Haloscope Axion Searches with the CAST Dipole Magnet: The CAST-CAPP/IBS Detector

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The CAST-CAPP/IBS Detector project will use tunable rectangular cavities inserted in the 43 mm twin-bore, 9T, CAST dipole magnet to search for axion DM, initially in the 21 to 25 μeV mass range. The sensitivity of this haloscope could reach into the QCD axion parameter space in a wider, yet-unexplored, mass region. Preliminary model results guiding the project design are presented.

1 Introduction and Motivation

Axions arise as consequence of the Peccei-Quinn solution to the strong CP problem [1]–[7]. They are natural cold dark matter (DM) candidates [8]–[10] if their mass lies within the range (1–100) μeV. In addition to the explicit axion there is a wide range of so-called axion-like particles (ALPs) having similar couplings, but with an often increased coupling constant. They could also be good dark matter candidates [11]–[12]. Axion searches can therefore shed light on the nature of DM, a major issue of contemporary physics. A convenient search method is based on the coupling of axions to two photons, as expressed by the Lagrangian term

$$\mathcal{L} \approx g_{a\gamma\gamma}\varphi_a \mathbf{E} \cdot \mathbf{B} \tag{1}$$

where $g_{a\gamma\gamma}$ is the (model dependent) coupling constant, and φ_a is the axion field. Haloscopes can detect axions in the μeV mass region [13]. They consist of microwave cavities immersed in a strong magnetic field. Similarly to the Primakoff effect [14], the axion-to-photon conversion rate is enhanced in a region of space where a strong magnetic field $\mathbf{B}$ is present. The conversion probability is further enhanced if the outgoing photon, represented by the electric field $\mathbf{E}$ in the previous equation, is detected in a microwave cavity resonating to the frequency of the axion mass. A number of searches using haloscopes have already been undertaken [15]–[17] with solenoid magnets producing the external field, such as the ADMX experiment [18]–[19]. Leveraging on [20] and adding some new ideas, members of the CAPP/IBS, now part of the CAST collaboration, have recently proposed to exploit the CAST dipole magnet to search for axion DM using rectangular cavities. The CAST collaboration then decided to submit a proposal to CERN, an effort that can probe the $\sim (2\text{–}3) \times 10^{-5}$ eV mass range with a sensitivity that could reach into the QCD axion domain. This region has never been explored before for cold DM searches.

2 Experimental Setup

The field strength (9 T) and geometry (9 m length, 43 mm diameter twin bores) of the CAST superconducting dipole magnet, formerly an LHC prototype, are appropriate for cold DM axion searches with rectangular cavities.

2.1 Rectangular Cavities in Dipole Magnets

The on-resonance axion conversion power in a microwave cavity is proportional to B^2, to the cavity quality factor Q (the ratio of the cavity stored-energy to its losses), to its volume V, and geometry factor C [21]

$$P \approx g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 \cdot Q \cdot V \cdot C \tag{2}$$

Here ρ_a is the axion field density and m_a is the axion mass. A suitable experimental setup in a dipole field consists of tunable rectangular cavities introduced into the magnet bore, with the magnetic field parallel to the resonator lateral sides. Equation (1) suggests that the sensitivity would be maximized if TE modes are used. The mode frequency depends on the cavity width (w), height (h), length (L), and mode indexes l, m, n, as

$$f_{lmn} \propto \sqrt{\left(\frac{l}{w}\right)^2 + \left(\frac{m}{h}\right)^2 + \left(\frac{n}{L}\right)^2} \tag{3}$$

Assuming L to be along the z direction, and the external B field along y, it is convenient to choose modes in which $m = 0$ so that the resonant electric field is parallel to B

$$E_y \propto \sin\left(\frac{l\pi}{w}x\right) \sin\left(\frac{n\pi}{L}z\right)$$
$$E_x = E_z \equiv 0 \tag{4}$$

The fundamental TE_{101} is the most favourable, giving a geometry factor of 0.66 for an empty cavity, the highest possible in our case. This mode is sufficiently isolated from other modes if the cavity aspect ratio is not too large ($\lesssim 100$). For our estimates we assumed inner cavity lateral sizes of 25 mm × 24 mm. If the cavity is tuned as described in Sec. 3, the maximum frequency will be 5.8 GHz, corresponding to an axion mass of 24×10^{-6} eV.

2.2 Sensitivity

The cavity on-resonance output power from axion to photon conversion can be estimated as [21] (and also [19])

$$P = 1.6 \times 10^{-23}\,\mathrm{W}\left(g_{a\gamma\gamma} 10^{14}\,\mathrm{GeV}\right)^2 \left(\frac{\rho_a}{300\,\mathrm{MeV/cm^3}}\right)\left(\frac{2.4 \times 10^{-5}\,\mathrm{eV}}{m_a}\right)$$
$$\times \left(\frac{B}{9\,\mathrm{T}}\right)^2 \left(\frac{V}{5\,\mathrm{L}}\right)\left(\frac{Q}{5 \times 10^3}\right)\left(\frac{C}{0.66}\right) \tag{5}$$

The value of 300 Mev/cm^3 in Eq. (5) is a commonly used value for the DM density in the vicinity of the Earth. The quality factor Q is the minimum between the loaded-Q, i.e. when the cavity is coupled to the rest of the detection system, and the DM Q-factor resulting from the energy spread of the axion, which is in the order of 10^6. Here a rather conservative $Q = 5,000$, with a critically coupled cavity, has been assumed. The volume of 5 L corresponds to filling one of the two magnet bores with multiple cavities, provided they can be phase-matched. Under the above conditions the on-resonance cavity power resulting from an axion signal would be $\sim 10^{-23}$ W, assuming a coupling constant $g_{a\gamma\gamma}$ of $10^{-14}\,\mathrm{GeV}^{-1}$. If we require a signal-to-noise ratio of 4, the time required to measure this power level at a given resonant frequency (axion mass) is, as deduced from the radiometer equation [22], in the order of 10 days, for a system temperature of 3.8 K resulting from adding the magnet operating temperature, 1.8 K, to a commercial amplifier noise temperature of 2 K. The signal bandwidth is taken equivalent to the axion DM velocity spread of 10^{-3} times the speed of light [13]. The assumed quality factor in the previous estimates is rather modest. At the experiment operating temperature, 1.8 K, we should expect a much higher Q. The sensitivity would scale accordingly, further demonstrating the good potential of this setup for axion DM search in a region of the parameter space, $g_{a\gamma\gamma}$ vs. axion mass, where no data currently exist.

3 Cavity Design

Since the experiment sensitivity increases with the resonator volume, it would be desirable to completely fill each of the two magnet bores with a single resonator or with phase-matched multiple cavities. As the aspect ratio L/w of the structure increases, however, the quality factor decreases, the resonant frequencies tend to converge to a single value (Eq. (3)), and mechanical tolerances become more demanding. In addition, since a tunable cavity is desired, a proper tuning mechanism must be included. All these aspects have been considered in a preliminary model of a relatively short cavity, 24 mm $\times$ 25 mm $\times$ 50 cm, that seems able to offer reliable TE_{101} mode operation, frequency separation, and reasonable sensitivity for a first stage experiment. Although a single such cavity will not be able to reach into the QCD axion parameter space, we should be able to set new limits into a yet unexplored domain of that region. Preliminary model results related to tuning, frequency spacing, and mechanical design tolerances are presented in the reminder of this contribution.

We have studied tuning mechanisms consisting in placing dielectric materials and/or metallic plates inside the cavity. Depending on its volume, position and shape, any material placed inside the cavity will alter the cavity mode structure and resonant frequency and, as a consequence, the cavity quality and geometry factors. A sensible tuning mechanism has been identified consisting in two dielectric bars of permittivity $\epsilon = 9$ and sizes 2.5 mm $\times$ 15 mm $\times$ 45 cm symmetrically placed parallel to the longitudinal sides, simultaneously moving towards the center, as conceptually depicted in the top-left of Fig. 1. This gives a sizable down-tuning range, from 5.8 to 4.2 GHz, as seen on the top right of the same figure.

The frequency spacing is the distance in frequency to the next higher order mode. If this spacing is small compared to the bandwidth of the cavity the two modes will couple to each other resulting in loss of sensitivity. It would be best to operate in single mode, if not however, the loss in sensitivity at the desired frequency might still be acceptable. An approximate criterion to establish the maximum cavity length for small values of the index n, in TE_{10n}, as given in [20], is confirmed by our preliminary modeling. In our example, mode spacing is not an issue as seen in the bottom left of Fig. 1.

Mechanical tolerances play a crucial role due to mode localization. This means that the mode field distribution in the resonator space is altered depending on the deviation of the cavity shape from its ideal design, thus causing a decrease in the geometry form factor. To observe mode localization and investigate sensitivity to mechanical tolerances we have modeled a trapezoidal resonator in which the width of the cavity, w, changes from the original 25 mm to 24.5 mm, on one side only, and we tracked the geometry form factor as a function of w, as illustrated in the bottom right Fig. 1. Mechanical tolerances at 50 μm level seem sufficient for our benchmark cavity.

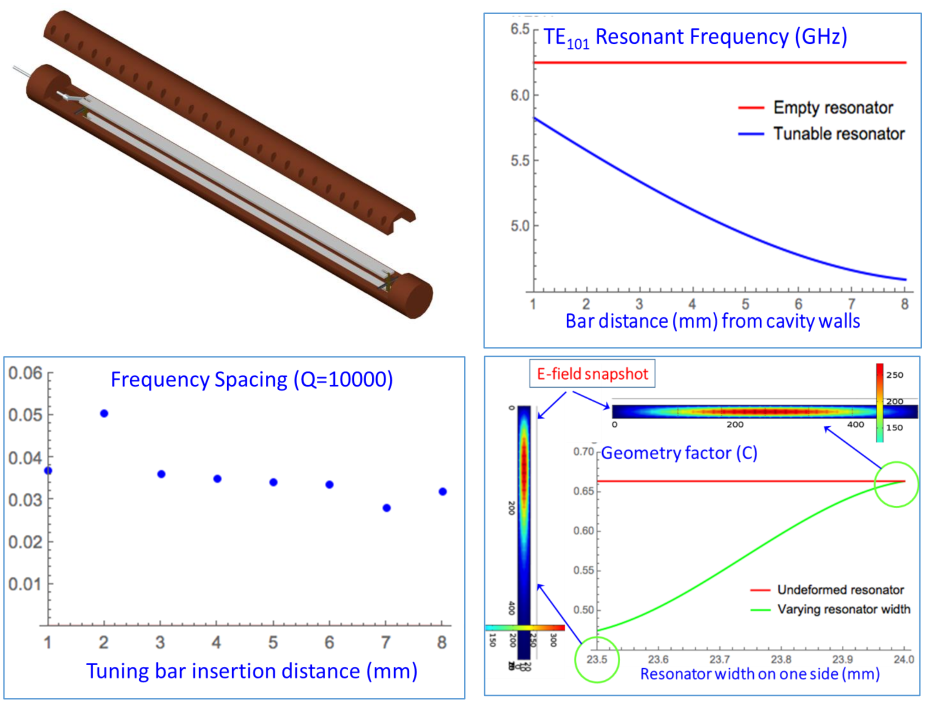

Figure 1: Preliminary modeling results. Top left: Cavity tuning conceptual design. Top right: Tuning range. Bottom left: ratio of resonant bandwidth to frequency spacing. Bottom right: Mode localization from cavity deformation.

4 Conclusion

The CAST-CAPP/IBS Detector project is a haloscope search for axion DM with rectangular cavities inserted in the bores of the CAST dipole magnet. Preliminary cavity engineering models are promising. The haloscope sensitivity may be able to reach into the QCD axion parameter space over the unexplored region of (2–3)$\times 10^{-5}$ eV axion mass range, provided that phase-matching of multiple cavities is possible.

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