# $^3$He gas handling system and RF discharge for optical pumping

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Axions are hypothetical pseudo scalar particles that appear in the solution of the strong CP problem. Axions can also be a dark-matter candidate if their mass is in light regime. Many of these haloscope experiments to detect axions are based on this assumption. In addition, Moody and Wilczek postulated an interaction between monopole and dipole masses that can be mediated by axions at macroscopic scale [1]. We propose new experiment that can detect axions by measuring by pseudo-magnetic field induced between monopole and dipole. For this experiment, we have developed $^3$He polarization system using metastable exchange optical pumping (MEOP) technique.

## 1 Introduction

Axion Resonant InterAction DetectioN Experiment (ARIADNE) is measuring monopole-dipole interactions to detect axion like particle. In ARIADNE concept is, the axion mediates interaction between monopole-dipole, and this interaction can be expressed as pseudo magnetic field. It is also macroscopic interaction, therefore one can detect pseudo-magnetic field as a function of distance of two objects. We calculated the potential in the case of monopole-dipole interaction case, the unpolarized mass is cylinder shape and polarized $^3$He, as the function of distance between two objects. $^3$He is used in this experiment because it has long relaxation time and can be treated as an elementary particle. To make polarized $^3$He, we used Metastable Exchange Optical Pumping (MEOP). To transport $^3$He gas to the optics and to do experiment we construct gas handling system and test $^3$He discharge using RF amplifier.

## 2 Theory

### 2.1 Monopole-dipole Interaction

According to monopole-dipole interaction potential,

$$U(r) = (g_s^1 g_p^2)\frac{\hat{\sigma_2} \cdot \hat{r}}{8\pi M_2}[\frac{1}{\lambda r} + \frac{1}{r^2}]e^{-\frac{r}{\lambda}} \ , \tag{1}$$

this interaction is spin dependent, and distance dependent potential. From experiment schematic, polarized $^3$He is needed rule of spin dependent part, and rotating mass with n-section cylinder will make distance dependent effective B- field. The potential form is $U(r) = -\nabla \cdot \hat{\sigma_2}$, and we detect the effective B- field $\vec{B}_{eff} = \frac{2\nabla V(r)}{\hbar\gamma}$, $\gamma$ is gyromagnetic ratio.

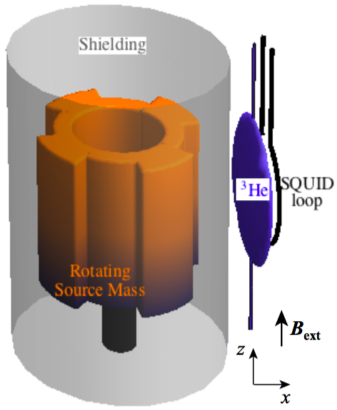


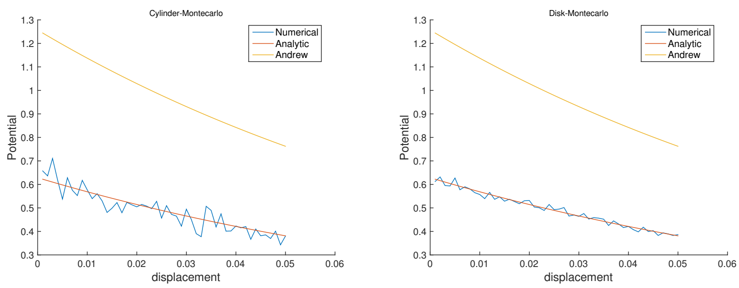

Figure 1: ARIADNE experimental schematic for monopole-dipole interaction [3].

### 2.1.1 Potential calculation for cylinder model

We calculate the potential generated by monopole dipole interaction with surface approximation, and get analytic solution,

$$U_T(r) = -(g_s^1 g_p^2)\frac{\hat{\sigma_2}\cdot\hat{z}}{4M_2}n_N \int_{\epsilon}^{\sqrt{C^2+\epsilon^2}} e^{-t/\lambda}dt \simeq -(g_s^1 g_p^2)\frac{\hat{\sigma_2}\cdot\hat{z}}{4M_2}n_N \lambda e^{-\epsilon/\lambda} \quad (2)$$

however it is 1/2 small than “Resonantly Detecting Axion-Mediated Forces with Nuclear Magnetic Resonance” paper [3]. In this approximation we assume the cylinder as disk with effective radius “C”. In Monte-Carlo calculation for this disk model and real cylinder model get similar trend line with our calculation.




(a) Cylinder (b) Disk

Figure 2: Monte-Carlo Calculation

## 2.2 MEOP

MEOP is polarizing method of $^3$He using RF discharge and 1083nm laser. RF discharge excites the atoms into the excited states, and ppm fraction of them will be in the metastable state,

$2^3S_1$. We apply magnetic field about 50G, spin state of electron and nuclei will couple and make hyperfine structure. Left circularly polarized 1083nm laser will pump the spin state to the $m_F = 1$, and it will decay into sub level of $2^3S_1$. By spin exchange collision, the spin state $1^1S_1$ in $m_F = -1/2$ will be in the $m_F = 1/2$ states.

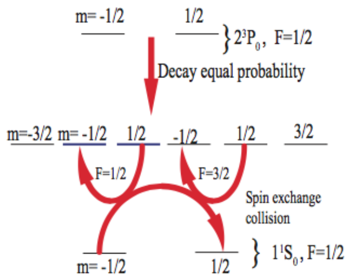



Figure 3: MEOP schemetic

# 3 Experiment setup

## 3.1 $^3$He gas handling system

### 3.1.1 Gas handling system

In ARIADNE experiment, we are going to use $^3$He as polarized mass object. We need to transport gas from $^3$He tank with 120atm in 0.46L to non magnetic part which contains polarization and experiment part. After experiment we need to deliver gas to recovery tank denote as $R_2$. Also we need to transport gas from $R_2$ to the other gas flow line. In emergency case, this system will separate non magnetic part and magnetic part and recover to the emergency tank. (a) is $^3$He gas bottle with 120 atm in 0.46L and compressor connected with 6 in gas handling

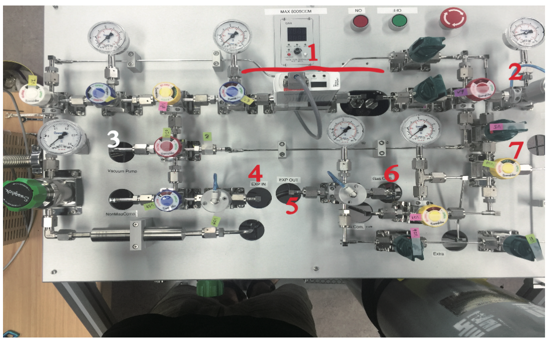
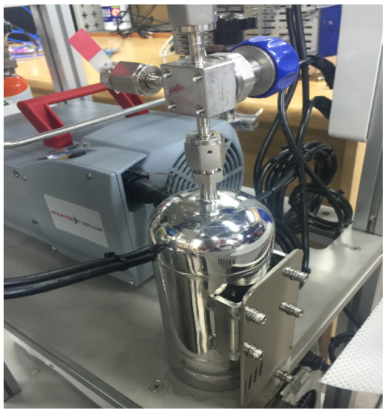



Figure 4: Gas handling system

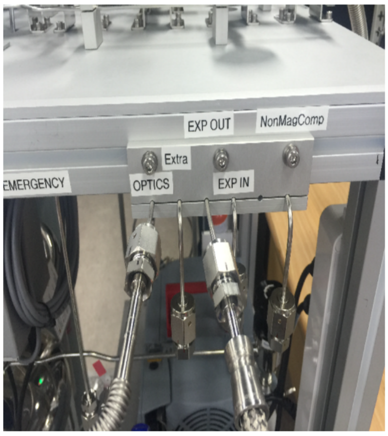
system. (b) is emergency tank which is connected to 7. (c) is recovery tank connected with gas

(a)



(b)

(c)




(d)

Figure 5: Part of gas handling system

compressor. (d) is the lines which will be connected to non-magnetic part, such as optics system, and non magnetic compressor and experiment part which is 2, 3, 4, 5 part in gas handling system.

### 3.1.2 Gas compression test

In gas handling system we need to restore almost of $^3$He used in experiment. We design the restore tank that can contain all of $^3$He gas which is filled in 120atm in 0.46L bottle. The gas used in experiment will be compressed to the restore tank using compressor. According to our compression test, we can compress gas to the tank over 1atm. That means we can restore the $^3$He gas which is used in experiment, and recycle it. As a graph, we can increase the restore tank pressure 0.1MPa per 20 minutes in highest flow rate (200sccm).

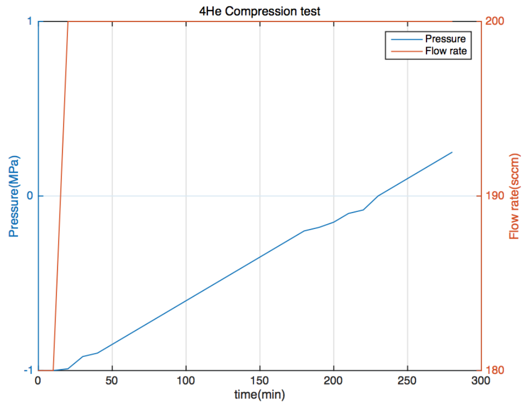



Figure 6: Compression test

### 3.2 RF discharge study

Our RF amplifier is IFI solid state amplifier, SXXL150 Model, designed to amplifying signal from function generator. This instrument can obtain 1.5 30.0MHz frequency wave and output power is 150W. Using function generator, we make input signal to the amplifier and changing gain of it, we check when $^3$He cell is discharged. Our $^3$He has 1mbar pressure and 2 inch diameter and 6cm height. We scan the frequency range from 1.6MHz to 3.0MHz. The amplitude that measured by oscilloscope was over 50V, and approximately about 70V and the frequency was about 400kHz. We measure the discharge maintaining time after $^3$He is discharged.

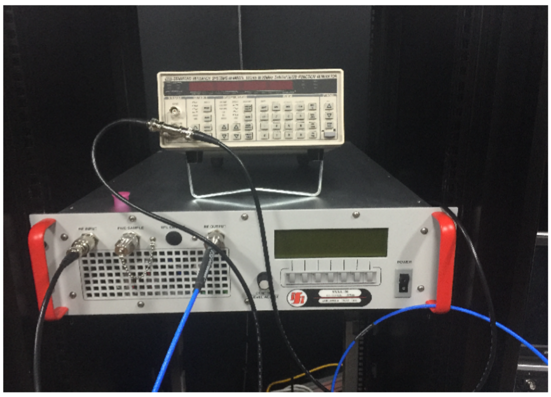


Figure 7: SXXL amplifier and function generator

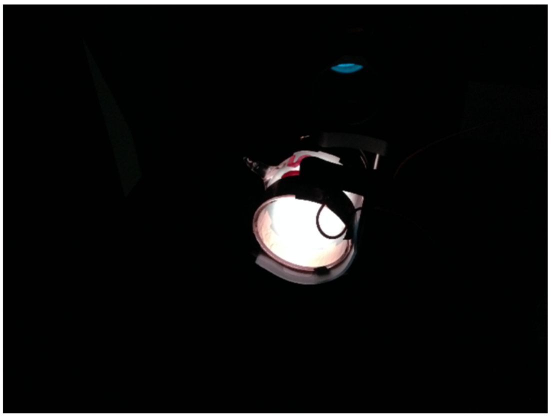
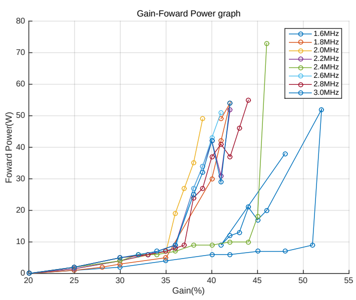


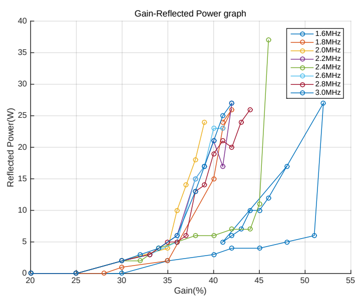
Figure 8: $^3$He discharge

### 3.2.1 Forward, Reflected power measurement

From this measurement if the gain is over 50W, the $^3$He is ignited and for 2.0MHz case and 2.6MHz case the fluctuation of forward and reflected power is stable, however the other cases? fluctuation is huge.



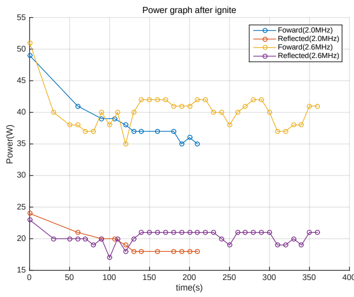

(a)



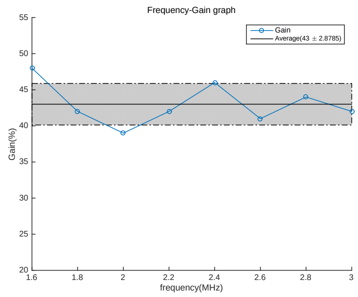

(b)

### 3.2.2 Discharge maintain time measurement and glow gain-frequency measurement

For 2.0MHz case, the fluctuation is small so we expect it will has long discharge time, however forwarding power decrease slowly, and it turns off at 220 second. For 2.6MHz case forward power is decreased to 40W and maintain over 6 minutes with average forward about 40W. We turn off discharging when 6minutes reached. The first gain when $^3$He starts discharge is at 43% gain average with standard deviation is 2.8785.




(c)




(d)

# 4 Conclusion

We construct gas handling system for transport $^3$He gas to the experiment part. We can compress the gas in the flow line to the restore tank which is designed to restore $^3$He gas in 1atm. According to the compression test using $^4$He gas, we get compression rate 0.1MPa per 20minutes in 200sccm flow rate. To do MEOP, we need to discharge the $^3$He cell. In real experiment we will discharge 1m long cell, so we use high power RF amplifier. For test cell with 2 inch diameter and 6cm long cell we can discharge this cell at 43% gain average. For 2.0MHz and 2.6MHz case we can discharge the cell stablely. The glass cell which will be filled with $^4$He or $^3$He gas in 1mbar and to increase relaxation time T2, we will construct cleaning system of wall of cell, and we will test polarization of $^3$He gas using optical polarimeter.

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