

# CULTASK, Axion Experiment at CAPP in Korea

Woohyun Chung<sup>1</sup>,

<sup>1</sup>Center for Axion and Precision Physics Research, IBS, Korea

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CAPP's flagship axion experiment, CULTASK has been built on a low vibration facility at Munji campus of KAIST in Korea. We have so far installed 4 dilution refrigerators with two 8T superconducting magnets, which allow us to explore axion mass range of 2~ 2.5 GHz and 1.35~1.6 GHz, respectively. A resonant cavity (10 cm OD) with a sapphire tuning rod driven by piezoelectric actuator system was successfully cooled down below 30 mK and showed very high unloaded Q-factor ( $\sim 120,000$ ) even under 8T magnetic field. RF receiver employs 1K HEMT amplifier out of the cavity, but the design is flexible enough to replace it with SQUID amplifier when R&D is completed soon. I will present the status and possibly the very first data of CULTASK and our future plans. I will also discuss about the progress of our R&D projects, development of superconducting cavities and SQUID amplifiers.

## 1 Introduction

The design of the axion experiment at the Center for Axion and Precision Physics Research (CAPP) of the Institute for Basic Science (IBS) of Korea is based on P. Sikivie's haloscope technique[1] which has been refined by the Axion Mark Matter eXperiment (ADMX)[2] since 1996. In this scheme, axions resonantly convert to microwave photons by a reverse Primakoff interaction inside a tunable cavity permeated by a strong magnetic field. The feeble signal from the cavity is amplified through a SQUID amplifier and transmitted to a room temperature RF receiver unit to be processed further. HAYSTAC[3] recently reported results from a new microwave cavity detector designed to search axions in a mass band above  $10 \mu eV$ , employing advanced quantum electronics.

CAPP's first small scale axion detector is ready to make an engineering run and we are in parallel driving a research and development plan to achieve the sensitivity required for the wider range of axion models. The R&D plan includes high field superconducting magnets with various bore sizes (18T with 7 cm, 25T with 10 cm and 12T 32 cm bore), high Q-factor superconducting cavities, high-gain gigahertz superconducting quantum interference device (SQUID) amplifiers and multi-cavity phase locking scheme for higher axion mass.

## 2 R&D Projects for Axion Research at CAPP

A powerful 25 T superconducting magnet is being developed and will be delivered by BNL (Brookhaven National Laboratory) in early 2019. This ultra high field magnet being developed by BNL has exceptionally big 10 cm bore and is based on a next generation technology called HTS (High Temperature Superconductor). Meanwhile, 18T superconductor magnet with 7 cm bore has been fabricated by Korean company, SuNAM with the same HTS technology will be delivered on September this year. Another superconducting magnet in the pipeline is a big bore (32 cm) LTS magnet with 12T. The compact (outer diameter of only 30 cm) design of the 25 T HTS magnet is intended to produce even higher field above 35T by adding a layer of 12T LTS magnet outside in the future. If successful, this magnet will be the highest-field superconducting magnet in the world with HTS technology.

The effort of developing high-Q factor cavity is lead by Prof. Jhinhwan Lee of KAIST (Korea Advanced Institute of Science and Technology). There are two routes we are trying to make the cavity's inner surface superconducting to increase the Q-factor for the frequency range of interest, 1 to 5 GHz. One is to coat superconductors directly (for example, by sputtering) to the inner surface of resonant cavities and the other is to apply HTS tapes to the inner wall. Various configurations and different coating materials are being experimented now to overcome the effect of high magnetic field ( $>8T$ ) that goes through the cavity and to achieve the high Q-factor ( $> 10^6$ ) for the resonant mode of choice ( $TM_{010}$ ). This is a rather long term project to pursue in parallel with others. Meanwhile we have prepared and tested variety of sample cavities (OFHC Cu, 5N Al and 6N Al) for enhancing Q-factors in a cryogenic temperature. The technique of annealing is crucial for improving a Q-factor and we are at the stage of calibrating annealing furnace. The other important factor that has an impact on Q-factor is surface roughness. The high precision diamond-cutting technology is employed and the surface tolerance is less than 50 nm.

Even though increasing the magnetic field inside and the Q-factor of the resonant cavity would raise the conversion power of axions to photons, the biggest effect could be the temperature of the whole detector system which is usually the sum of the physical temperature of the resonant cavity including a tuning rod and the noise temperature of RF components. The RF noise temperature is dominated by that of the first amplifier, 1K HEMT or SQUID amplifier in our case. In order to search the wide range of axion mass in a reasonable time period, lowering the system temperature is essential to increase the scanning speed of the detector. Our axion detector already exhibits the coldest physical temperature ( $<30$  mK), however 1K HEMT shows around 1 K of noise temperature yet. It is therefore crucial for CAPP to utilize recent progress in quantum electronics technology of SQUID or JPA (Josephson Parametric Amplifier), to reduce the noise and push it close to quantum limit ( $\sim 50$  mK per GHz) in order to improve the signal-to-noise ratio and speed up the experiment.

The first sample of dc SQUID amplifiers (center frequency of 2.5 GHz) developed by Dr. Yong-Ho Lee of KRISS (Korea Research Institute of Standards and Science) and commercially available ez-SQUID (by Michael Mueck) have been delivered and being tested now. We are also considering the collaboration with IPHT(Leibniz Institute of Photonic Technology) for developing SQUIDS working for different ranges of frequencies. JPA is another excellent candidate for extremely low noise amplifier that becomes very popular these days because of quantum computing (Qubits). We are currently testing one JPA from Konrad Lehnert of JILA (Joint Institute for Laboratory Astrophysics), but the JPC(Josephson Parametric Converter) from Yale's spin-off company, QCI is also on our list of future purchase.

### 3 CAPP Ultra Low Temperature Axion Search in Korea (CULTASK)

Refrigerators					Magnets			
Manufacturer	Model	Installation	Usage	Location	Strength & Bore size	Material	Manufacturer	Delivery
<b>BlueFors (BF3)</b>	LD400	2016	RF and Cavity test	RF room				
<b>BlueFors (BF4)</b>	LD400	2016	JPA & RF chain test	RF room				
<b>Janis</b>	HE3	2017	Magnet test	LVP 4	9T 12 cm	NbTi	Cryo-Magnetics	2017
<b>BlueFors (BF5)</b>	LD400	2017	Axion Exp DAQ & RF	LVP 6	8T 16.5 cm	NbTi	AMI	2016
<b>BlueFors (BF6)</b>	LD400	2017	Axion Exp Large bore	LVP 7	8T 12 cm	NbTi	AMI	2017
<b>Leiden</b>	DRS1000	2017	Axion Exp	LVP 3	25T 10 cm	HTS	BNL/CAPP	2019
<b>Oxford</b>	Kelvinox	2017	Axion Exp	LVP2	12T 32 cm	NbSn	Oxford	2019

Figure 1: Refrigerators and Magnets at CAPP (KAIST Munji campus)

CAPP’s experimental hall is finally ready in a building located at KAIST Munji campus with completed low vibration facility for 7 stations, each with a 20 ton concrete block sitting on air springs. Adding two more dilution refrigerators (BlueFors LD400) installed and tested in March 2017, we are now operating 4 dry-type dilution refrigerators and three wet-type refrigerators will be added to the low vibration pads (LVP) later this year.

Currently, two refrigerators are designed for testing RF components (directional couplers, cryogenic circulators, resonant cavities and HEMT or SQUID amplifiers) and the other two refrigerators equipped with 8T superconducting magnet (12 cm and 16.5 cm inner bores) are for setting up small scale axion engineering runs. These refrigerators are designed to cool down and warm up relatively quick (20 ~ 24 hours or 40 ~ 48 hours when there is a 50 kg magnet attached) and fully automatic with a script so that it could cool down all the way with a touch of a button. Figure 1 lists refrigerators and superconducting magnets installed and to be installed in 2017.

#### 3.1 Engineering Run in 2016

We have set up a small scale but rather complete, mid-to-low sensitivity axion experiment with one of the BlueFors dilution refrigerators as a starter. This detector includes 8T NbTi superconducting magnet, 9 cm inner diameter OFHC Cu cavity (split type), cryogenic RF chain (antenna probe, directional coupler, cryogenic circulators and 1K HEMT amplifiers), and a system of room temperature RF receiver for readout. In addition, there is a DAQ system (CULDAQ) that controls, monitors the whole detector, and collects and stores data for analysis.

The split-type microwave resonant cavity of 9 cm inner diameter (2.5 GHz for  $TM_{010}$  mode) was fabricated and a support structure with frequency tuning system. The frequency tuning system with a sapphire tuning rod controlled by piezoelectric actuator has gone through a

precision test recently, with a rotator resolution of 1/1000 degree, which corresponds to 2.5 ~ 5 kHz per step. The linear piezoelectric actuator controls the antenna to extract the signal from the cavity. After the annealing and surface treatment, cavity's Q-factor at low temperature reached around 120,000 when sapphire tuning rod was at the center. The physical temperature of the cavity and the support structure reaches 28 mK with complete setup including antenna probe and frequency tuning rod that are connected to piezoelectric actuators. Sapphire tuning rod is designed to be thermally linked to the cavity.

The cryo-RF receiver chain has been set up with 1K HEMT amplifier (right out of the cavity) that dominates noise temperature budget and the total system temperature ranges from 1.4 to 2 K, as expected. Without quantum-limited SQUID amplifiers, we won't be able to reach KSVZ[4][5] sensitivity, however, this engineering run could provide us a great opportunity to prepare ourselves for evaluating and maximizing performance of other RF electronics components. SQUID amplifier test is well on the way and it is possible to incorporate one in our chain before this year ends.

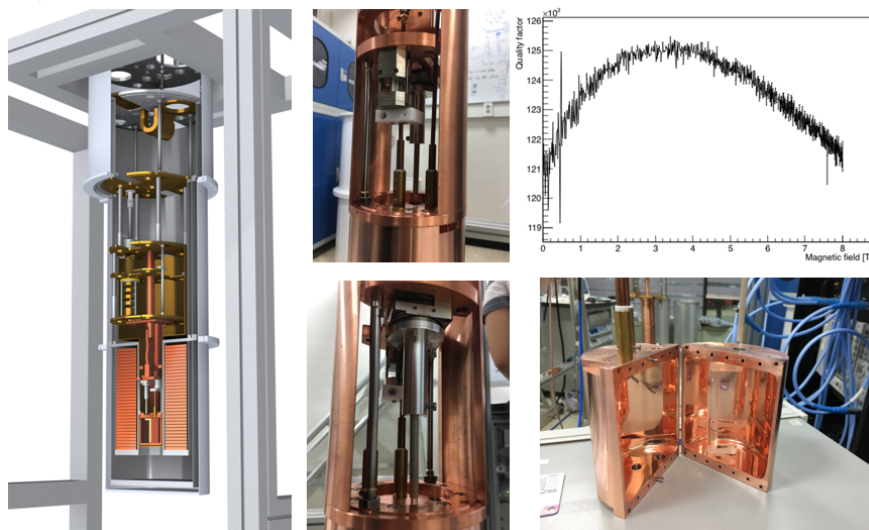


Figure 2: CULTASK Resonant cavity and Frequency Tuning System in Dilution Refrigerator

Figure 2 shows a complete axion detector set-up with frequency tuning system. The split cavity with sapphire rod is also shown and the plot exhibits how the cavity Q-factors changes when magnetic field ranging 0 to 8 teslar.

## 4 Plans beyond 2017

Four dilution refrigerators are operational now with two 8T NbTi superconducting magnets (12 cm and 16.5 cm inner bore) for CULTASK engineering runs. Three more wet-type refrigerators will be added and the more powerful 18T 7cm bore HTS magnet is scheduled to be delivered at the end of this year. More superconducting magnets with much higher field (25 T) and bigger bore size (35 cm) are also planned in the pipeline. Powerful magnets with different bore

sizes along with efforts on multi-cavity phase locking study would help us to search axions throughout the whole possible mass range. Employing quantum-limited SQUID amplifier or JPA will provide huge improvements on booting axion conversion power and scanning speed, and eventually pave a way to search axions KSVZ QCD axion sensitivity region and beyond.

## 5 Conclusion

Our quest to establish a state-of-the-art axion experiments in Korea is well on the way. The low vibration experimental space is complete, 7 dilution refrigerators are going to be running next year, powerful and bigger bore superconducting magnets are going to be delivered, and the engineering run of CULTASK is ready to go forward at this stage. We should be able to start collecting physics quality data this year, at least for a single frequency. The addition of SQUID amplifiers, ultra high field magnets and high Q-factor cavities with superconducting coating will improve the sensitivity and make a major contribution to axion research in coming years.

## 6 Acknowledgments

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