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

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nEDM@SNS

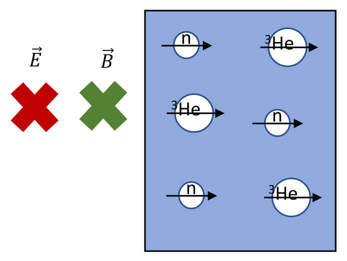
The standard model predicts the neutron's electric dipole moment (nEDM) is on the order of 10^{-32} e·cm. However, extensions to the standard model such as supersymmetry tend to predict much greater EDMs. The nEDM experiment at the spallation neutron source (SNS) plans to measure the EDM to a precision of 10^{-28} e·cm. The EDM is measured using precessing ultra cold neutrons (UCN) and ^{3}He in parallel electric and magnetic fields. A linear in E shift in the precession frequency due to flipping the electric field indicates an EDM.

$$\text{Flip E} \Rightarrow \Delta\nu = \mp\frac{4|d_n|E_0}{h}$$

The precession frequency is measured by detecting scintillation light produced by the spin dependent reaction

$$\vec{n} + {}^3\vec{He} = p + t + 765 \text{ keV}$$

The $\vec{v}\times\vec{E}$ frequency shift is an important source of systematic error for this experiment



Superfluid filled measurement cell

Frequency Shifts and Correlation Functions

The magnetic field gradient seen by the spins while traversing the cell results in a shift in the Larmor frequency ($\delta\omega$). Without the electric field there is a single frequency shift proportional to ∇B^2 ($\delta\omega_{\nabla B^2}$). With the addition of an electric field there is also a linear in E frequency shift due to the $\vec{v}\times\vec{E}$ motional field seen by the particles ($\delta\omega_{\nabla BE}$). These frequency shifts can be described in terms of the spectrum of the trajectory correlation functions of the spins.

Definition of trajectory correlation functions [1]

$$S_{rr}(\tau) = \langle \vec{r}(0)\cdot\vec{r}(\tau)\rangle = \langle x(0)x(\tau)\rangle + \langle y(0)y(\tau)\rangle$$
$$S_{rv}(\tau) = \langle \vec{r}(0)\cdot\vec{v}(\tau)\rangle$$

The spectrum of trajectory correlation functions can be used to calculate frequency shifts and polarization decay times [1]

$$\bar{S}_{rr}(\omega_0) \Leftrightarrow \delta\omega_{\nabla B^2}, T_2 \text{ and } T_1$$
$$\bar{S}_{rv}(\omega_0) \Leftrightarrow \delta\omega_{\nabla BE}$$

By measuring $\bar{S}_{rr}$ you can calculate $\bar{S}_{rv}$ and determine the expected $\delta\omega_{\nabla BE}$ without having an E field

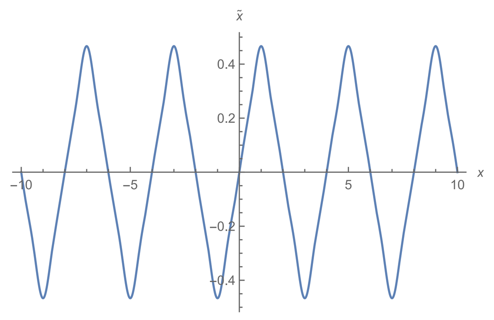
$$\bar{S}_{rr} = -\frac{i}{\omega_0}\bar{S}_{rv} \quad [1]$$

$\bar{S}_{xx}$ can be written in terms of the spectrum of the conditional probability of finding a spin at position r given initial position r_0 over an infinite domain $(\bar{P}(q,\omega))$. $\tilde{x}$ is a periodic extension of the x axis that generates image cells to account for the wall collisions. A similar extension is used for the y axis. $\bar{S}_{rr} = \bar{S}_{xx} + \bar{S}_{yy}$

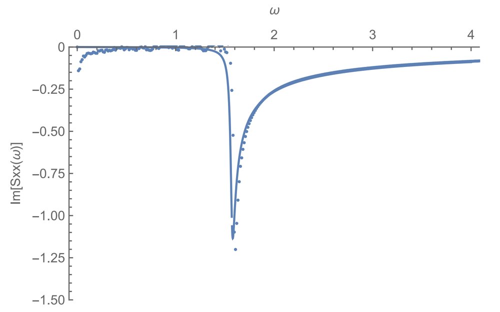
$$\bar{S}_{xx}(\omega) = \frac{1}{2\pi L_x}\int dq \int_{-L/2}^{L/2} dx_0 \int_{-\infty}^{\infty} dx \bar{P}(q,\omega)e^{-iq(x-x_0)}\tilde{x}x_0 \quad [2]$$

Square cell with specular walls. L_x is the length of the cell in the x direction. Swank et al 2016 [2]

$$\tilde{x} = \sum_{odd} -\frac{i^n 2L_x}{\pi^2 n^2} e^{i\frac{\pi x}{L_x}}$$



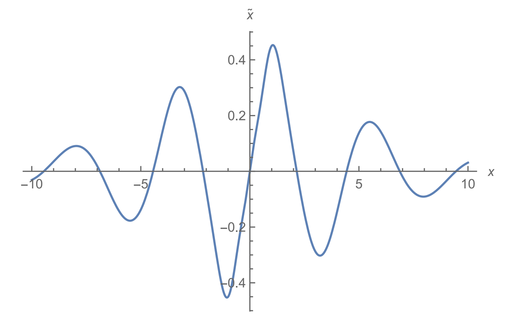
Periodic extension for specular walls with $L_x = 2$. Defines the positions of the images along the x axis. Physical cell ranges from -1 to 1



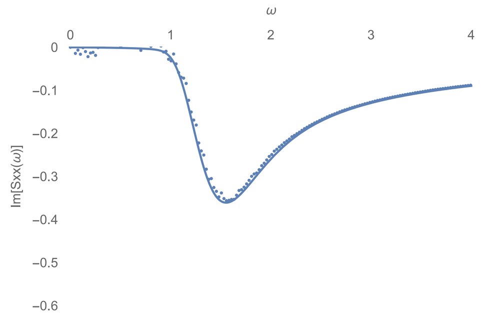
The specular calculation[2] for a 2x2 square cell in the ballistic limit with Lambert scattering walls compared to simulation. The calculation (line) has good agreement with the simulation (points)

Square cell with Lambert scattering walls. We use a heuristic approach, averaging over a distribution of specular periodic extensions with length l. The described results assume a Gaussian distribution $\left(\frac{1}{\sqrt{2\pi}\sigma}e^{\frac{(l-L_0)^2}{2\sigma^2}}\right)$ of image cell dimensions

$$\tilde{x} = \sum_{odd}\left\langle -\frac{i^n 2l}{\pi^2 n^2} e^{i\frac{\pi x}{l}}\right\rangle_l$$



Periodic extension for Lambert scattering walls with $L_x = 2$. Defines the effective positions of the images along the x axis. Physical cell ranges from -1 to 1. $L_{x0} = 2.13, \sigma_x = 0.393$

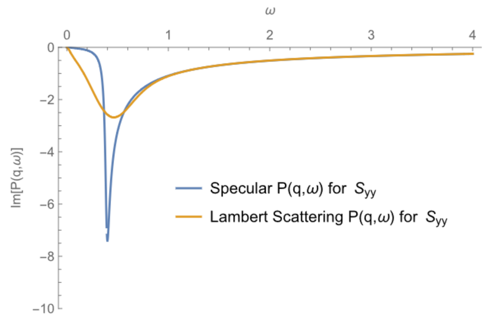


Our calculation using the described heuristic approach for a 2x2 square cell in the ballistic limit with Lambert scattering walls compared to simulation. Our calculation (line) results in the best agreement with the simulation (points) when using

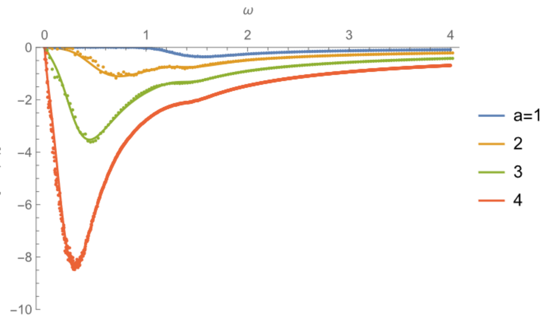
$$L_{x0} = L_{y0} = 2.13 = L_{square}$$
$$\sigma_x = \sigma_y = 0.393 = \sigma_{square}$$

Rectangular cell with Lambert scattering walls. To account for the mixing of the x and y components of the velocity during wall collisions, the conditional probability used to calculate $\bar{S}_{yy}$ is averaged over a Gaussian distribution $\left(\frac{1}{\sqrt{2\pi}\sigma_v}e^{\frac{(v-v_{nom})^2}{2\sigma_v^2}}\right)$ of effective velocities. v_{nom} is set to nominal velocity of the spins. This effect isn't seen in the square cell due to the symmetry between x and y

$$P(q,\omega) \rightarrow \langle P(v,q,\omega)\rangle_v$$



Imaginary part of the original conditional probability density used in calculating S_{yy} for the specular case, and the velocity averaged conditional probability used for the case of Lambert scattering walls. Plot is for $q = \pi/L_y$, $L_y = 8$ and $L_x = 2$. $\sigma_v = 0.405v_{nom}$



Our heuristic Ballistic limit Lambert scattering wall calculation for 4 different aspect ratios (a=Ly/Lx) compared to their corresponding simulation. Lx=2 for all for curves. Our calculation (line) has good agreement with the simulation (points) when

$$L_{y0} = a^2(L_{square} - L_x) + aL_x, \qquad L_{x0} = L_{square}$$
$$\sigma_{y0} = 0.5\sigma_{square}(a^2 + a), \qquad \sigma_{x0} = \sigma_{square}\frac{2a}{a^2 + a}$$
$$\sigma_v = \sigma_{v0}\frac{a^2 - a}{a^2}, \sigma_{v0} = 0.54 \text{ (best fit to simulation)}$$

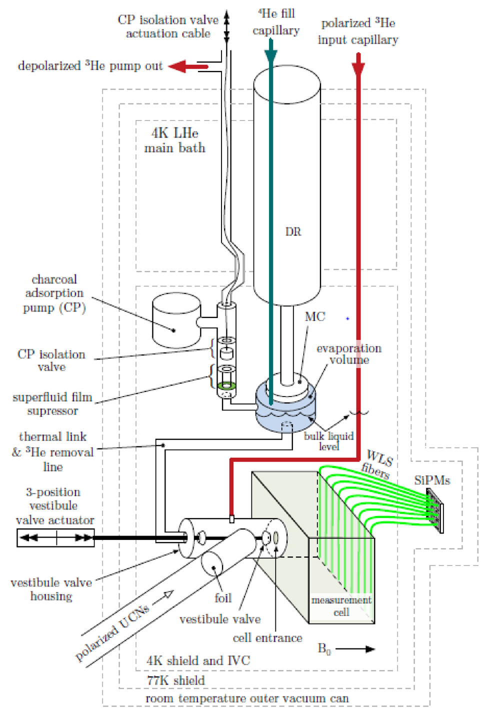
[1] R. Golub, C. Kaufman, G. Müller, and A. Steyerl Phys. Rev. A **92**, 062123 (2015)

[2] C.M. Swank, A.K. Petukhov, R. Golub Phys. Rev. A **93**, 062703 (2016)

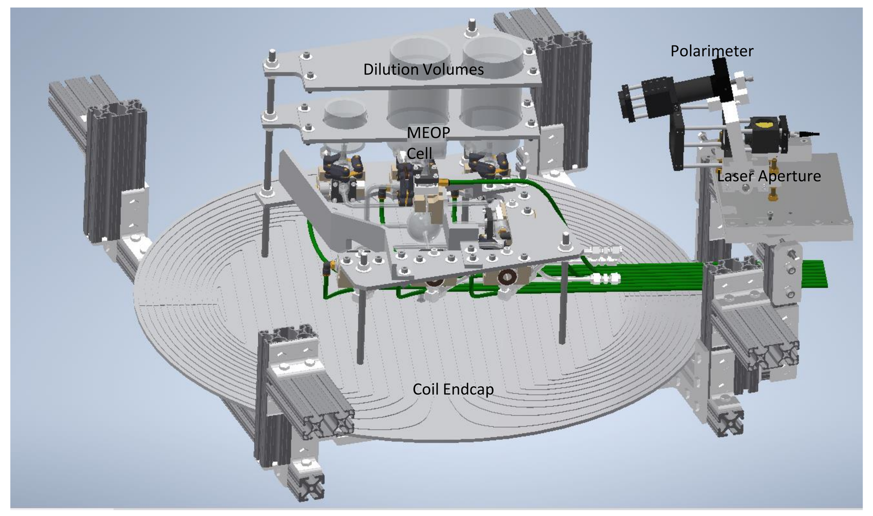
SOS Apparatus

The SOS apparatus is effectively a scaled down version of the final experiment without the electric field needed to measure an EDM. It will be used to determine the correlation functions of ^{3}He (@Duke) and neutrons (@PULSTAR) by measuring the T_1, T_2 and $\delta\omega_{\nabla B^2}$. Additionally, the SOS will be used to study spin dressing. The measured values can then be used to predict the size of $\delta\omega_{\nabla BE}$ 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

Picture of SOS@Duke apparatus. At Duke no UCN are present. The precession of the ^{3}He is measured using SQUIDS



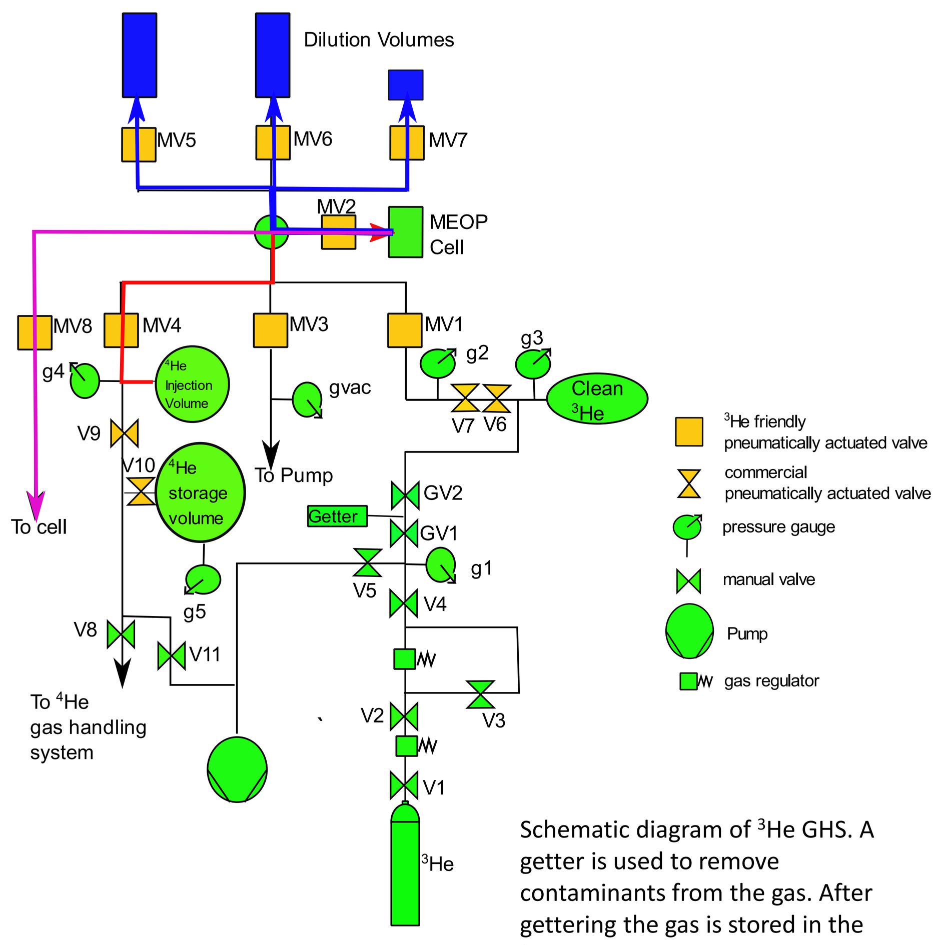
Schematic drawing of SOS@PULSTAR. Includes UCN beamline and light collection fibers, used to measure neutron precession, which aren't present at Duke



Model of the metastability exchange optical pumping (MEOP) system used to polarize and inject ^{3}He. Located on top of the SOS cryostat. The laser is used to optically pump the ^{3}He. The polarimeter optically measures the polarization of the gas. There is also a magnetic holding field coil that encloses the glass manifold (not shown except for bottom endcap). As well as a RF coil attached to the MEOP cell used to populate the $2S_1$ state used for optical pumping (not shown)

^{3}He Gas Handing System

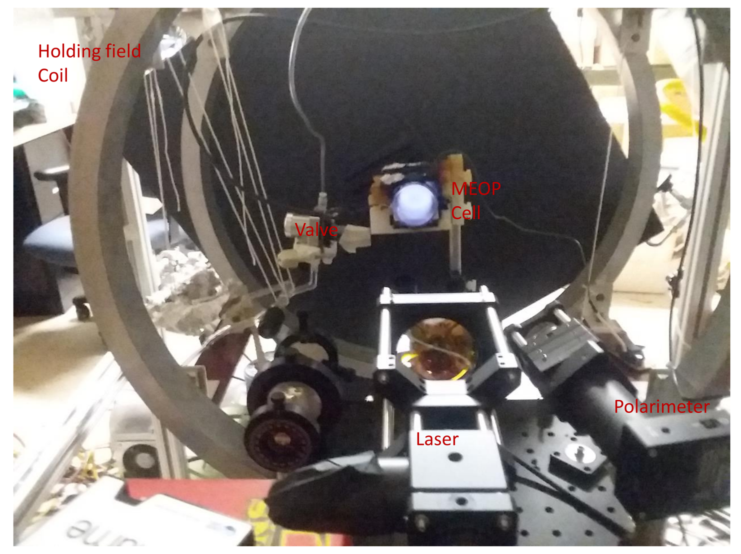
The SOS experiment uses Metastability Exchange Optical Pumping (MEOP) to produce 80% polarized ^{3}He. MEOP is performed with 1.3 mbar of ^{3}He in an 80cc MEOP cell. If all of this ^{3}He is injected into the measurement cell the concentration will be much larger than the desired concentration of 10^{-10}. But if the concentration is reduced by pumping ^{3}He out of the cell the decrease in pressure will significantly reduce the lifetime of the polarized state. To prevent this, 500 mbar of isotopically pure ^{4}He is injected into the cell (red path) before diluting the ^{3}He. Then once the cell is pressurized the cylindrical "dilution volumes" are used to "pump" out the excess the ^{3}He (blue paths). To reach the desired concentration of 10^{-10} three rounds of dilution, with pressurizing in between, is required. Once enough ^{3}He is removed from the MEOP cell the gas is injected into the 0.4 K measurement cell inside the cryovessel (purple path).



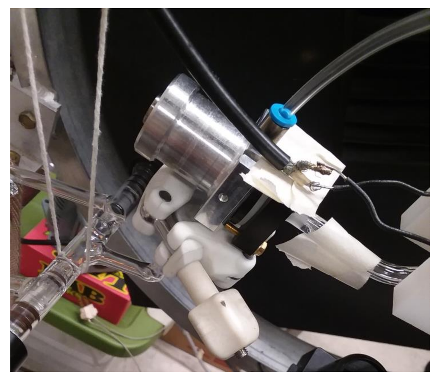
Schematic diagram of ^{3}He GHS. A getter is used to remove contaminants from the gas. After gettering the gas is stored in the ^{3}He clean volume. Using v7 and v6 small amounts of ^{3}He can be used to fill the MEOP cell to 0.1 mbar precision

MEOP Test Apparatus

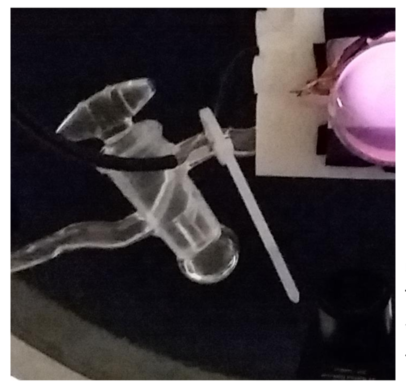
A MEOP test apparatus exists at Duke which is used to test that the pneumatic valves in the magnetic field region (MV1-MV8) do not introduce any magnetic gradients that could reduce the lifetime of the polarized state (T_1). T_1 measurements have been made with the pneumatic valves as well as a glass stopcock installed in the system. Comparing the T_1 with a pneumatic valve installed to the T_1 with the glass stopcock allows us to determine if the pneumatic valves will introduce depolarizing gradients



MEOP test apparatus

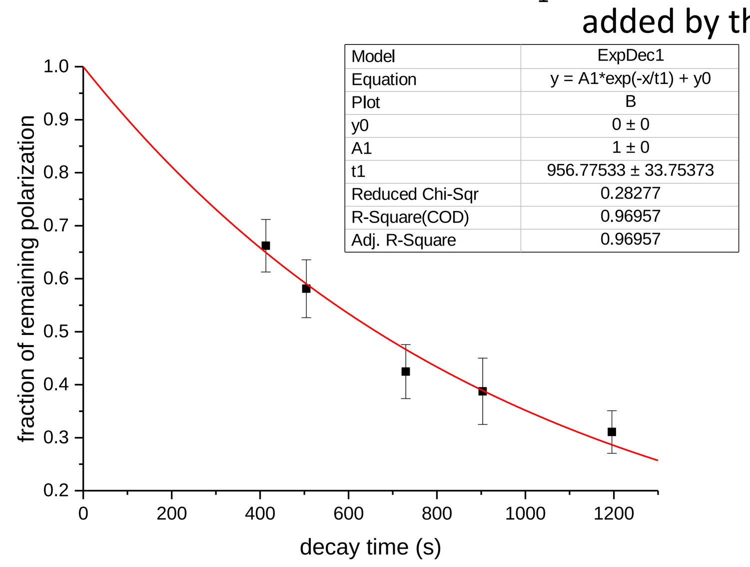


Close up a pneumatic valve being tested



Close up of the glass stopcock. T_1 measurements with this valve in were used to get a baseline T_1 of the system

8 pneumatically actuated valves, based on an ILL design, made from Al 5083 have been tested. The T_1s measured indicated no significant gradients are added by the valves



T1 measurement with MV6 installed. The T1 is consistent with what was measured for the glass stopcock indicating no additional gradients were introduced by the valve

Valve	T_1 (s) at 10 G and 1.3 mbar
Glass stopcock	940±30
MV1	1100±90
MV2	970±90
MV3	1080±70
MV4	1120±70
MV5	760±40
MV6	960±30
MV7	940±30
MV8	940±30

Injection Simulations

Injecting the ^{3}He will result in a significant heat load to the 0.4 K measurement cell. The size of this heat load was simulated using COMSOL. The polarized helium input capillary, shown in the schematic drawing of the SOS, is made from Kapton tube, is approximately 1.5 m long, and is 2 mm in diameter.

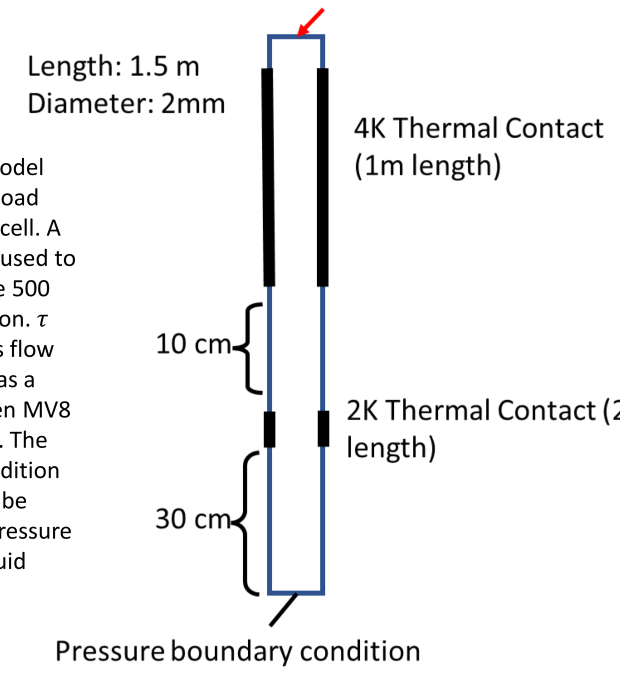
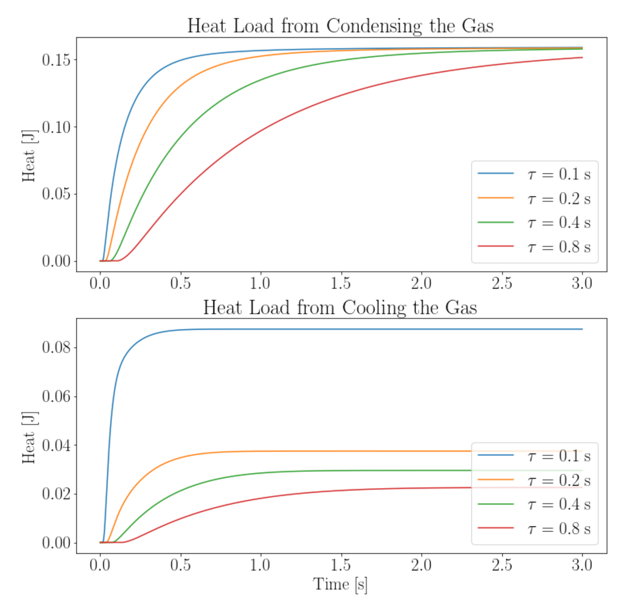


Diagram of COMSOL model used to calculate heat load into the measurement cell. A time dependent flux is used to model the inflow of the 500 mbar gas during injection. τ controls the rate of this flow and can be thought of as a flow restriction between MV8 and the input capillary. The pressure boundary condition at the bottom of the tube represents the vapor pressure from the superfluid liquid level.



Simulation indicates most of the heat load comes from the helium condensing into the vestibule, not cooling the helium to 0.4 K. As such a room temperature flow restriction isn't critical. However, the heat load into the measurement cell could be reduced by forcing the helium to condense inside the line instead of at the vestibule. This can be accomplished by heat sinking the input capillary to the dilution refrigerator still and adding a flow restriction at that location