Axion Haloscopes with Toroidal Geometry at CAPP/IBS

Byeong Rok Ko
Center for Axion and Precision Physics Research, Institute for Basic Science (IBS), Daejeon 34141, Republic of Korea

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The present state of the art axion haloscope employs a cylindrical resonant cavity in a solenoidal field. We, the Center for Axion and Precision Physics Research (CAPP) of the Institute for Basic Science (IBS) in Korea, are also pursuing halo axion discovery using this cylindrical geometry. However, the presence of end caps of cavities increases challenges as we explore higher frequency regions for the axion at above 2 GHz. To overcome these challenges we exploit a toroidal design of cavity and magnetic field. A toroidal geometry offers several advantages, two of which are a larger volume for a given space and greatly reduced fringe fields which interfere with our preamps, in particular the planned quantum-based devices. We introduce the concept of toroidal axion haloscopes and present ongoing research activities and plans at CAPP/IBS.

1 Axion haloscopes at CAPP/IBS

One of the primary targets of the Center for Axion and Precision Physics research (CAPP) of the Institute for Basic Science (IBS) in Korea is to search for axion cold dark matter using the method proposed by Sikivie [1], also known as the axion haloscope search. We, CAPP/IBS, are pursuing traditional axion haloscopes with cylindrical geometry, where two significant solenoids are employed. One has 12 T of $B$ field and 32 cm of cold bore and the other has 25 T of $B$ field and 10 cm of cold bore. The former can scan the axion frequency from 0.5 to 1.3 GHz, while the latter can scan from 1.8 to 10 GHz. The details of halo axion searches using these cylindrical geometry will be given in the near future.

In the same pipeline, we are also considering axion haloscopes with toroidal geometry which offer a larger volume and greatly reduced fringe $B$ fields. In view of these advantages, we introduce currently ongoing research activities and plans for toroidal axion haloscopes at CAPP/IBS in this proceedings.

2 Cylindrical geometry vs. toroidal geometry

We compare two axion haloscopes with two different geometry, cylindrical and toroidal, to reveal the advantages of toroidal axion haloscopes mentioned above. Cylindrical cavities have an electromagnetic cavity mode parallel to an external static magnetic field $B_{\text{external}}$ provided by the magnet employed in an axion haloscope, which is the TM$_{010}$ mode, and so do toroidal...
### Table 1: Comparison of characteristics between cylindrical and toroidal axion haloscopes, where $B_0$ is a constant, $B_{\text{avg}}^2 V \equiv \int B_{\text{external}}^2 dV$, and $V$ is the cavity volume.

| characteristics | cylindrical geometry | toroidal geometry |
|-----------------|----------------------|------------------|
| $B_{\text{external}}$ | $\sim B_0 \hat{z}$ | $\sim \frac{B_0}{R} \hat{\phi}$ |
| $B_{\text{avg}}^2 V$ | independent of the cavity location inside a solenoid | depends on the cavity location inside a toroidal magnet |
| cavity mode $\parallel B_{\text{external}}$ | TM$_{010}$ | QTM |
| form factor | $C_E = C_M \propto B_{\text{avg}}^2 V$ | $C_E = C_M \propto B_{\text{avg}}^2 V$ |
| $B_{\text{fringe}}$ | unavoidable | avoidable with additional coils |
| mode crossing | Yes | No |

This no mode crossing in toroidal geometry enables us to increase the cavity volume very effectively.

The fringe $B$ fields, from toroidal magnets, $B_{\text{fringe}}$ are ideally zero and even practically very small compared to those from solenoids. Furthermore, the $B_{\text{fringe}}$ from toroidal magnets can be reduced with additional coils. With greatly reduced $B_{\text{fringe}}$, the handling of quantum preamps in toroidal geometry is much easier than that in cylindrical geometry.

Table 1 summarizes the comparison between axion haloscopes with cylindrical and toroidal geometry. Note that $z$, $\rho$, and $\phi$ refer to cylindrical coordinates.

### Figure 1: Form factors of the QTM mode of the toroidal cavity as a function of frequency.

| QTM mode frequency (MHz) | Form factor $C_{\text{QTM}}$ |
|--------------------------|-----------------------------|
| 235                      | 0.45                        |
| 250                      | 0.75                        |
| 317                      | 0.70                        |

3 Axion haloscopes with toroidal geometry at CAPP/IBS

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We are considering the two toroidal axion haloscopes whose magnet specifications are shown in Table 2.

The large toroidal magnet illustrated in Fig. 2 can hold a cavity with 200 cm of major radius and 50 cm of minor radius, which enables us to scan the axion parameter space down to 190 MHz with a dielectric ($\epsilon_r = 9.9$) tuning rod. Thanks to 9,870 liters of the cavity volume which is about 50 times larger than the ADMX cavity [5], we can achieve a reasonable scanning rate [6] even with a semiconductor-based preamp and cavity cooling with liquid helium (LHe) which results in the relatively high system noise of $\sim 6$ K, with 2 K from the preamp and 4 K from the cavity. The large toroidal magnet also can hold 4 cavities, each of them having 200 cm of major radius and 20 cm of minor radius, which enables us to scan the axion parameter space up to 850 MHz with a conductor tuning rod. With the 4-cavity system, we can achieve a reasonable scanning rate even with a system noise of $\sim 6$ K. Figure 3 shows the relevant parameter space and expected sensitivity from the large toroidal axion haloscopes which will be realized in about ten years.

The small toroidal magnet can hold a cavity with 50 cm of major radius and 9 cm of minor radius, which enables us to search for axion parameter space from 1.3 to 1.8 GHz with a conductor tuning rod. The cavity can be cool down to 100 mK with a dilution fridge. Then, we can be sensitive to KSVZ [7, 8] axion search using a semiconductor preamp or DFSZ [9, 10] using a quantum version preamp with acceptable scanning rates. Figure 3 also shows the relevant parameter space and expected sensitivity from the small toroidal axion haloscopes which will be realized in a few years.

|          | small toroid | large toroid |
|----------|--------------|--------------|
| $B_{\text{avg}}$ | 12 T         | 5 T          |
| number of coils | 36           | 9            |
| major radius    | 50 cm        | 200 cm       |
| minor radius    | 11 cm        | 60 cm        |

Table 2: Specifications of the two toroidal magnets.

4 Summary

CAPP/IBS realizes several advantages in axion haloscopes with toroidal geometry, two of which are a larger volume for a given space and greatly reduced fringe fields. Thanks to the very large volume of the cavity in the large toroidal axion haloscopes, we can realize...
a reasonable scanning rate even with 4 K cavity cooling which can be achieved easily with LHe. The capability of cooling a system using LHe shows how powerful the large toroidal axion haloscopes are. In the near future, we will realize the small toroidal axion haloscopes to demonstrate the feasibility of the large toroidal axion haloscopes.

Acknowledgments

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