Snowmass2021 - Letter of Interest

Haloscopes for axion dark matter detection in the 30 μeV range with RADES

Thematic Areas: (check all that apply □/■)

□ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
□ (CF3) Dark Matter: Cosmic Probes
□ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
□ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
□ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
□ (CF7) Cosmic Probes of Fundamental Physics
□ (Other) *[Please specify frontier/topical group]*

Contact Information:
Babette Döbrich (CERN, Geneva, Switzerland) [babette.dobrich@cern.ch]
Collaboration (optional): RADES

Authors: A. Álvarez Melcón, S. Arguedas Cuendis, S. Calatroni, C. Cogollos, A. Díaz-Morcillo, B. Döbrich, J.D. Gallego, J.M. García Barceló, B. Gimeno, J. Golm, J Gutierrez, I.G. Irastorza, A. Kanareykin, A.J. Lozano-Guerrero, C. Malbrunot, J. Miralda, P. Navarro, C. Peña Garay, T. Puig, J. Redondo, and W. Wuensch

Abstract: (maximum 200 words)

The RADES project is developing axion dark matter detectors above the 30μeV scale employing custom-made microwave filters in magnetic dipole fields. At the present day, RADES is taking data in the CAST LHC dipole with a 1-m long rectangular filter. In a future, RADES is planning the use of the BabyIAXO magnet to take data using custom designs with QCD benchmark sensitivity. In this Letter of Interest we describe what we did so far (research and development, measurements and publications) and what our research lines are for the future. We place special emphasis on describing the development of a novel electrical tuning system using ferroelectrics, which is a new R&D activity being developed in cooperation with US-based companies.

The Relic Axion Detector Experimental Setup (RADES) is an axion search project devoted on the design of scalable haloscopes around and above $\sim 30\ \mu$eV. Our structures, made of copper-coated stainless steel, are based on an arrangement commonly used in radio-frequency filters: an array of small microwave sub-cavities, whose size controls the operation frequency, connected by rectangular irises. Also, such an arrangement allows the connection of a large number of cavities providing high volumes, an important factor for increasing the probability of axion detection.

The detection principle, the theoretical framework and the first haloscope details, can be found in [1]. This first structure is based on a five-cavity microwave filter with a detecting mode operating at around ~8.4 GHz. This structure has been characterized at 2 K and 298 K, and two more prototypes were designed and built in 2018. The goal of the new structure designs is to find and test the best cavity geometry in order to scale up in volume and to introduce an effective tuning mechanism in order to sweep a range of axion masses. For the first concept, a 6 sub-cavities structure with an alternating arrangement of coupling irises (capacitive and inductive windows) is used, which provides good results in avoiding mode-mixing [2]. For the second one, a 5 sub-cavities structure with a vertical cut is employed together with a mechanical tuning [3], which allows controlling the width (and thus the frequency) of the sub-cavities. Also, a fourth structure based on the alternating structure, but with 30 sub-cavities (~1 meter long haloscope), has been designed and manufactured in 2019. In Figure 1 we can observe the four RADES structures produced so far and in Figure 2 we project the sensitivity of our most recent detector.

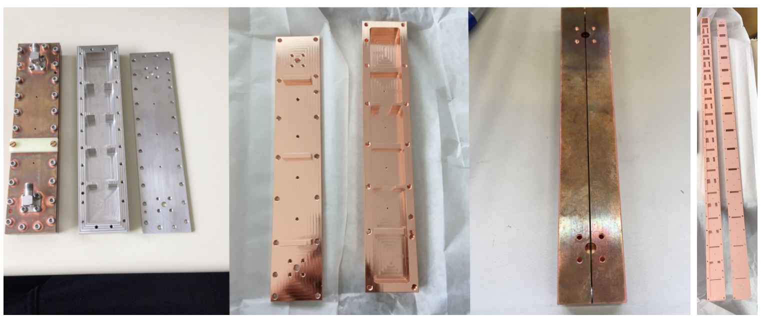

Figure 1: From left to right: first 5 sub-cavities structure with inductive couplings (non-tunable), alternating 6-cav structure (non-tunable), 5 sub-cavities vertical cut structure (tunable), alternating 30-cavities structure. The first three structures are each about 15cm long, the 4th one is of about approximately 1m length.

Around 350 hours of data has been taken at CAST (CERN Solar Axion Telescope), an experiment that uses a decommissioned LHC (Large Hadron Collider) 9T dipole magnet, with the first prototype in 2017 and 2018. Data analysis results are forthcoming. At this point in time, we are taking data with the 30-cavities structure at CAST.

Besides the goal of increasing the sensitivity of detection through achieving large geometric factors and high quality factors, a key feature of the system must be the tuning of the resonant frequency. For this reason, the vertical cut structure was designed and built. Proof of principle tests to tune the cavity were done at CERN, where spacers were manually introduced between the two halves and the resonant frequency was measured using a vector network analyzer. A structure for automatization of the tuning procedure has also been designed and tested at cryogenic temperatures. First results show a tuning range of approximately 650 MHz.

In addition, the RADES team is working as well on another tuning method: electrical tuning by ferroelectric materials. Most axion haloscopes tune their cavity mechanically. Tuning with ferroelectrics instead can provide an avenue that is less prone to mechanical failures and thus complements and expands existing techniques. Another advantage of the ferroelectric tuning for multi-cavity systems is the ability to independently adjust the many different cavity frequencies to maintain the correct mode structure and field pattern, and thus keep a good form factor across the tuning range, which is an important parameter for the detection sensitivity. A collaboration with Euclid Techlabs has arised, who proposes using as a tuning element Potassium Tantalite, $KTaO_3$ (KTO), a ferroelectric that exhibits excellent loss factor ($\sim 10^{-5}$ at X band) and still can be tunable in the cryogenic 2K-10K temperature range.

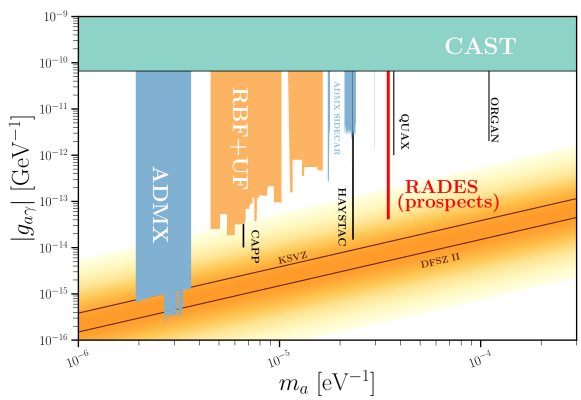

Figure 2: Prospects of the RADES setup with 2020 data in the context of other haloscope searches: BFRT-UF, ADMX, HAYSTAC, QUAX and ORGAN. Figure taken from[2].

The steps to be done for the electrical tuning are: 1. HFSS/CST modeling of a resonant cavity for the KTO crystal testing at 2-10K, 2. Machining and polishing the acquired KTO crystals to optical grade and biasing contacts deposition on the KTO single crystal surface, 3. Liquid Helium temperature testing of KTO crystals loss tangent and tuning range at DC biasing voltage applied, 4. HFSS/CST modeling of the RADES haloscope operating at ~8.4 GHz with the introduced KTO ferroelectric inside the multi-cavity array, and 5. Manufacturing of the previous structure with the tuning system. Euclid Techlabs was encourage to re-apply for a US-based funding opportunity (more specifically, a Small Business Innovation Research and Small Business Technology Transfer funding: https://science.osti.gov/sbir/Funding-Opportunities) in the next year for the development of this ferroelectric tuning system for haloscopes in the RADES project.

On the other hand, new ideas are under study with the aim of increasing the sensitivity of detection. On one side, new cavity designs using HTS (High-Temperature Superconductors) are promising good results in the Quality Factor. HTS tests are foreseen in early 2021. Also, new geometry (like 3D arrangement and taller cavities) are under test in order to increase the volume, which is another key factor for the Figure of Merit of the detector.

Since these haloscopes can work with any dipole magnet, for 'axion hunters' this is a very versatile concept. Our current designs constitute R&D towards searching axions at relatively large masses with the future International Axion Observatory (IAXO), a dedicated toroidal magnet with B^2V ~300 $\mathrm{T}^2\mathrm{m}^3$ (for comparison the magnet at CAST has: B^2V = 2.4 $\mathrm{T}^2\mathrm{m}^3$).

References

[1] A. Á. Melcón *et al.*, JCAP **1805**, no. 05, 040 (2018), doi:10.1088/1475-7516/2018/05/040, [arXiv:1803.01243v2 [hep-ex]], https://arxiv.org/abs/1803.01243.

[2] A. Á. Melcón *et al.*, JHEP **2020**, 84 (2020), doi.org/10.1007/JHEP07(2020)084, [arXiv:2002.07639v3 [hep-ex]], https://arxiv.org/abs/2002.07639.

[3] S. Arguedas Cuendis *et al.*, Springer Proc. Phys. **245** (2020), 45-51 doi:10.1007978-3-030-43761-9_6 [arXiv:1903.04323 [physics.ins-det]].