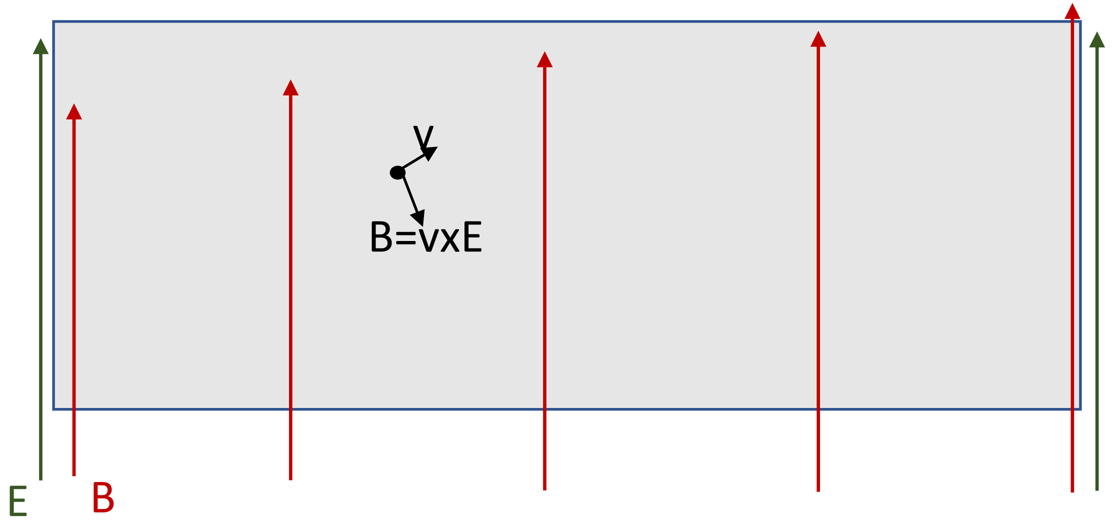


Correlation Functions and Geometric phase

- The T_2 , ∇B^2 frequency shift, and E shift are determined by the magnetic gradient the particles see while traversing the cell
- As a result, they are related to the Fourier transform of the trajectory correlation functions of the spins
- If one of the correlation functions is known the other correlation functions can be calculated from it
- Measuring the ∇B^2 frequency shift or the T_2 time, of a system of precessing spins, can be used to calculate the expected linear in E shift
- The T_1 (depolarization time) of the spins is also related to S_{xx} and can be used to determine expected E shift

$$S_{xx}(\tau) = \langle \vec{x}(0) \cdot \vec{x}(\tau) \rangle$$
$$S_{xv}(\tau) = \langle \vec{x}(0) \cdot \vec{v}(\tau) \rangle$$

$$\bar{S}(\omega_0) = \int_0^\infty e^{i\omega_0 \tau} S(\tau) d\tau$$

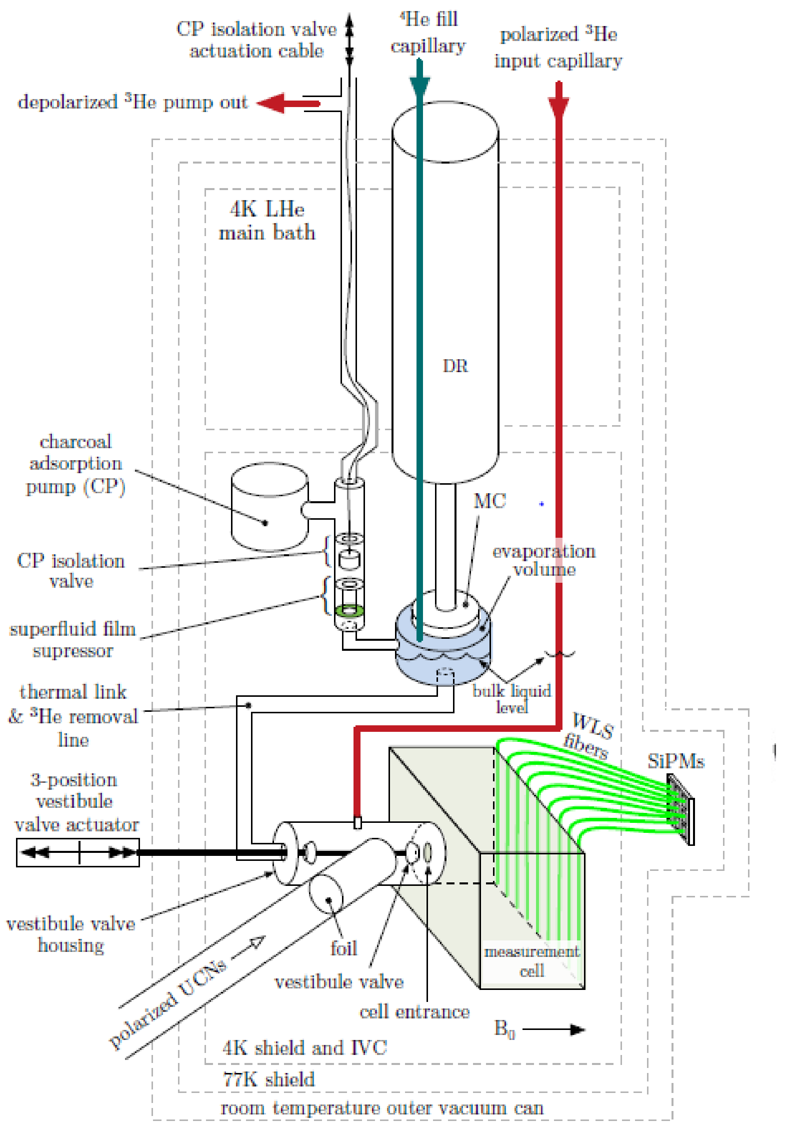
$$\bar{S}_{xx}(\omega_0) \Rightarrow \delta\omega_{\nabla B^2}, T_2 \text{ and } T_1$$
$$\bar{S}_{xv}(\omega_0) \Rightarrow \delta\omega_{\nabla BE}$$

$$\bar{S}_{xx} = -\frac{i}{\omega_0} \bar{S}_{xv}$$

R. Golub, C. Kaufman, G. Müller, and A. Steyerl
Phys. Rev. A **92**, 062123 – Published 15 December 2015

Systematic and Operational Studies for nEDM

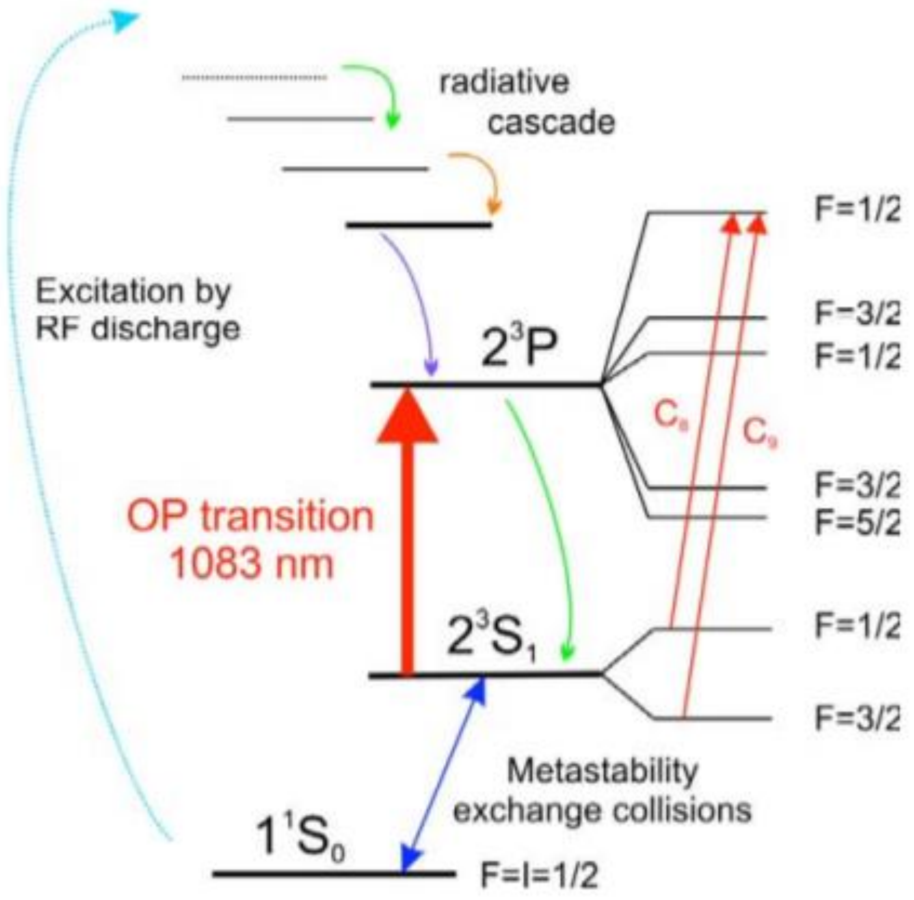
- SOS apparatus is effectively a scaled down version of the final experiment without the electric field needed to measure an EDM
- The SOS apparatus will be used to determine the correlation functions of ^{3}He (@Duke) and neutrons (@PULSTAR) by measuring the T_1 , T_2 and ∇B^2 frequency shift
- The measured values can then be used to predict the size of the geometric phase that will be seen in the nEDM apparatus
- For this to work we need a way of getting polarized ^{3}He with a concentration of 10^{-10} into the cell



Reid, Austin Randolph. Helium-3 Polarization and Origami Folded Cryogenic Actuators and Metamaterials.

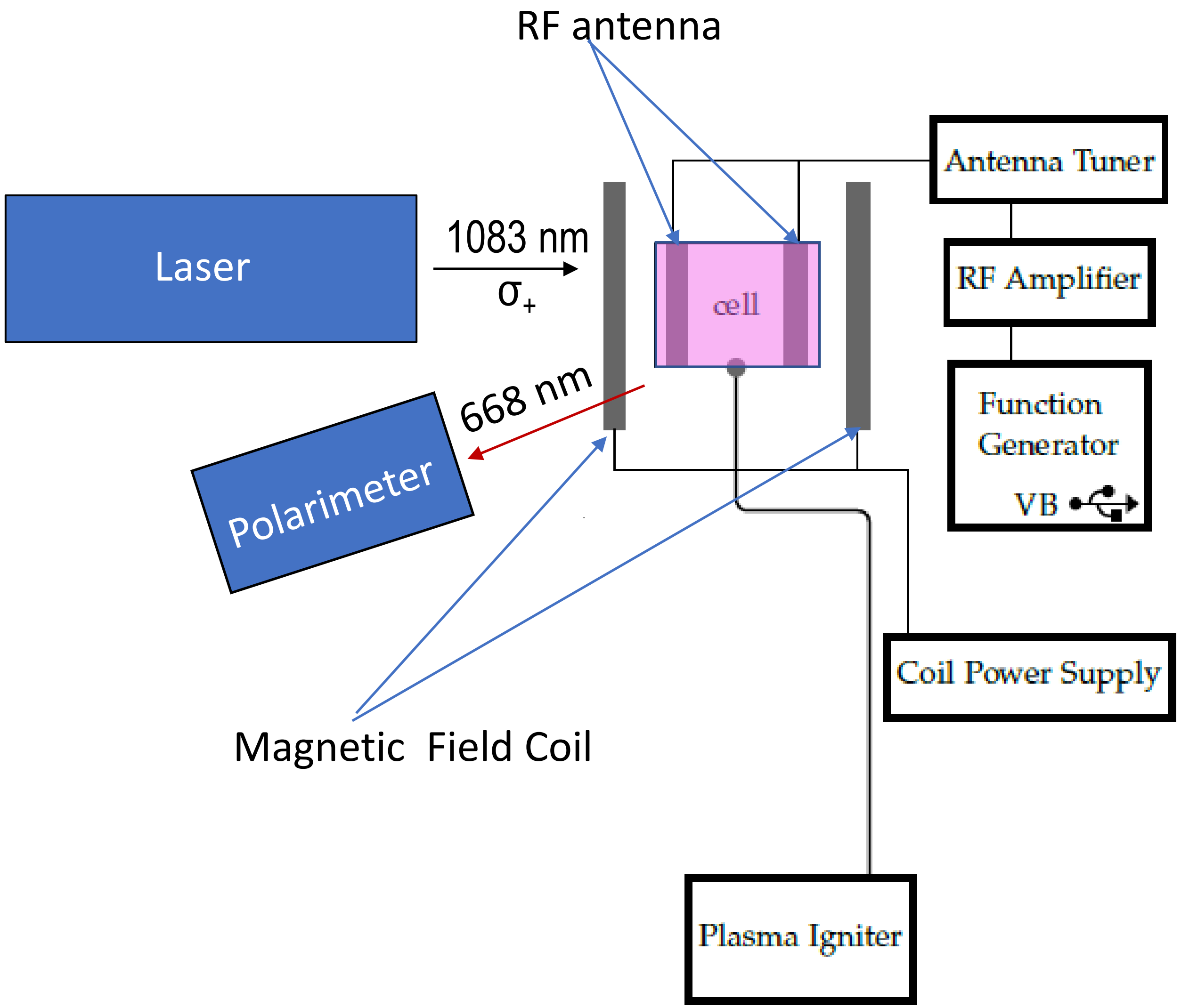
Polarizing ^3He with MEOP

- Metastability Exchange Optical pumping (MEOP)
- Method of polarizing ^3He nuclei
  1. $2S_1$ level of ^3He is populated using RF discharge
  2. Optical pumping is used to polarize $2S_1$ ($2S_1 \rightarrow 2P_0$)
  3. Metastable polarized ^3He atoms transfer polarization to nuclei of ground state atoms via collisions
- Can get 80% ^3He polarization with this method



Guilhem Collier *Metastability Exchange Optical Pumping (MEOP) of ^{3}He in Situ* (2011)

MEOP Electronics



Plasma ignitor starts discharge

RF antenna sustains discharge

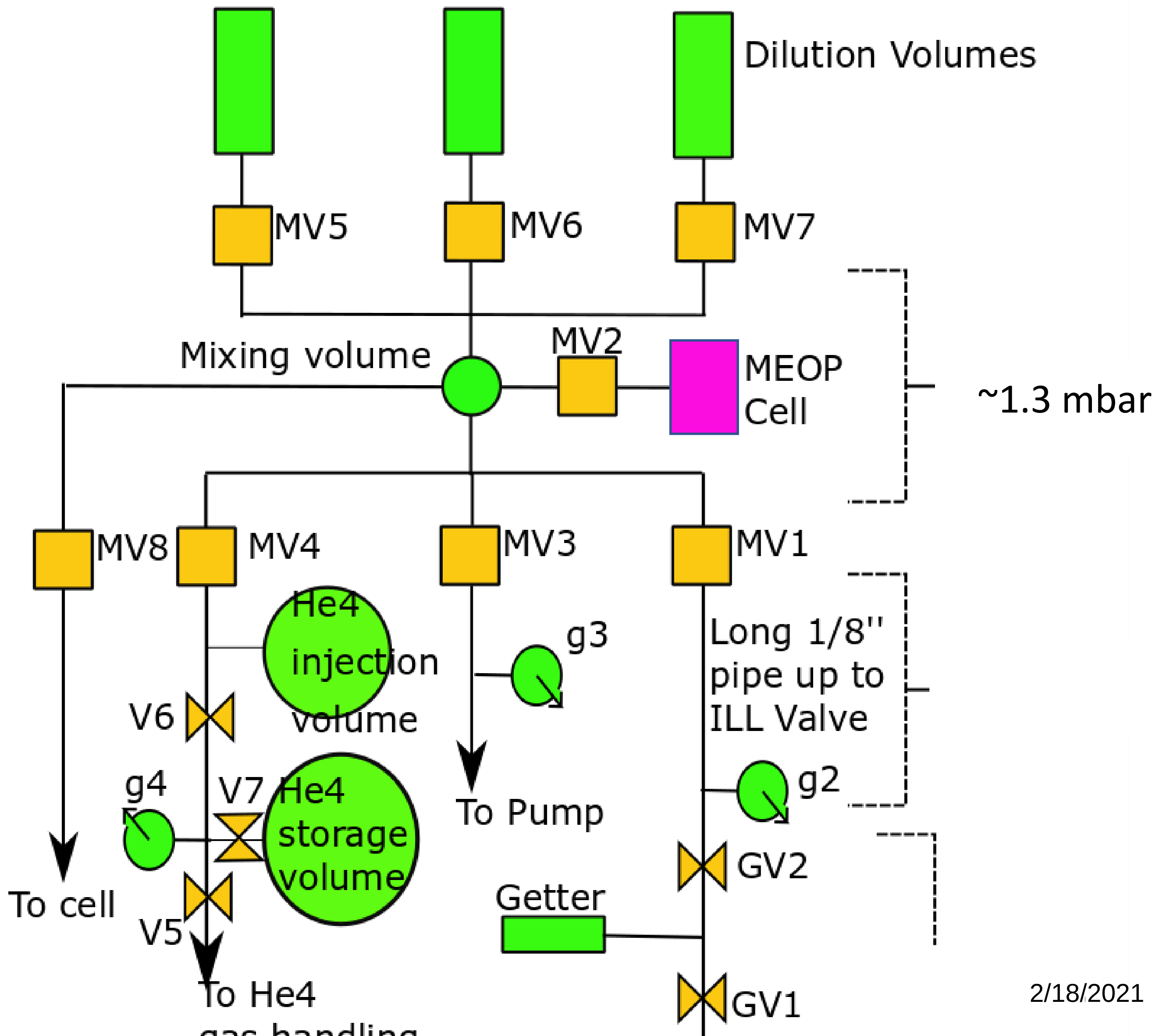
Magnetic field coil for B0

Laser pumps C8 transition

Polarimeter determines nuclear polarization from fluorescence ($3D_2$-$2P_1$)

Getting Concentration of 10^{-10}

- MEOP is performed with 1.3 mbar of ^{3}He in an 80cc cell. If all of this ^{3}He is injected into the measurement cell the concentration will be too large
- Pumping ^{3}He out of the cell will reduce the pressure in the cell reducing the lifetime of the polarized state.
- 500mbar of ^{4}He is injected into the cell to maintain pressure.
- Cylindrical “dilution volumes” are used to “pump” out excess ^{3}He
- Process repeated 2 more times
- Once enough ^{3}He is removed from the MEOP cell to get the desired concentration the gas is injected into measurement cell inside the cryovessel
- Gas handling system is currently being fabricated



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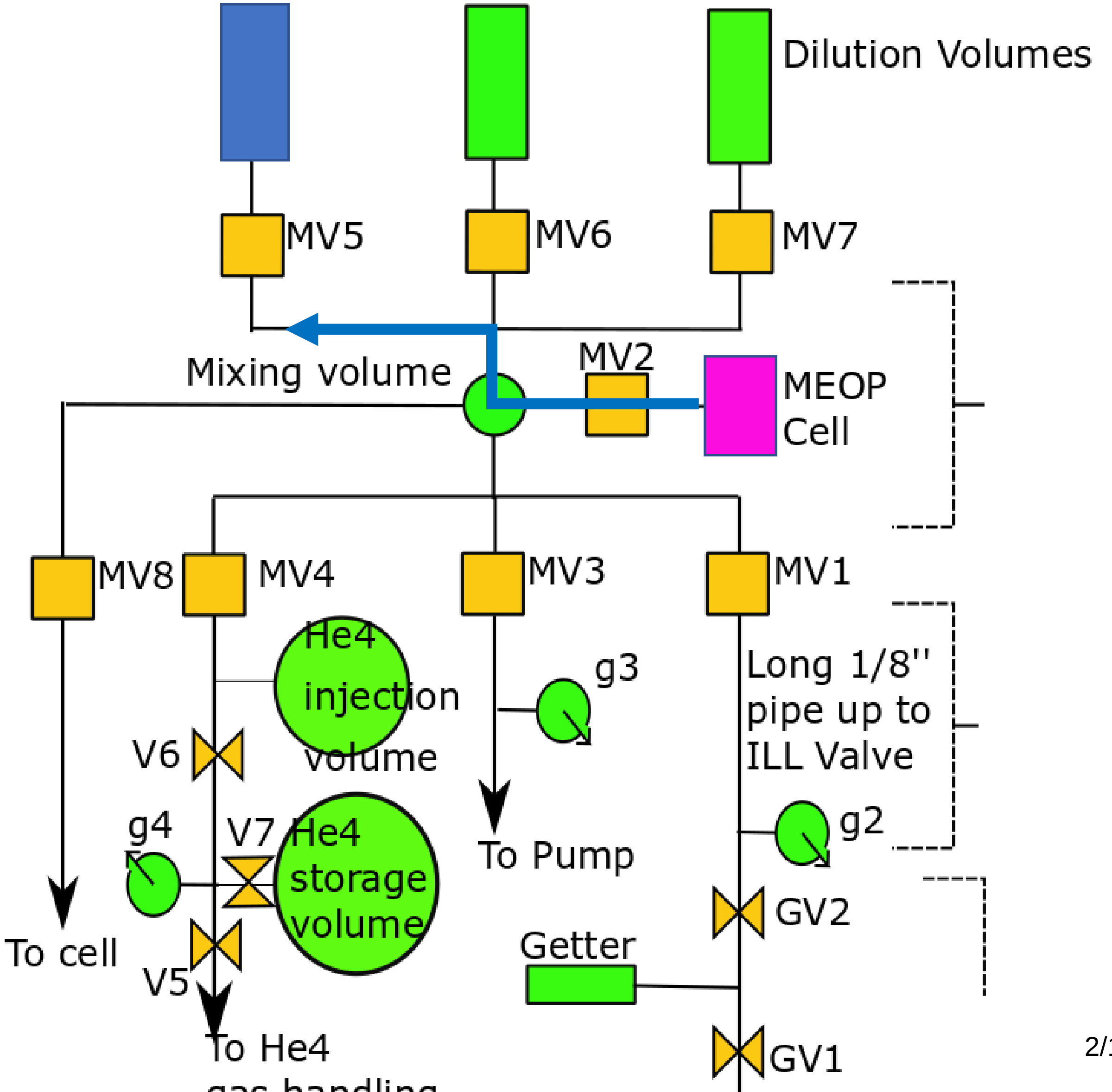

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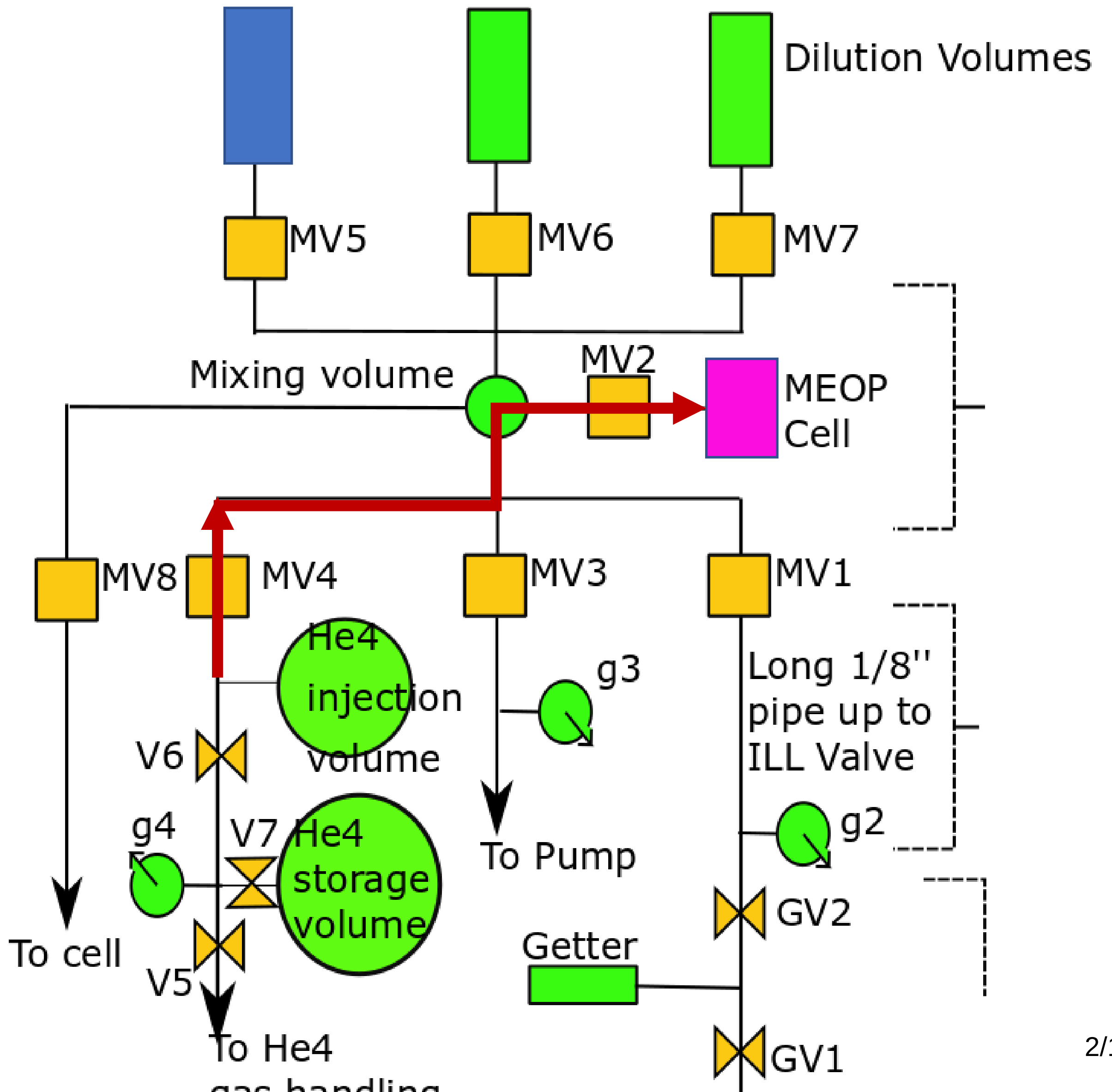

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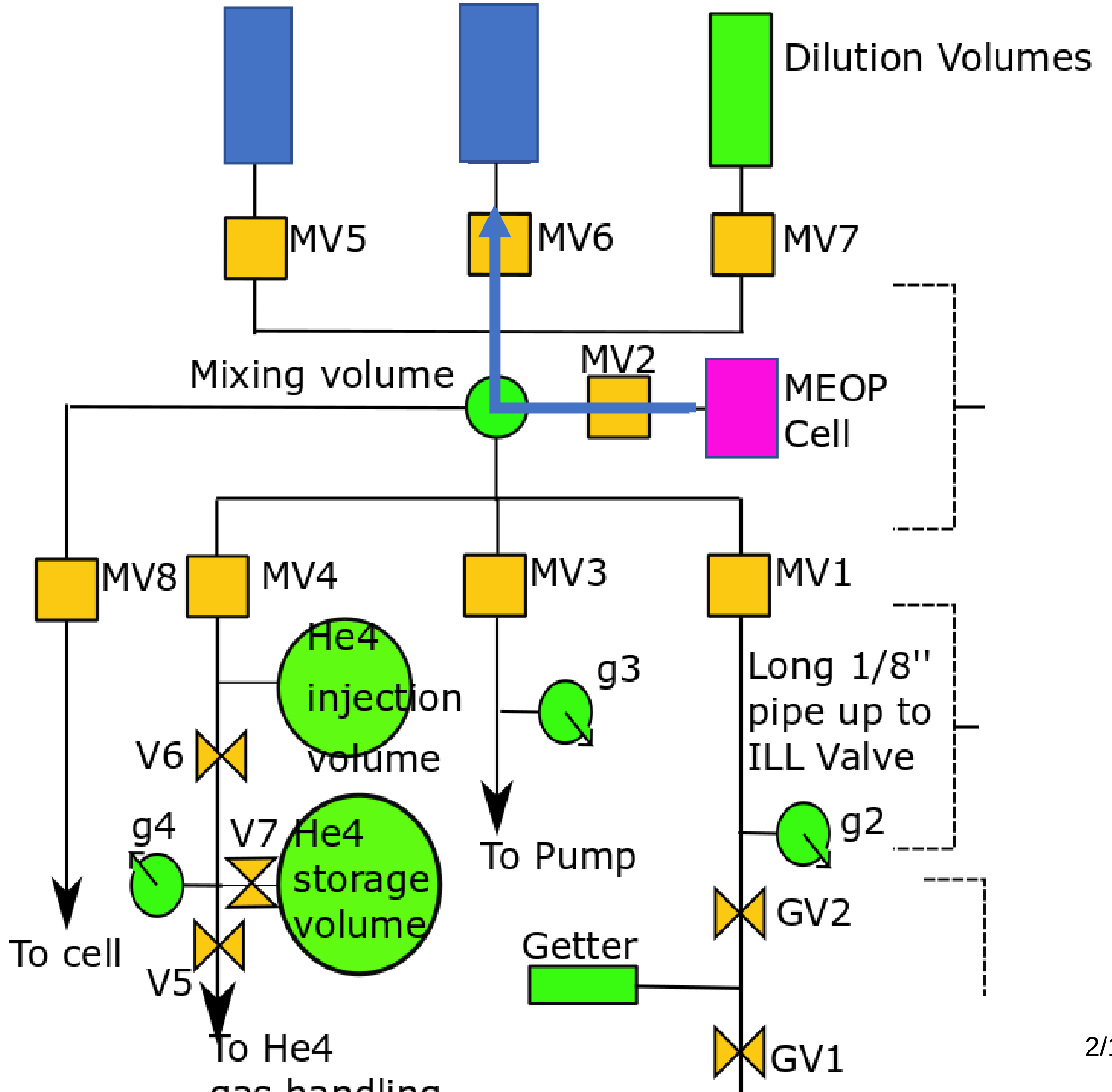
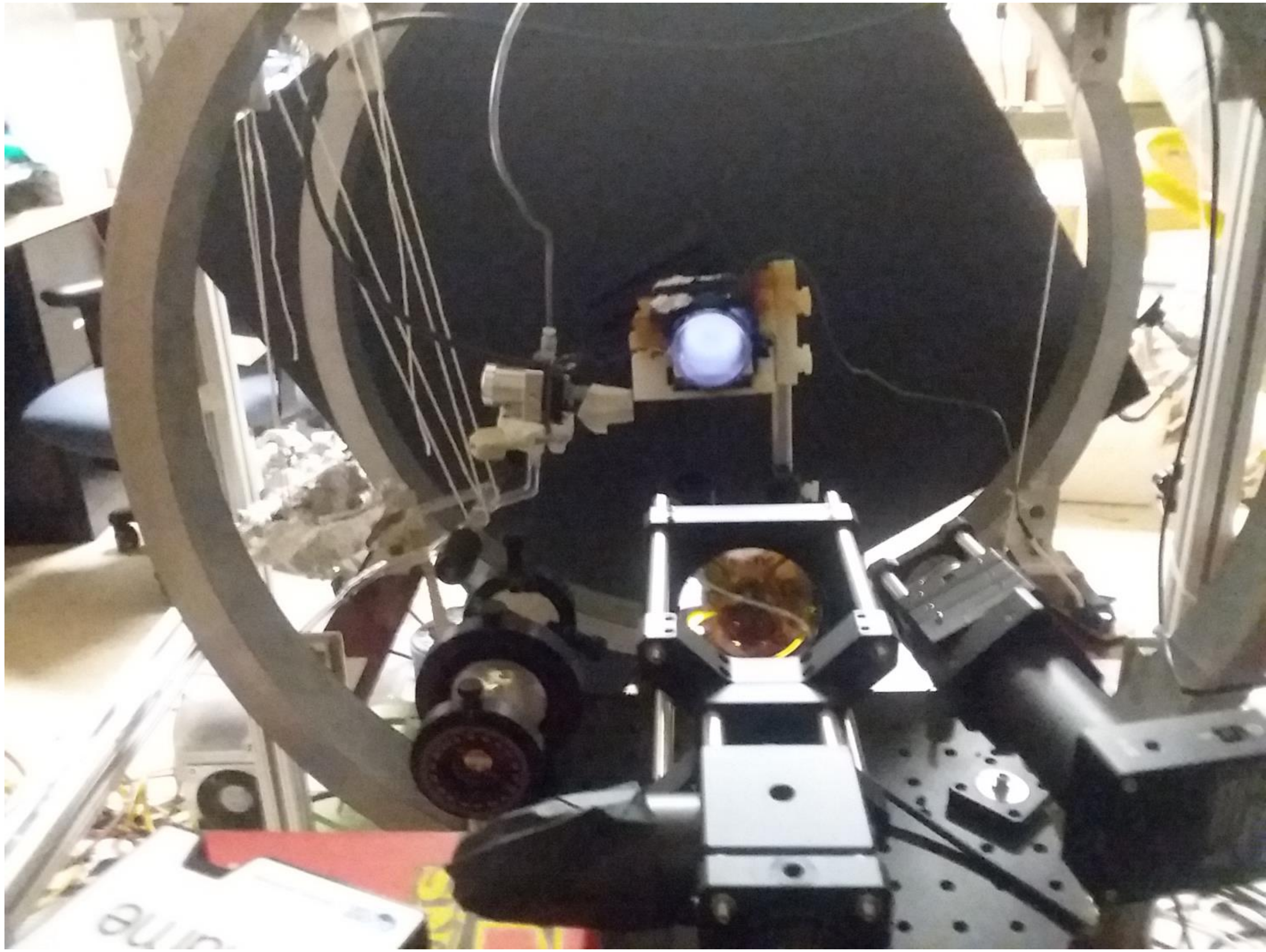


MEOP Test System

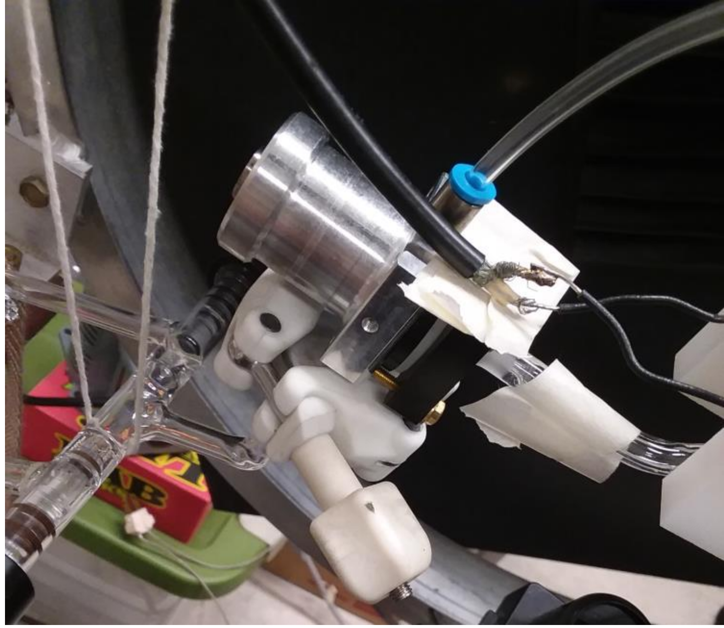
- Used to practice our polarization technique
- Testing parts
  - Spare cells
  - Pneumatically actuated MEOP valves



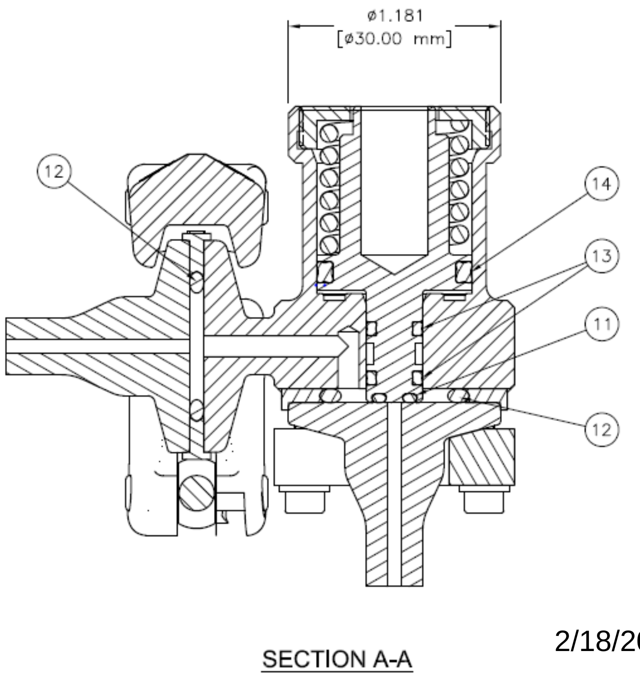
Test of Pneumatic Valves

- Pneumatic valves that will be inside of magnetic field region need to be nonmagnetic in order to minimize gradients that can depolarize ^3He
- T_1 (polarization lifetime) measurements have been made with the pneumatic valves as well as a glass stopcock
- Comparison to the T_1 with the glass stopcock allows us to determine if the pneumatic valves will introduce depolarizing gradients into the 3He system

glass stopcock

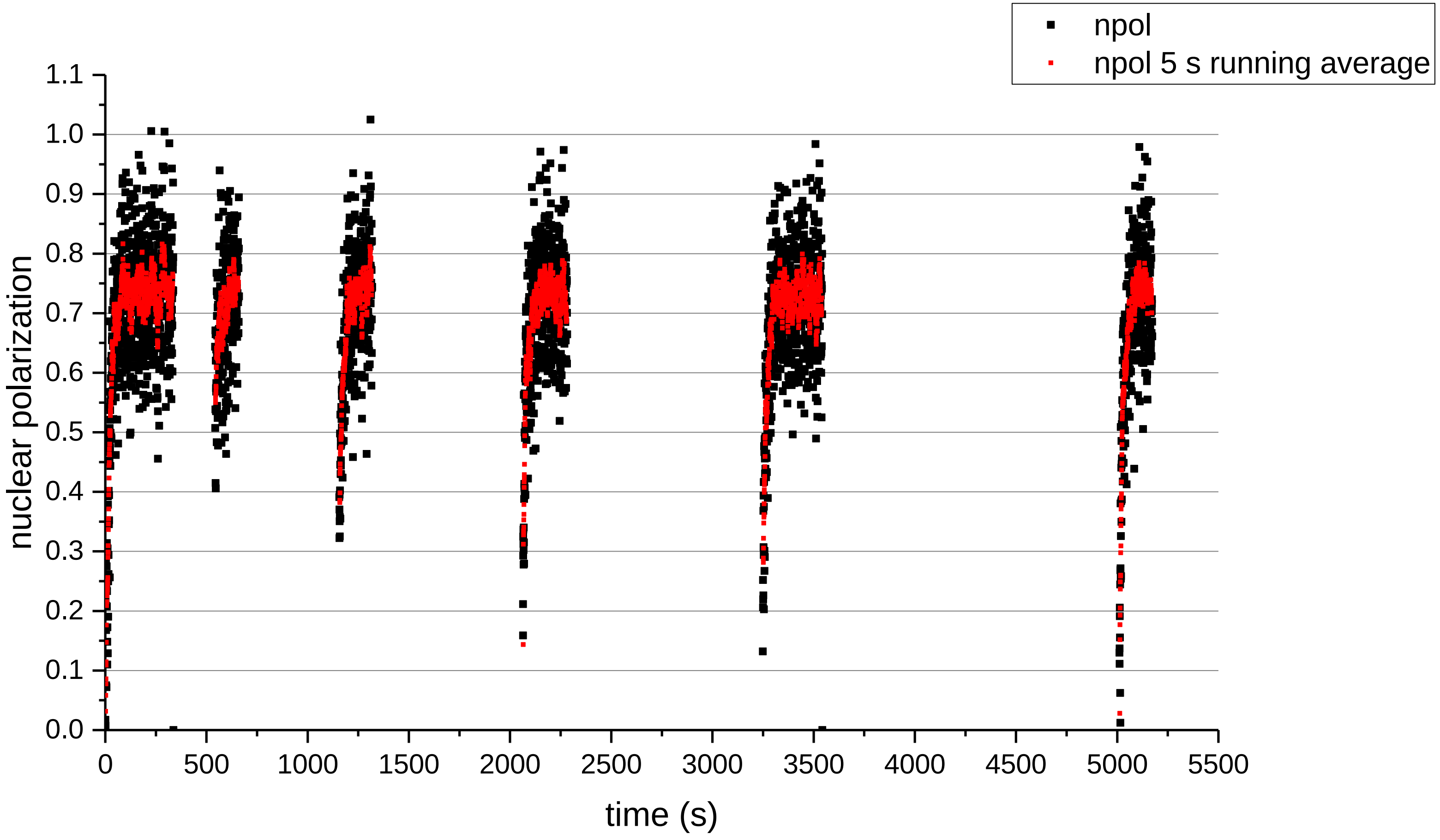


Pneumatic valve



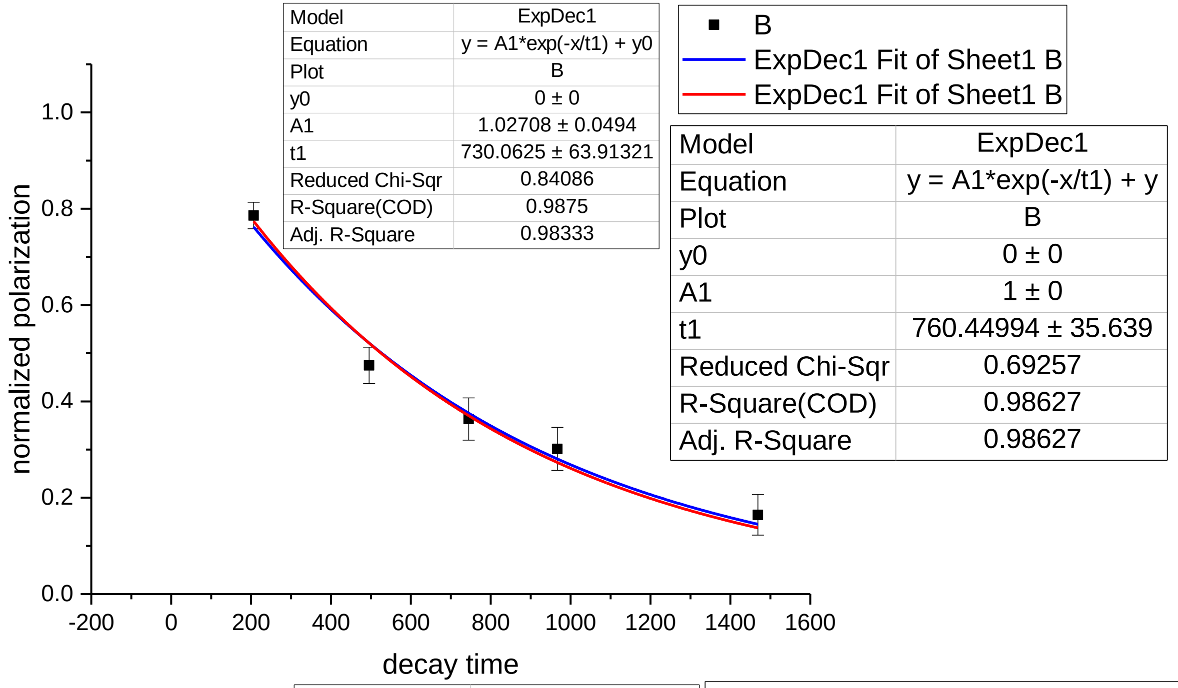
Measuring T_1

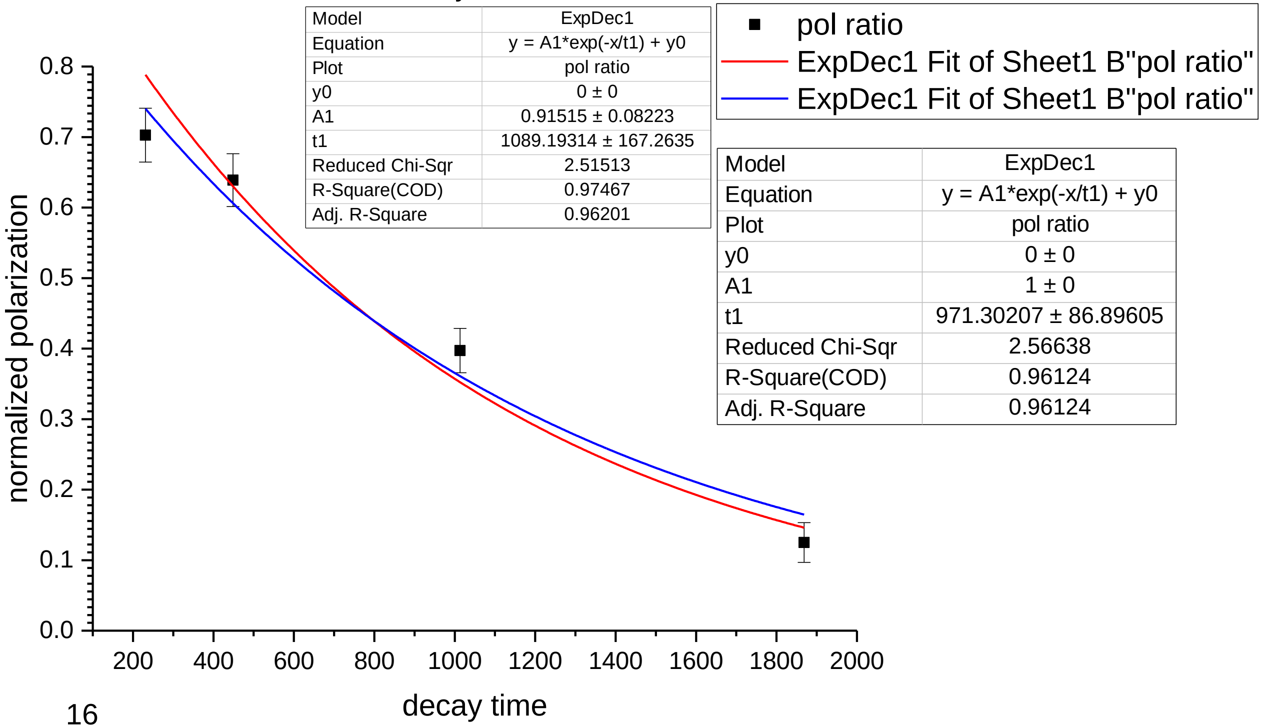
- Polarize ^3He
- Turning off RF results in loss of polarization
- Use ratio between remaining pol and initial pol to determine T_1
- Fit resulting curve as a function of time with RF off (decay time) to exponential decay



T_1 Results

- Two valves have been tested so far
- For 1 torr of gas the T_1 with the gas stopcock is 900s
- The first valve we tested has a T_1 consistent with 900s (970s±90s)
- The second valve has a T_1 of 760±40s indicating the valve indicating a 9% increase in the magnetic gradient



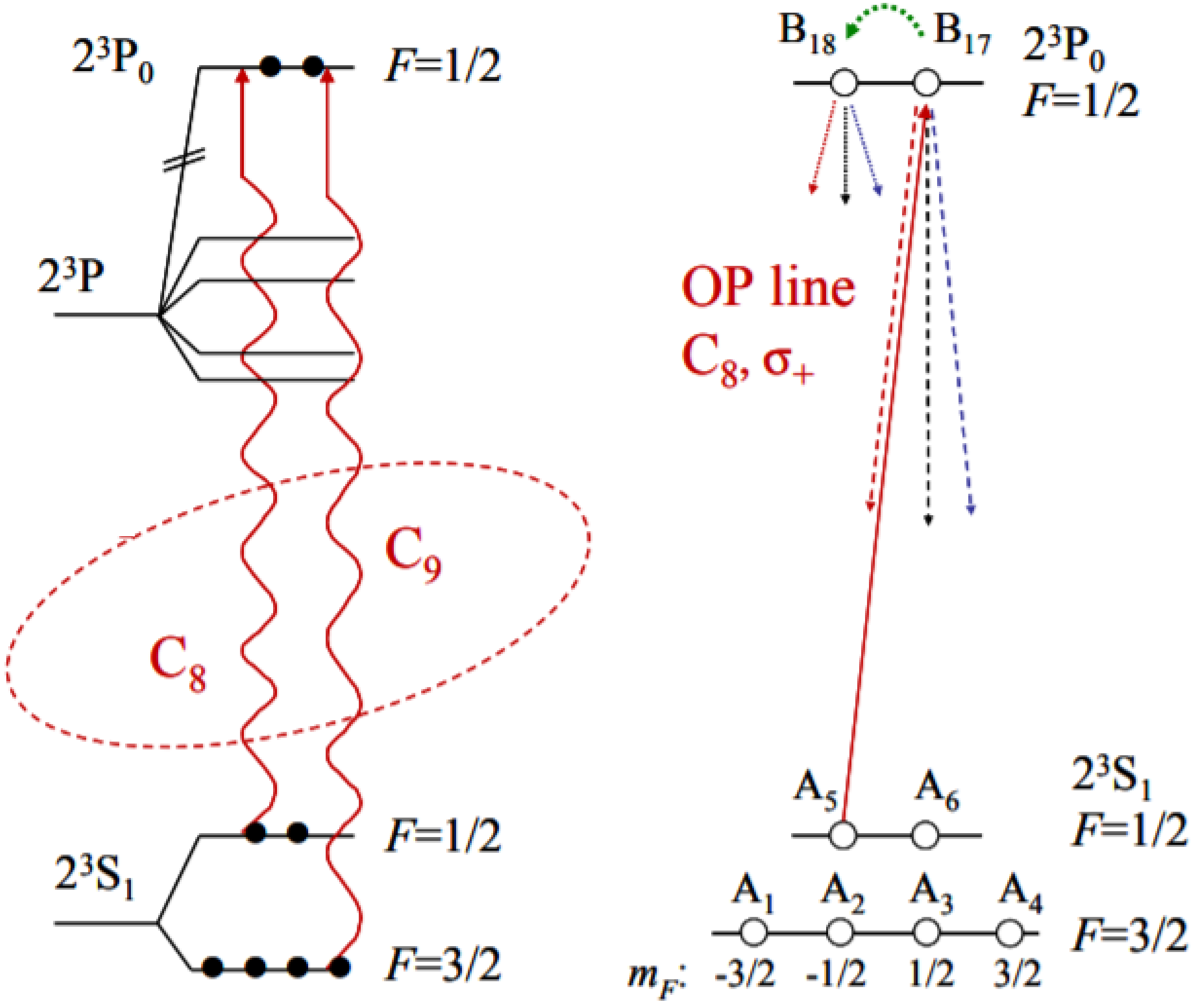


Summary

- $\vec{v} \times \vec{E}$ magnetic field gives rise to false EDM signal in the nEDM experiment
- The size of this effect can be determined by measuring the T_1 , T_2 , or ∇B^2 frequency shift in a system without an electric field
- The SOS apparatus will be used to make this measurement for ^3He and for neutrons
- Polarized ^3He for the SOS apparatus is produced via MEOP
- a ^3He GHS is be fabricated to produce polarized ^3He for the SOS apparatus at concentrations as low as 10^{-10}
- A test MEOP system is being used to test parts for this apparatus

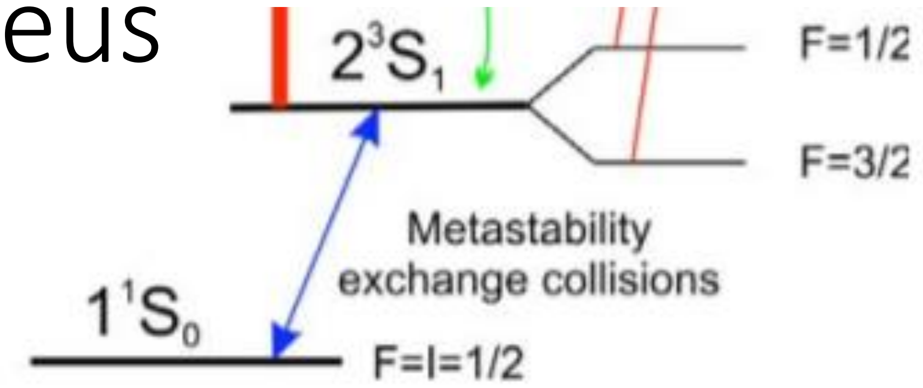
Polarizing the Metastable State

- Magnetic field needed to define polarization axis
- Laser aligned with field
- Optical pumping with 1083 nm Right Circularly Polarized laser tuned to C8 (A5-B17) transition provides polarization



M Batz PJ Nacher G Tastevin *Journal of Physics* **294** (2011)

Transferring Polarization to Nucleus



Guilhem Collier *Metastability Exchange Optical Pumping (MEOP) of ^{3}He in Situ* (2011)

- Atoms in metastable state undergo collision with ground state atoms
- No angular momentum other than spins
- Ground state electrons can't be polarized
- Polarization is transferred to nucleus to conserve angular momentum

$$ {}^3He^* \uparrow + {}^3He \rightarrow {}^3He \uparrow + {}^3He^* $$

$$ |S\rangle \otimes |I\rangle + |I\rangle \rightarrow |I\rangle + |S\rangle \otimes |I\rangle $$

MEOP GHS Layout