

Spiral tuning of wire-metamaterial cavity for a plasma haloscope

Jacob Lindahl¹,^{*} Rustam Balafendiev^{2,3}, Gagandeep Kaur¹, Gaganpreet Singh¹,
Andrea Gallo Rosso¹, Jan Conrad¹, Jon E. Gudmundsson^{2,1} and Junu Jeong^{1,*}

¹The Oskar Klein Centre, Department of Physics, *Stockholm University*, AlbaNova, SE-10691 Stockholm, Sweden

²Science Institute, *University of Iceland*, Dunhagi 5, 107 Reykjavik, Iceland

³School of Physics and Engineering, *ITMO University*, Kronverksky Pr. 49, 197101 St. Petersburg, Russia



(Received 11 September 2025; revised 23 November 2025; accepted 28 January 2026; published 24 February 2026)

Axions are hypothetical particles that provide a compelling solution to two major mysteries in modern physics: the strong CP problem and the nature of dark matter. The plasma haloscope has been proposed as a promising approach for probing the higher-mass regime for dark-matter axions by employing a periodic arrangement of conducting wires. In this work, we introduce an alternative tuning mechanism for such wire-based structures by arranging the wires into a spiral configuration. This design enables continuous frequency tuning of 25% with a single central rotation while maintaining the form factor. It also achieves scanning speeds several times faster than traditional tuning approaches, primarily due to the circular perimeter geometry, making it well suited for solenoidal magnet bores. To validate the concept, we fabricated a prototype cavity with six spiral arms and experimentally demonstrated its feasibility, obtaining frequency tuning in close agreement with numerical simulations.

DOI: [10.1103/n1hb-9d3p](https://doi.org/10.1103/n1hb-9d3p)

I. INTRODUCTION

Axions are hypothetical particles proposed by the Peccei-Quinn mechanism to dynamically resolve the charge-parity symmetry problem in quantum chromodynamics [1–3]. Ultralight axions with masses below the electronvolt scale are strong dark-matter candidates due to their nonrelativistic production in the early-universe and extremely weak interactions with Standard Model particles [4–6]. Prominent theoretical models include the Kim-Shifman-Vainshtein-Zakharov (KSVZ) [7,8] and Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) [9,10] frameworks.

Numerous experimental efforts worldwide are dedicated to the search for axion dark matter [11–13]. Among these, the cavity haloscope technique [14] remains the most sensitive, as it has been reaching out to the theoretically predicted axion-photon coupling in the microwave frequency range. However, the sensitivity of this method decreases at higher axion masses, primarily because the resonant volume diminishes with increasing frequency, thereby reducing the scanning speed.

Recent independent theoretical studies for early-universe simulations, based on the postinflationary scenario, indicate a preference for axion masses above 10 GHz to account for the observed dark-matter abundance [15–20]. This motivates the further development of experimental strategies capable of probing this high-frequency regime [21–27].

One promising approach is the plasma haloscope [28], which employs a periodic array of conducting wires to form a metamaterial medium with a tunable effective plasma frequency. This configuration supports efficient axion-photon conversion by matching the axion mass with the plasma frequency of the metamaterial structure.

The periodic wire array can be interpreted as a cavity resonator, where the fundamental transverse magnetic (TM) mode resonates near the effective plasma frequency. The resonant frequency depends strongly on the spacing between adjacent wires, necessitating coordinated mechanical adjustments for tuning. Several methods have been proposed to achieve a tunability of this design [28–30].

In this work, we introduce another tuning method based on bundling wires into a spiral configuration. This design enables frequency tuning through a single central rotation that simultaneously adjusts the spacing between adjacent spiral bundles. To validate this concept, we designed and fabricated a prototype cavity and demonstrated that its measured resonant behavior is in agreement with numerical simulations.

*Contact author: jun-woo.jeong@fysik.su.se

Published by the American Physical Society under the terms of the [Creative Commons Attribution 4.0 International](https://creativecommons.org/licenses/by/4.0/) license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Funded by [Bibsam](https://www.bibsam.org/).

Section II introduces the underlying principles of the spiral tuning method, presents a design protocol for determining wire placement along the spiral arms, and evaluates its performance against alternative methods. Section III describes the prototype cavity construction and measurement procedure, and compares the results with simulations. In Sec. IV, we discuss the advantages of the spiral-arm geometry, possible optimizations, and its application to plasma haloscope experiments.

II. SPIRAL TUNING METHOD

A periodic array of conducting wires forms a wire metamaterial characterized by a reduced effective plasma frequency. This frequency is predominantly determined by the wire diameter and spacing. When the effective plasma frequency matches the axion mass, axion-photon conversion is resonantly enhanced, enabling sensitive searches in the high-mass regime.

Among various possible geometries, the spiral configuration offers an efficient means to compactly arrange wires within a cylindrical volume, as illustrated in Fig. 1. The configuration fully utilizes the available volume of a solenoid, forming the wire-metamaterial structure shown in Figure 2. This design enables a simple and scalable tuning mechanism. The spiral arms are divided into two sets of equal size: one fixed and one rotatable. Rotating one set relative to the other alters the spacing between adjacent spiral arms while maintaining a constant wire spacing along the spiral direction, thereby tuning the cavity's resonant frequency, as shown in Fig. 3. This mechanism can be regarded as a polar-coordinate analog of the linear-translation method, employed in the original plasma haloscope designs [28].

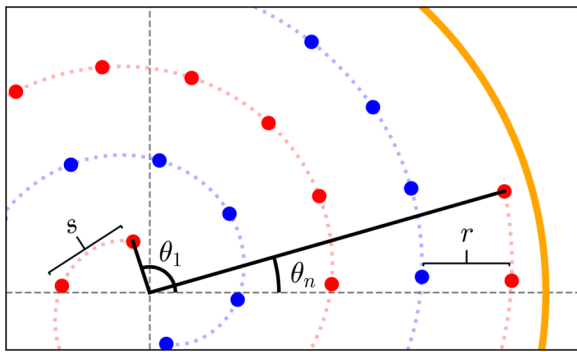


FIG. 1. Illustration of the spiral bundle geometry used for wire positioning. Red and blue dots represent the locations of metallic wires arranged in a two-arm spiral configuration, with each color corresponding to one spiral arm. The initial and final angular positions are denoted by θ_1 and θ_n , respectively. The spiral arc length is labeled as s , while the radial length is indicated as r . The outermost orange boundary denotes the cavity wall.

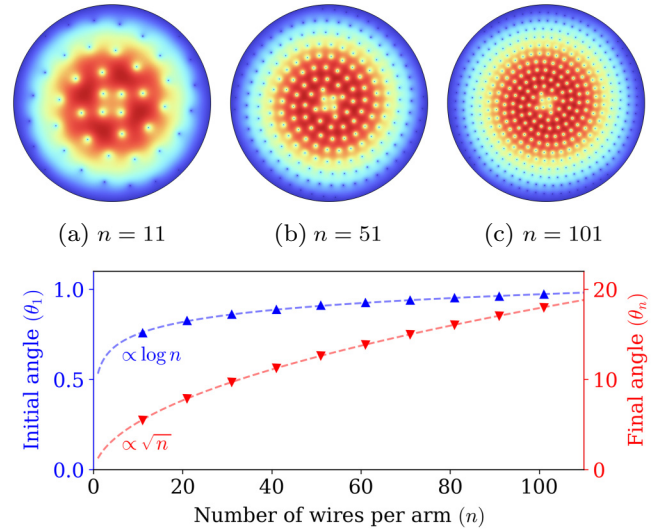


FIG. 2. Electric-field profiles of the desired TM mode for a four-arm spiral wire array with varying numbers of wires per arm (top). The optimized initial and final spiral angles (bottom) are determined to produce uniformly distributed fields in the desired mode. The initial angle follows a logarithmic scaling, while the final angle follows a square-root scaling as the number of wires increases. (a) $n = 11$. (b) $n = 51$. (c) $n = 101$.

Wire positioning along each spiral arm follows a geometric rule designed to maintain approximately uniform spacing in both radial and azimuthal directions. Consistent spacing in both directions is achieved if the spiral follows a linear polar equation of the form $\rho = a\theta$ for large θ , where ρ is the radial coordinate, θ denotes the cumulative angular coordinate, and a is a characteristic length scale. The deviation at small θ affects only the innermost wires and has a negligible impact on the overall cavity performance.

This spiral configuration is defined by four key parameters: the number of spiral arms N_s , the number of wires per spiral arm n , the angular position θ_1 of the innermost wire, and the scale factor a . The total number of wires in the cavity is then given by $N_s \times n$.

The remaining parameters are determined so as to yield a uniform distribution of wires. The radial spacing between adjacent wires is expressed as

$$r \approx \frac{2\pi a}{N_s}. \quad (1)$$

To ensure uniform spacing along the spiral, the angular positions of wires are determined by the condition

$$r = s = \int_{\theta_i}^{\theta_{i+1}} a\sqrt{1 + \theta^2} d\theta. \quad (2)$$

If dielectric materials are present, such as support structures used for spiral bundling in the tuning mechanism, their effect can be accounted for by scaling distances

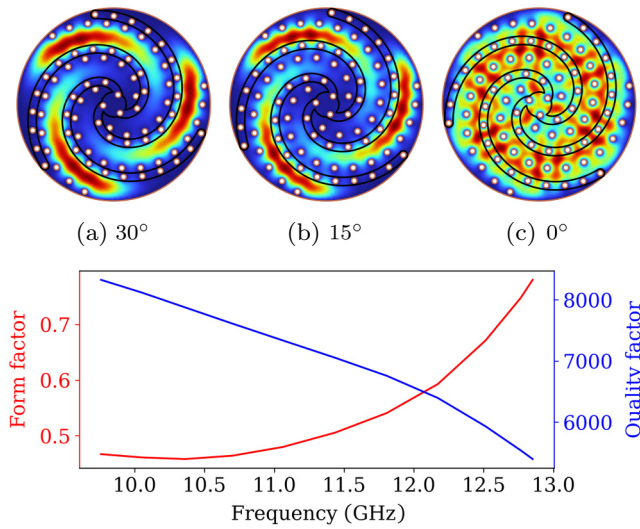


FIG. 3. Simulated performance of the spiral tuning mechanism for a six-arm configuration. Top: Cross-sectional electric-field distributions at various tuning angles (given in the subcaptions), illustrating the evolution of the lowest TM mode across the tuning range. The color scale indicates the electric-field strength, with red denoting high intensity and blue denoting low intensity. Brown boundaries represent conducting surfaces, and the black spiral lines correspond to the supports holding the rotatable wires. Bottom: Simulated form factor (red, left axis) and quality factor for room-temperature copper (blue, right axis) as functions of frequency. (a) 30°. (b) 15°. (c) 0°.

with the square root of the relative permittivity ε , i.e., $l \rightarrow l/\sqrt{\varepsilon}$.

An approximate solution to Eq. (2) yields

$$\theta_i \approx \sqrt{\theta_1^2 + \frac{\theta_n^2 - \theta_1^2}{n-1} \cdot (i-1)}, \quad (3)$$

where θ_i is the angular position of the i th wire ($i = 1, 2, \dots, n$), and θ_n is the angular position of the outermost wire.

The design procedure begins by fixing a cavity radius r_c and wire radius r_w . The number of spiral arms N_s is then chosen based on mechanical considerations. With a selected value of n , the wire density is defined. The corresponding resonant frequency for uniformly distributed wires is approximately

$$f \approx \frac{c}{\pi\sqrt{2}} \sqrt{\frac{N_s \times n}{\text{Cross-sectional area}}}, \quad (4)$$

where c is the speed of light. This formula can guide the selection of n to target a desired frequency range.

If no support is present, approximate relations for θ_1 and θ_n follows below proportionality from the numerical

simulations as illustrated in Figure 2.

$$\theta_1 \propto \log n, \quad \theta_n \propto \sqrt{n}. \quad (5)$$

With these angles, the field distribution remains unchanged, indicating the formation of a wire-metamaterial medium within a cylindrical geometry. When dielectric supports are included, small corrections to these angles must be introduced to account for the altered boundary conditions.

The tuning mechanism is conceptually simple, as noted earlier. The underlying principle is illustrated in Fig. 3. It depicts a representative example based on a six-arm spiral configuration with the same dimensions as described in the next section. The wire array is divided into fixed and rotatable sets. The rotatable wires are bundled through a spiral-shaped dielectric support, and rotation of this set about the central axis alters the azimuthal spacing between the spiral arms. This geometric reconfiguration changes the boundary conditions inside the cavity, thereby shifting its resonant frequency. The spiral configuration gives rise to a galaxylike electromagnetic-field distribution.

The performance of the cavity design is primarily characterized by the form factor and the quality factor. The expected axion-photon conversion power is proportional to the product of these two quantities, while the scanning speed scales linearly with the quality factor and quadratically with the form factor.

The quality factor characterizes the dissipation properties of the cavity, while the form factor quantifies the overlap between the resonant mode's electric field and the externally applied static magnetic field.

$$\text{Form factor} = \frac{|\int \mathbf{E} \cdot \mathbf{B}_{\text{ext}} dV_c|^2}{\int \varepsilon |\mathbf{E}|^2 dV_c \int |\mathbf{B}_{\text{ext}}|^2 dV_c}, \quad (6)$$

where $\mathbf{E}$ is the electric field of the cavity mode, ε is the dielectric constant of the material inside the cavity, and $\mathbf{B}_{\text{ext}}$ is the externally applied magnetic field. In typical haloscope experiments, $\mathbf{B}_{\text{ext}}$ is aligned along the axial direction, as the system is placed inside a solenoidal magnet. In this configuration, the fundamental TM mode provides the highest form factor.

The plot in Fig. 3 shows that the total tuning range exceeds 25%, with the form factor remaining around 0.5 at low frequencies and increasing at higher frequencies. The quality factor, estimated using the room-temperature conductivity of copper, decreases at higher frequencies due to increased surface losses, as the fields are uniformly distributed across the conducting wires.

Figure 4 compares the scanning speeds of two previously proposed tuning methods for plasma haloscopes [28, 29] with the present approach in a two-dimensional study. The magnet bore is held fixed throughout the evaluation, with all cavities constrained to a 165-mm inner diameter

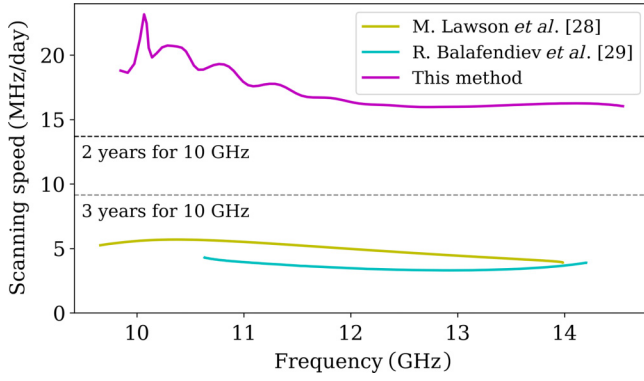


FIG. 4. Scanning speed comparison at KSVZ sensitivity for different tuning methods, as indicated in the legend. The black and gray dashed lines indicate the scanning rates required to cover a 10-GHz range within 2 and 3 years, respectively.

and 500-mm inner height, relevant to the ALPHA (Axion Longitudinal Plasma HALoscope) experiment [31]. Within this fixed volume, the spiral layout occupies a significantly larger fraction of the available cross section through its circular packing, whereas the alternative designs are limited by rectangular perimeters that leave unused regions inside a solenoidal magnet. This boundary modification results in approximately a twofold increase in usable volume, which in turn constitutes the dominant contribution to the observed fourfold enhancement in the overall scanning rate.

The oscillation in the scanning rate observed in the low-frequency regime for this method is attributed to variations in field confinement. At specific rotation angles, the electromagnetic fields alternate between being localized and being more broadly distributed between the spiral arms. This behavior is particularly pronounced in geometries with a large number of wires.

This comparison employs a wire diameter of 0.5 mm, which increases the achievable frequency tuning range relative to the previous example. The evaluation further assumes a 9-T magnetic field, an axion dark-matter density of 0.45 GeV/cm^3 [32,33] under a standard halo model giving a signal quality factor of 10^6 , KSVZ coupling strength, and a standard quantum-limited noise temperature. A surface conductivity of $5.998 \times 10^8 \text{ S/m}$ (ten times as high as for room-temperature copper) is also assumed, consistent with typical cryogenic values at microwave frequencies.

III. PROTOTYPE CAVITY

To evaluate the feasibility of the spiral tuning mechanism, we constructed a prototype cavity incorporating six spiral arms. The cavity body is fabricated from copper with a cylindrical geometry, featuring an inner diameter of 116 mm and a height of 100 mm.

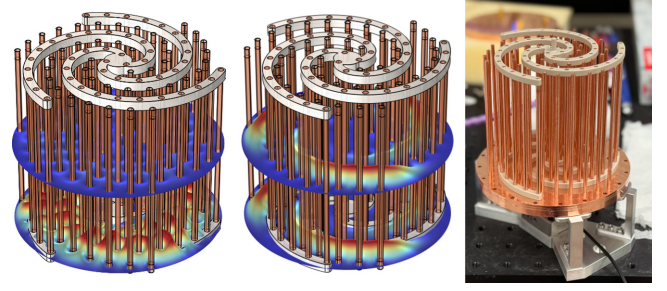


FIG. 5. Simulated and experimental images of the six-arm prototype cavity. The two panels on the left show the simulated electric-field distributions obtained with COMSOL for rotation angles of 0° (left) and 30° (center). Brown vertical rods represent the conducting wires, with one set fixed and the other rotatable. The top and bottom spiral-shaped structures are PEEK dielectric supports that hold the rotatable wires in place and define their angular positions. The right panel is a photograph of the partially assembled prototype, shown without the outer cylindrical enclosure to reveal the inner spiral structure. The spiral support is mechanically coupled to a rotary piezoelectric actuator via its central shaft, which is visible at the bottom of the assembly.

The fixed wires are anchored directly to the cavity endcaps, while the rotatable wires are mounted on a spiral dielectric disk. Two 5-mm-thick disks made of polyether ether ketone (PEEK) were installed at the top and bottom of the cavity to support the rotatable wires while minimizing dielectric loading in the central volume.

The number of wires per arm was set to 15 to achieve a resonant frequency above 10 GHz. Each wire has a diameter of 3.175 mm, corresponding to standard 1/8 inch copper tubing.

The angular positions of the wires are determined using Eq. (3), with the initial and final positions optimized in COMSOL [34]. The optimization aims to maximize the frequency of the fundamental TM mode in the unrotated configuration, thereby ensuring a widespread field distribution throughout the cavity volume.

Figure 5 shows a photograph of the half-assembled prototype cavity alongside the corresponding three-dimensional simulated electric-field distribution.

Each cavity endcap is equipped with three antenna ports to allow flexible coupling configurations. The spiral support disks incorporate a central shaft extending along the cavity axis, which passes through metal bearings mounted on each endcap to enable smooth, controlled rotation. One end of the shaft is connected to a piezoelectric rotary actuator, allowing fine tuning of the rotatable spiral wires.

Tuning is achieved by rotating the central shaft. The cavity resonant modes were characterized through reflection and transmission measurements using two weakly coupled antennas mounted on the endcaps. As the spiral arms were rotated, transmission spectra were recorded at room temperature, and the resulting mode map is shown in Figure 6 alongside the simulation for comparison.

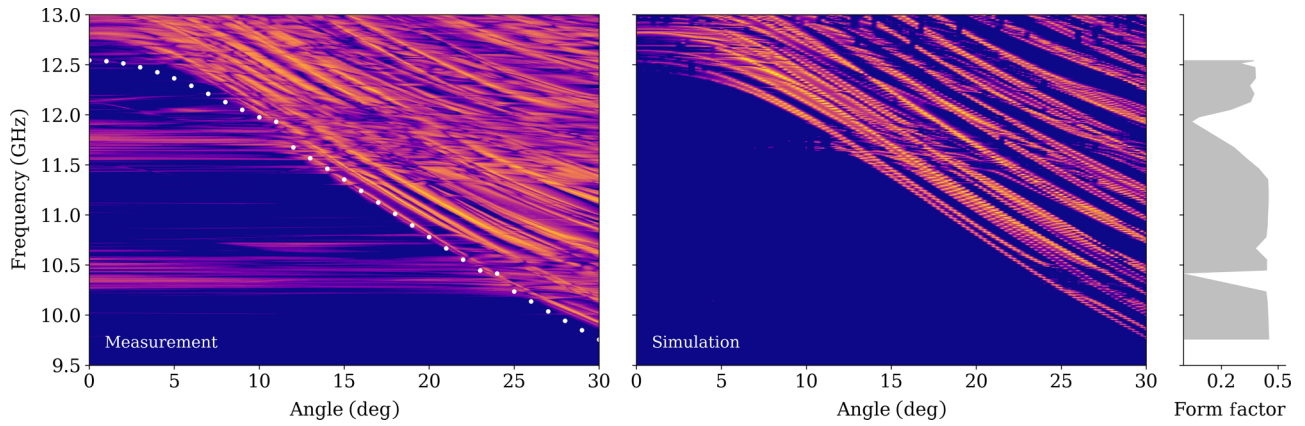


FIG. 6. Measured (left) and simulated (center) mode maps of the six-arm prototype cavity as functions of the spiral rotation angle. The color scale indicates the transmission amplitude, with brighter colors corresponding to stronger signals. The horizontal axis represents the relative rotation angle between the rotatable and fixed spiral bundles. White dots in the measured plot indicate the simulated frequencies of the desired mode obtained from an eigenmode study in COMSOL. The simulated mode map was generated using CST [35]. Missing resonances in the simulated map at certain angles arise because CST skipped some solutions during the frequency sweep. The gray curve on the right shows the simulated form factor of the mode.

The measured mode map shows good agreement with both COMSOL and CST results, validating the spiral tuning mechanism as a viable approach for plasma haloscope applications. Our target mode corresponds to the lowest-frequency tuned mode, consistent with the eigenmode solutions indicated by the white dots on the measured map. Several transverse electric (TE) modes and strong transverse electromagnetic (TEM) modes mixing appear as nearly horizontal bright lines. The mixing band appears broadened, as expected from imperfect wire alignment on the supports, machining and assembly errors, and possible support bending. The number of undesired TE mode crossings can be further reduced by implementing a photonic band-gap structure [30,36].

The achieved tuning range is approximately 25% in frequency. Three-dimensional electromagnetic simulations show that the form factor remains around 0.45, with a decrease in the highest-frequency region caused by mode mixing and field localization. This effect arises from the dielectric supports holding the wires at the top and bottom, as well as their gaps to the endcaps, which break the longitudinal symmetry. As a result, both the frequency coverage and overall form factor are reduced compared to the two-dimensional study.

IV. DISCUSSION

A key advantage of the spiral-arm geometry is its ability to accommodate a high density of conducting wires with minimal mechanical complexity. Conventional metamaterial cavities typically require multiple independent tuning shafts, since the spacing between wires must be individually controlled in each unit cell [29,30]. In contrast, the spiral-bundling approach enables collective tuning of

the wires through a single rotational degree of freedom, while maintaining a relatively stable form factor across the tuning range.

Enhanced mode mixing arises from longitudinal symmetry breaking introduced by the spiral support disks. These dielectric supports could be extended to span the full height of the cavity or replaced with a conducting support concealed from the cavity interior, thereby suppressing arm bending and improving axial symmetry. Such a modification is expected to reduce mode hybridization and localization while enhancing the overall electromagnetic performance.

The quality factor expected in this design can be significantly improved through the use of superconducting cavity techniques [37–39]. The dominant source of loss arises from the large number of conducting surfaces introduced by the wire array. Replacing the copper wires with superconducting ones is expected to substantially increase the quality factor by suppressing ohmic losses.

This initial study focused on demonstrating the tunable range and mechanical feasibility of the spiral-arm concept under room-temperature conditions. As the PEEK-based support structure is unsuitable for cryogenic operation due to its poor thermal conductance and dielectric losses, a revised design incorporating metallic supports thermally anchored to the cavity is currently under development. Even within these constraints, the present room-temperature demonstration already illustrates another approach to tuning a plasma haloscope, offering a mechanically simple structure that maximizes the usable volume within the magnet bore. Future iterations will explore refinements of the geometric layout and tuning mechanism to further enhance cryogenic performance and overall cavity efficiency.

The spiral geometry developed in this work is naturally aligned with the requirements of high-mass axion searches employing plasma haloscope techniques above the 10-GHz range. Its scalability and tunability make it a promising cavity design for the ALPHA experiment, providing the technology required to probe the QCD axion in the 10–50 GHz band with quantum-noise-limited sensitivity.

V. CONCLUSION

We have proposed and demonstrated an alternative spiral-based tuning mechanism for plasma haloscope cavities. This approach enables dense packing of metallic wires within a cylindrical volume while permitting mechanically simple tuning through a single rotational axis, independent of the number of wires. Two-dimensional electromagnetic simulations show a tuning range exceeding 25%, with the form factor remaining approximately 0.5 or higher across the frequency coverage. This method achieves scanning rates several times faster than traditional plasma haloscope tuning approaches, primarily due to the circular perimeter. The feasibility of the concept was demonstrated with a six-arm prototype cavity, showing good agreement with simulations in its frequency-tuning characteristics. This cavity design offers a promising route toward scalable and tunable high-frequency structures for future plasma haloscope experiments, including ALPHA.

ACKNOWLEDGMENTS

This research is supported by the Knut and Alice Wallenberg Foundation, Olle Engkvists Foundation, and the Swedish Research Council (VR) under Dnr 2019-02337 “Detecting Axion Dark Matter In The Sky And In The Lab” (AxionDM). The authors gratefully acknowledge valuable discussions within the ALPHA Collaboration. This research utilized the Sunrise HPC facility supported by the Technical Division at the Department of Physics, Stockholm University. <http://doi.org/10.5281/zenodo.TBD> The numerical modeling work of Rustam Balafendiev was supported by the Russian Science Foundation (Grant No. 25-12-00261 <https://rscf.ru/project/25-12-00261/>).

DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

-
- [1] R. D. Peccei and H. R. Quinn, CP conservation in the presence of pseudoparticles, *Phys. Rev. Lett.* **38**, 1440 (1977).

- [2] S. Weinberg, A new light boson? *Phys. Rev. Lett.* **40**, 223 (1978).
- [3] F. Wilczek, Problem of strong p and t invariance in the presence of instantons, *Phys. Rev. Lett.* **40**, 279 (1978).
- [4] J. Preskill, M. B. Wise, and F. Wilczek, Cosmology of the invisible axion, *Phys. Lett. B* **120**, 127 (1983).
- [5] L. F. Abbott and P. Sikivie, A cosmological bound on the invisible axion, *Phys. Lett. B* **120**, 133 (1983).
- [6] M. Dine and W. Fischler, The not-so-harmless axion, *Phys. Lett. B* **120**, 137 (1983).
- [7] J. E. Kim, Weak-interaction singlet and strong CP invariance, *Phys. Rev. Lett.* **43**, 103 (1979).
- [8] M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Can confinement ensure natural CP invariance of strong interactions? *Nucl. Phys. B* **166**, 493 (1980).
- [9] A. R. Zhitnitsky, On possible suppression of the axion hadron interactions (in Russian), *Sov. J. Nucl. Phys.* **31**, 260 (1980).
- [10] M. Dine, W. Fischler, and M. Srednicki, A simple solution to the strong cp problem with a harmless axion, *Phys. Lett. B* **104**, 199 (1981).
- [11] I. G. Irastorza and J. Redondo, New experimental approaches in the search for axion-like particles, *Prog. Part. Nucl. Phys.* **102**, 89 (2018).
- [12] C. O’Hare, cajohare/axionlimits: Axionlimits, 2020, <https://cajohare.github.io/AxionLimits/>
- [13] Y. K. Semertzidis and S. Youn, Axion dark matter: How to see it? *Sci. Adv.* **8**, eabm9928 (2022).
- [14] P. Sikivie, Experimental tests of the invisible axion, *Phys. Rev. Lett.* **51**, 1415 (1983).
- [15] M. Kawasaki, K. I. Saikawa, and T. Sekiguchi, Axion dark matter from topological defects, *Phys. Rev. D* **91**, 065014 (2015).
- [16] L. Fleury and G. D. Moore, Axion dark matter: Strings and their cores, *J. Cosmol. Astropart. Phys.* **2016**, 004 (2016).
- [17] M. Gorghetto, E. Hardy, and G. Villadoro, More axions from strings, *SciPost Phys.* **10**, 050 (2021).
- [18] H. Kim, J. Park, and M. Son, Axion dark matter from cosmic string network, *J. High Energy Phys.* **2024**, 150 (2024).
- [19] K. Saikawa, J. Redondo, A. Vaquero, and M. Kaltschmidt, Spectrum of global string networks and the axion dark matter mass, *J. Cosmol. Astropart. Phys.* **2024**, 043 (2024).
- [20] J. N. Benabou, M. Buschmann, J. W. Foster, and B. R. Safdi, Axion mass prediction from adaptive mesh refinement cosmological lattice simulations, *Phys. Rev. Lett.* **134**, 241003 (2025).
- [21] D. J. E. Marsh, K. C. Fong, E. W. Lentz, L. Šmejkal, and M. N. Ali, Proposal to detect dark matter using axionic topological antiferromagnets, *Phys. Rev. Lett.* **123**, 121601 (2019).
- [22] B. Majorovits and for the MADMAX interest group, Madmax: A new road to axion dark matter detection, *J. Phys. Conf. Ser.* **1342**, 012098 (2020).
- [23] J. Liu *et al.*, Broadband solenoidal haloscope for terahertz axion detection, *Phys. Rev. Lett.* **128**, 131801 (2022).
- [24] J. Chiles, I. Charaev, R. Lasenby, M. Baryakhtar, J. Huang, A. Roshko, G. Burton, M. Colangelo, K. Van Tilburg, A. Arvanitaki, S. W. Nam, and K. K. Berggren, New constraints on dark photon dark matter with superconducting

- nanowire detectors in an optical haloscope, *Phys. Rev. Lett.* **128**, 231802 (2022).
- [25] F. Bajjali, S. Dornbusch, M. Ekmedžić, D. Horns, C. Kase-
mann, A. Lobanov, A. Mkrtchyan, L. H. Nguyen, M.
Tluczykont, G. Tuccari, J. Ulrichs, G. Wieching, and A.
Zensus, First results from brass-p broadband searches for
hidden photon dark matter, *J. Cosmol. Astropart. Phys.*
2023, 077 (2023).
- [26] J. Jeong, S. Youn, and Y. K. Semertzidis, Horn-array halo-
scope for volume-efficient broadband axion searches, *Phys.*
Rev. D **108**, L051101 (2023).
- [27] J. De Miguel, A. Kryemadhi, K. Zioutas, and On behalf of
the DALI Collaboration, Dali sensitivity to streaming axion
dark matter, *Phys. Rev. D* **111**, 023016 (2025).
- [28] M. Lawson, A. J. Millar, M. Pancaldi, E. Vitagliano, and
F. Wilczek, Tunable axion plasma haloscopes, *Phys. Rev.*
Lett. **123**, 141802 (2019).
- [29] R. Balafendiev, G. Kaur, J. A. Enriquez, G. Singh, A. J.
Millar, J. E. Gudmundsson, and P. Belov, Tunable epsilon
near zero metamaterial with rotating obround-shaped meta-
atoms, [arXiv:2506.04428 \[physics.optics\]](https://arxiv.org/abs/2506.04428).
- [30] D. Goulart, A. M. Sindhwa, H. M. Jackson, N. I. Kowitt,
K. A. Dones, P. C. Basurto, A. Dawes, S. Jois, S. M. Lewis,
and K. van Bibber, Practical photonic band gap structures
for high frequency axion haloscopes, *Rev. Sci. Instrum.* **96**,
094704 (2025).
- [31] A. J. Millar *et al.*, Searching for dark matter with plasma
haloscopes, *Phys. Rev. D* **107**, 055013 (2023).
- [32] X. Ou, A.-C. Eilers, L. Necib, and A. Frebel, The dark
matter profile of the milky way inferred from its circular
velocity curve, *Mon. Not. R. Astron. Soc.* **528**, 693 (2024).
- [33] S. H. Lim, E. Putney, M. R. Buckley, and D. Shih, Mapping
dark matter in the milky way using normalizing flows and
Gaia DR3, *J. Cosmol. Astropart. Phys.* **2025**, 021 (2025).
- [34] COMSOL, COMSOL Multiphysics, Version 6.3 COMSOL
AB, Stockholm, Sweden, 2024, <https://www.comsol.com>
- [35] CST Studio Suite, CST Microwave Studio, 2023,
<https://www.cst.com>
- [36] S. M. Lewis, D. T. Goulart, M. C. Barbosa, A. F. Leder, A.
M. Sindhwa, I. Urdinaran, and K. van Bibber, A tunable
photonic band gap resonator for axion dark matter searches,
[arXiv:2408.03861 \[physics.ins-det\]](https://arxiv.org/abs/2408.03861).
- [37] D. Alesini *et al.*, Galactic axions search with a supercon-
ducting resonant cavity, *Phys. Rev. D* **99**, 101101 (2019).
- [38] D. Ahn, O. Kwon, W. Chung, W. Jang, D. Lee, J. Lee, S. W.
Youn, H. Byun, D. Youm, and Y. K. Semertzidis, Biaxially
textured $\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$ microwave cavity in a high mag-
netic field for a dark-matter axion search, *Phys. Rev. Appl.*
17, L061005 (2022).
- [39] S. Ahyoune *et al.*, Rades axion search results with a high-
temperature superconducting cavity in an 11.7 T magnet, *J.*
High Energy Phys. **2025**, 113 (2025).