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Science reach and electromagnetic modeling of DMRadio-m^3

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The DMRadio suite of experiments uses lumped LC resonators to search for axions in lower frequency ranges than those accessible to cavity haloscopes. DMRadio-m^3 has sensitivity to DFSZ axions in the 30–200 MHz range corresponding to masses of $0.12\ \mu\text{eV}/c^2 < m_a < 0.83\ \mu\text{eV}/c^2$, and KSVZ axions in the 10–30 MHz range, corresponding to masses of $41\ \text{neV}/c^2 < m_a < 0.12\ \mu\text{eV}/c^2$ range. In this paper we present the design of DMRadio-m^3 as well as the method to extract the sensitivity of this experiment in a general form which applies to frequencies where the Compton wavelength of the axions is within a factor of order unity of the dimension of the detector. We also discuss the motivation and plan to use several coaxial pickup structures to cover the entire frequency range of the experiment.

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1. Introduction

The QCD axion is an attractive dark matter candidate due to its production mechanism which can naturally populate the universe at the observed density cold dark matter [1–3] as well as its ability to resolve the Strong CP problem [4–7]. Over the past few decades, significant progress has been made in searching for axions through their coupling to standard-model photons. These experiments utilize microwave cavities in a magnetic field. Axions convert into photons in the magnetic field and then are resonantly enhanced when the axion Compton wavelength matches that of an appropriate cavity mode [8]. While such experiments currently have the highest sensitivity to axions in the GHz range, they cannot be realistically designed to search for frequencies below hundreds of MHz due to the prohibitively long wavelength modes they would need to support. The DMRadio series of experiments searches for axions in the 20 peV/c^2 – 0.8 μeV/c^2 range (5 kHz – 200 MHz) by converting axions in a magnetic field and resonantly enhancing them using LC circuits. Specificially, the DMRadio-m^3 experiment searches for axions at Dine-Fischler-Srednicki-Zhitnisky (DFSZ) [9, 10] axion sensitivity in the 30 – 200 MHz and at Kim-Shifman-Vainshtein-Zakharov (KSVZ) axion [11, 12] sensitivity in the 10 – 30 MHz range [13].

2. DMRadio-m^3 Design

Electromagnetically coupled axions lead to a modification of Maxwell's equations by adding terms that depend on the axion field. In particular, a spatially uniform axion field with a local density of ρ_{DM} will interact with a dc magnetic field, $\mathbf{B}$, to produce an oscillating effective current [8]:

$$\mathbf{J}_{\mathrm{eff}} = g_{a\gamma\gamma}\frac{\sqrt{\hbar c}}{\mu_0}\sqrt{2\rho_{\mathrm{DM}}}\cos\left(\frac{m_a c^2}{h}t\right)\mathbf{B} \tag{1}$$

where $g_{a\gamma\gamma}$ is the coupling constant associated with an axion-photon-photon vertex. For limits set by DMRadio, the dark matter density is set to $\rho_{\mathrm{DM}} = 0.45$ GeV cm^{-3} [14]. The AC magnetic field sourced by the oscillating effective current is picked up by a coaxial copper pickup inside the bore of a solenoidal magnet. A cross section of the magnetic field for DMRadio-m^3 and a corresponding coaxial pickup structure are shown in Figure 1a. The axion current as well as the physical electron current it sources on the coaxial pickup's walls are shown in Figure 1b. The magnet is designed such that there exists a low field region at the top of the coaxial pickup where field sensitive dc SQUIDS are placed. The radial points at which the readout and tuning elements electrically connect to the coaxial pickup are shown as points A and B in Figure 1b.

It is instructive to consider an effective circuit model for this system as shown in Figure 1c. Across points A and B, the coaxial pickup has an associated impedance, $Z_p(\omega)$, as well as an induced voltage, $|V(\omega)|$, sourced by the axion current . The tuning elements which connect to the coaxial pickup have an impedance $Z_{\mathrm{tuning}}(\omega)$. The values of these quantities enter into sensitivity calculations which are discussed in the following section.

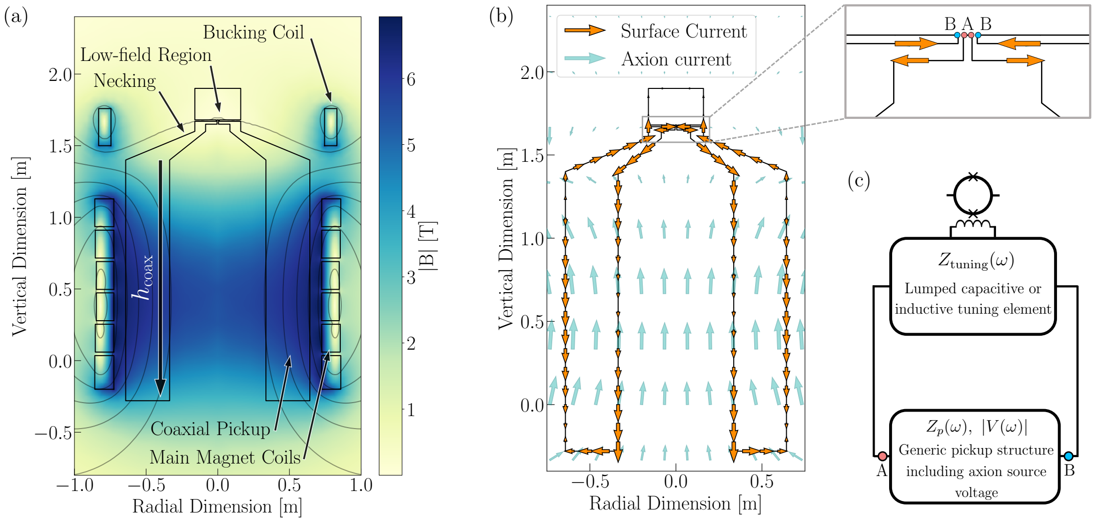

Figure 1: (a) A 2D cross section of the magnet and coaxial pickup used in DMRadio-m^3. A solenoidal magnet produces a ~ 5 T peak magnetic field. Bucking coils reduce the magnetic field at the top of the coaxial pickup such that superconducting elements can be placed in this region where the magnetic field is less than their H_{c1}. (b) The axion induced current (in green), as calculated in Eq. 1, oscillates along the magnetic field lines. The screening current on the inner walls of the coaxial pickup at a given frequency is shown in orange. This current then flows to tuning and readout elements (not shown) which are connected across the radial points A and B. (c) The coaxial pickup can be modeled as a circuit element with a given impedance $Z_p(\omega)$ as well as a voltage, $|V(\omega)|$, induced by the axion current. The tuning elements as well as readout elements then connect across points A and B.

3. Extracting sensitivity

For a DMRadio-like lumped-element search for axions, the circuit can be modeled as a series RLC circuit [15]. In this case, the scan rate for an axion with mass m_a can be expressed as

$$\frac{d\nu}{dt} = \frac{\pi(6.4 \times 10^5)}{\mathrm{SNR}^2} \frac{\hbar^2}{16c^8 m_a^4} \frac{|V(m_a, B, g_{a\gamma\gamma})|^4 Q(\nu_r)\bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]}{L_{\mathrm{eff}}(\nu_r)^2} \tag{2}$$

where $|V(m_a, B, g_{a\gamma\gamma})|$ is the magnitude of the axion induced voltage on the coax, $Q(\nu_r)$ is the quality factor of the system at a frequency ν_r, and L_{eff} is the value of the total combined effective inductance of the effective RLC circuit.

Since DMRadio-m^3 searches for axions up to 200 MHz, it must scan for wavelengths as short as 1.5 m. In this regime, the coaxial pickup's impedance can no longer be modeled simply as that of a lumped inductor, whose impedance is $Z_{\mathrm{ind}} = i\omega L$, but in a way that takes into account the behavior of the coaxial pickup at frequencies where it no longer behaves as a simple inductor.

We consider the impedance of the coaxial pickup, $Z_p(\omega)$, across points A and B. As this geometry resembles that of a shorted coaxial pickup structure, the reactance roughly behaves like a tangent function in frequency. Finite element modeling (FEM) simulations carried out on COMSOL provide a numeric form for this impedance, as shown in blue in Figure 2. These zeroes (both asymptotic and smooth) of this curve correspond to TEM-like resonances of the coaxial

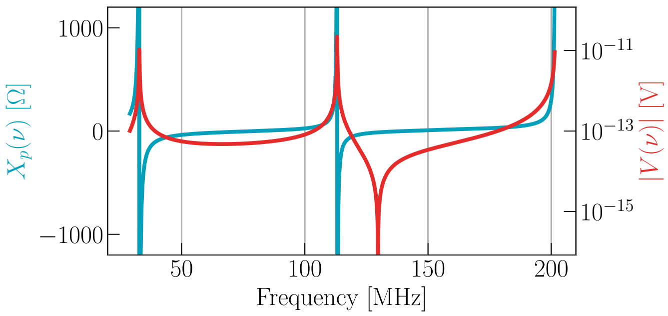

Figure 2: Reactance curve, $X_p(\nu) = \text{Im}\left[Z_p(\nu)\right]$, in blue and voltage curve induced by the axion induced current, $|V(\nu)|$, in red. These are extracted using COMSOL as measured across the slit of a coaxial pickup. Zeroes in the reactance curve indicate resonances that can be associated with TEM-like resonances in a coaxial line.

pickup. At each frequency, we can model the coaxial pickup as an effective series RLC. By considering the real and imaginary components of the coaxial pickup at each frequency, we extract numeric values for the effective series RLC at each frequency [13].

To achieve a resonance at a given frequency ω_0, the total reactance of this structure must be zero. Ignoring contributions due to the readout, this means that on resonance, for a tuning element connected in series:

$$\text{Im}\left[Z_p(\omega_0)\right] = -\text{Im}\left[Z_{\text{tuning}}(\omega_0)\right] \tag{3}$$

Since the reactance of the coaxial pickup shown in Figure 2 has both positive and negative values across frequency ranges of interest, the impedance of the tuning elements too must have either positive or negative values at different frequencies. In order to achieve resonance then, the tuning element must be inductive (i.e. have a positive reactance) when $X_p(\omega_0) < 0$, and capacitive (i.e. have a negative reactance) when $X_p(\omega_0) > 0$. Alternatively, parallel reactances can be used.

Once the values for the effective series RLC circuit as well as the required tuning element value have been determined at each frequency, the parameters for $Q(\nu_r)$ and $L_{\text{eff}}(\nu_r)$ in Eq. 2 can be extracted. L_{eff} is the combined inductance of the L in the series RLC along with any tuning inductance. The quality factor can be extracted as $\frac{1}{R}\sqrt{\frac{L_{\text{eff}}}{C_{\text{eff}}}}$, where C_{eff} also is the series combination of the effective C of the coaxial pickup and any tuning element component.

The voltage induced by the axion current in the coaxial pickup, $|V(m_a, B, g_{a\gamma\gamma})|$, can also be calculated using a similar FEM simulation on COMSOL. These simulations utilize the magnetic field shown in Figure 1 and produce the voltage shown in red in Figure 2. Once this value is extracted, and specifics of the noise physics and the SNR are set, a scan rate can be calculated using Eq. 2.

4. Multiple coaxes and science reach

For a given coaxial pickup, such as the one whose reactance and voltage are shown in Figure 2, there exist regions in frequency where this coaxial pickup is not optimal for data taking. Specifically, there exist regions where the voltage drops to very low values, leading to prohibitively low scan rates. Equivalently, by considering the reactance, there exist regions where the value of tuning

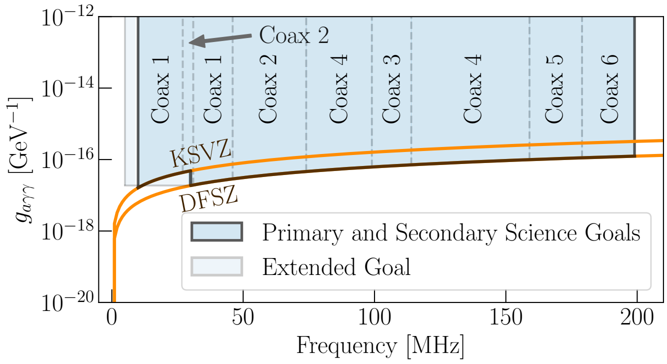

Figure 3: The science goals for DMRadio-m^3. The two QCD axion models, KSVZ and DFSZ, are depicted as the orange lines. The primary science goal covers DFSZ axions in the 30–200 MHz region and the secondary covers KSVZ axions in the 10–30 MHz region. The extended goal covers $g_{a\gamma\gamma} = g_{a\gamma\gamma,\mathrm{DFSZ}}(30\text{ MHz}) = 1.87\times10^{-17}\text{ GeV}^{-1}$ in the 5–30 MHz range. The frequency regions that each of the six coaxial pickups will cover is depicted.

elements is unphysically large or small, as well as regions where the value of the inductance or capacitance must vary significantly over a small range in frequency. Since such tuning elements cannot be realized in these scenarios, the particular coaxial pickup will have regions that will not be used for data taking.

To cover the entire parameter space of DMRadio-m^3 a set of six coaxial pickups will be exchanged within the solenoidal magnet to cover different frequency regimes. These will have different values for h_{coax} as shown in Figure 1a. By adjusting h_{coax}, the frequency regions where either the voltage is too low or the tuning elements are physically unrealizable shifts, and so the set of six coaxial pickups can cover 5–200 MHz with a sufficiently high scan rate.

The primary science goal of DMRadio-m^3 is to search for axions with DFSZ sensitivity in the 30–200 MHz range, corresponding to masses of $0.12\ \mu\text{eV}/c^2 < m_a < 0.83\ \mu\text{eV}/c^2$, with the secondary science goal covering 10–30 MHz, i.e. $41\text{ neV}/c^2 < m_a < 0.12\ \mu\text{eV}/c^2$. The extended goal of the experiment is to search for axions with $g_{a\gamma\gamma} = g_{a\gamma\gamma,\mathrm{DFSZ}}(30\text{ MHz}) = 1.87\times10^{-17}\text{ GeV}^{-1}$ in the 5–30 MHz range ($21\text{ neV}/c^2 < m_a < 0.12\ \mu\text{eV}/c^2$) [13].

5. Acknowledgements

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