Snowmass2021 - Letter of Interest

Magnet R&D for Low-Mass Axion Searches

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

■ (AF5) Accelerator Technology R&D
■ (CF2) Dark Matter: Wavelike
■ (IF1) Quantum Sensors

Contact Information:

A. F. Leder (aleder@berkeley.edu)

Collaboration: DMRadio (dmradiocollaboration@gmail.com)

Authors: A. F. Leder (UC Berkeley/LBNL), L. Brouwer (LBNL), S. Chaudhuri (Princeton), H.-M. Cho (SLAC), C. S. Dawson (Stanford), A. Droster (UC Berkeley), A. Gavin (UNC), P. W. Graham (Stanford), R. Henning (UNC/TUNL), S. P. Ho (Stanford), K. D. Irwin (Stanford/SLAC), F. Kadribasic (Stanford), Y. Kahn (UIUC), A. Keller (UC Berkeley), R. Kolevatov (Princeton), S. Kuenstner (Stanford), D. Li (SLAC), J. L. Ouellet (MIT), K. Pappas (MIT), A. Phipps (CSU East Bay), S. Rajendran (JHU), N. M. Rapidis (Stanford), B. R. Safdi (UC Berkeley/LBNL/UMich), C. Salemi (MIT), M. Simanovskaia (Stanford), J. Singh (Stanford), E. C. van Assendelft (Stanford), K. van Bibber (UC Berkeley), K. Wells (Stanford), L. Winslow (MIT), B. A. Young (Santa Clara)

Abstract:

Most axion dark matter searches take advantage of the coupling between axions and photons in the presence of a magnetic field. Up until now, most experiments have used stock magnet designs to generate this coupling. DMRadio and future axion searches have reached a scale where significant magnetic-field engineering is required to enhance sensitivity of axion searches into the QCD band. These next generation experiments will require larger fields without sacrificing volume while also taking into account several practical considerations, such as the ability to be cooled to cryogenic temperature, in order to reach these sensitivity goals. Next-generation experiments will need to collaborate with national magnet labs, in addition to partnerships with industry, to design, construct and test the magnets that will power these upcoming axion searches.

Science landscape: Over the past decade there has been increased theoretical and experimental interest in the axion as a leading Dark Matter (DM) candidate. While the axion was originally motivated as a solution to the strong CP problem in QCD[1–3], it has gained additional interest as a potential cold DM candidate, thanks in part to recent experimental developments in quantum sensor technology. Axion searches are still highly unconstrained in both mass (over 12 orders of magnitude) and coupling strength to photons, providing a wide-open parameter space[4]. Cavity based resonator experiments (ADMX[5] and HAYSTAC[6]) dominate in the region between 1 μeV - 80 μeV with upgraded field strengths between 8-30 T. In the mass region of 20 neV - 0.8μeV, DMRadio-m^3 plans to explore new regions of QCD parameter space with a 4 T magnet subject to precise magnetic-field profile requirements. Finally MRI experiments (CASPEr[7]) can probe below 1 neV, requiring extremely uniform fields. All of these axion search experiments require large and precisely-understood magnetic fields. Experimental sensitivity, given as the inverse coupling between an axion and two photons, scales as (refer to other DMRadio LOIs in CF2 for more details):

$$g_{a\gamma\gamma}^{-1} \propto \frac{B_0 V^{\alpha} Q^{1/4}}{\eta^{1/4} T^{1/4}} \tag{1}$$

where B_0 is the magnetic field, V is the detector volume, and α is some scaling power. For low mass experiments, $m_a \lesssim 1\,\mu\text{eV}$, $\alpha = 5/6$[8;9], while for higher masses α = 1/2. As these experiments grow in size, the need for a better understanding of the magnetic field and engineering constraints will grow along with them. We seek to collaborate with partners in academia, industry, and national labs in order to design, construct and test these next generation axion detectors.

Magnet Science Goals: Nearly all current axion experiments have utilized commercially available solenoid/toroid/ dipole accelerator designs. However, upcoming axion experiments now have unique field requirements that require additional R&D efforts. DMRadio-50L builds on the work of previous toroidal DM searches[10] and aims to construct a magnetic field profile that optimizes the coupled energy between the axion and the instrument.[8;11;12]. An additional optimization of the DMRadio-50L toroidal magnet maximizes the peak magnetic field in the largest overall science volume as dictated by Eq. (1). At the same time, we seek to minimize the pick-up of any parasitic losses from magnet components that couple to a high-Q resonator outside the toroid. Finally, the profile of the magnetic field is required to minimize any strays that could interfere with our superconducting pickup elements.

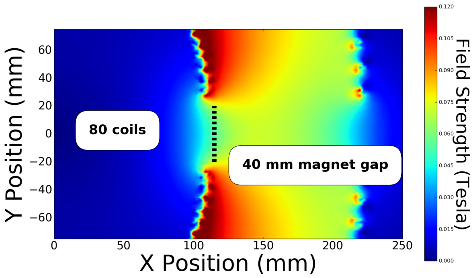

Figure 1: Magnetic field profile for a toroidal magnet design. The strongest field leakage occurs not only in the gap region, but also in between individual magnet coils

All these considerations require precisely modeled magnetic field profiles. The result is a design that interweaves the pickup design with the magnet design, as shown by the separate but parallel optimization schemes utilized by the DMRadio-50L and DMRadio-m^3 experiments. These lessons can also be applied towards the optimization of any experiment with an operating field in the 1-12 Tesla range. Magnetic field engineering/optimization opens the door for improved axion experimental designs, allowing for the possibility of experiments with specialized magnetic field profiles that have a maximal coupling to the axion field while minimizing backgrounds/losses and under the practical engineering constraints - as discussed in the next section.

Magnet Engineering Constraints: The design of an idealized magnet for an axion search must be balanced against practical considerations in the construction and implementation of such magnets see Fig. 2. All these magnets require the use of superconducting wiring and therefore must be mounted in cryogenic systems which come with a host of their own constraints. Future studies will be required to understand and minimize the effect of mechanical vibrations and external EMI interference on the magnetic field profiles and in turn the operation of the experiment. We must also take into account the magnetic forces during ramping and operation that will affect the individual components and design support structures accordingly, balancing against the use of lossy or paramagnetic materials, particularly with larger magnetic fields. For safe and reliable operation of these magnets with minimal downtime over the course of months or even years, quench protection elements must be developed. Co-optimizing across all these considerations, we wish to design a series of toroidal and solenoidal magnet designs that are cost-effective and allow for the maximum possible science reach across the widest possible axion parameter space.

Current and Future Projects: For the DMRadio-50L and DMRadio-m^3 design efforts we have collaborated closely with the magnet design groups at LBNL and SLAC respectively. These two designs utilize different pickup geometries and specialized field profiles due to the complementary axion masses/frequencies being probed by each while only utilizing comparatively moderate peak magnetic fields. Moving towards future experiments such as DMRadio-GUT will require not only better detector readouts, but even stronger magnetic fields, pushing the envelope of engineering and science constraints. The DMRadio program seeks to take into account all of the above scientific and engineering constraints towards realizing these ambitious goals. This effort can be adapted to any axion experiment seeking to optimize their axion coupling boosting their sensitivity reach.

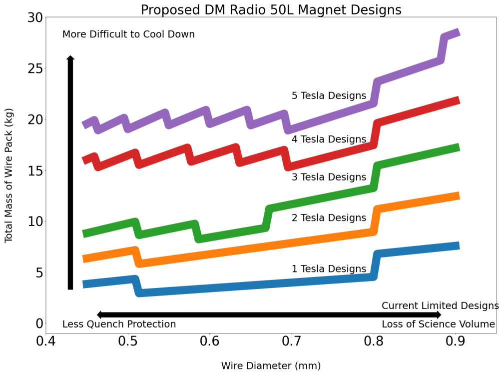

Figure 2: Example engineering space for DMRadio-50L experiment with various peak field design goals. The jagged edges stem from the additional layers added to the wire pack in order to reach the intended peak field at the cost of science volume.

Conclusion As experiments probe ever deeper into axion parameter space, the magnetic fields required will grow commensurately. These larger magnets will have to be optimized to the axion signal while simultaneously minimizing any potential signal losses, necessitating precision magnetic field engineering. At same time, these magnets will push the engineering capabilities of current technologies, requiring additional R&D for their construction/operation. DMRadio-50L is currently laying the groundwork for a design process by which a magnet is designed with an eye towards optimizing the sensitivity reach across a wide range of axion masses. This process entails taking into account a wide variety of constraints listed here, each of which will require an R&D effort for next generation experiments:

- Precision control of the magnetic field profile to reduce leakage into sensitive volumes.
- Integration of magnets into complex multi-temperature cryogenic systems capable of cooling components below 100 mK.
- Reduction in environmental backgrounds such as mechanical vibrations and external EMI sources.
- Development of cost-effective large-volume high-field magnet designs.

We are interested in partnering with experts at national labs as well as in industry in order to design, construct and test the next generation of axion magnets. The lessons learned in the DMRadio program, see additional LOIs submitted to CF2, are more broadly applicable to all next generation axion experiments. These advances will enable the field to probe QCD axion DM over the full 12 orders of magnitude in mass, perhaps perhaps one day unlocking one of the greatest mysteries of modern physics.

References

[1] R. D. Peccei and Helen R. Quinn. ”CP Conservation in the Presence of Instantons”. *Phys. Rev. Lett.*, 38:1440–1443, 1977. URL `https://doi.org/10.1103/PhysRevLett.38.1440`.

[2] Frank Wilczek. ”Problem of Strong P and T Invariance in the Presence of Instantons”. *Phys. Rev. Lett.*, 40:279–282, 1978. doi: 10.1103/PhysRevLett.40.279. URL `https://doi.org/10.1103/PhysRevLett.40.279`.

[3] Steven Weinberg. ”A New Light Boson?”. *Phys. Rev. Lett.*, 40:223–226, 1978. URL `https://doi.org/10.1103/PhysRevLett.40.223`.

[4] Pierre Sikivie. ”Invisible Axion Search Methods”. *arXiv preprint arXiv:2003.02206*, 2020. URL `https://arxiv.org/abs/2003.02206`.

[5] T. Braine et al. ”Extended Search for the Invisible Axion with the Axion Dark Matter Experiment”. *Phys. Rev. Lett.*, 124:101303, 2020. URL `https://link.aps.org/doi/10.1103/PhysRevLett.124.101303`.

[6] L. Zhong et al. “Results from Phase 1 of the HAYSTAC Microwave Cavity Axion Experiment“. *Phys. Rev. D*, 97:092001, 2018. URL `https://link.aps.org/doi/10.1103/PhysRevD.97.092001`.

[7] Dmitry Budker, Peter W. Graham, Micah Ledbetter, Surjeet Rajendran, and Alexander O. Sushkov. ”Proposal for a Cosmic Axion Spin Precession Experiment (CASPEr)”. *Phys. Rev. X*, 4:021030, May 2014. URL `https://link.aps.org/doi/10.1103/PhysRevX.4.021030`.

[8] Saptarshi Chaudhuri, Kent D Irwin, Peter W Graham, and Jeremy Mardon. ”Optimal Electromagnetic Searches for Axion and Hidden-Photon Dark Matter”. *arXiv preprint arXiv:1904.05806*, 2019. URL `https://arxiv.org/abs/1904.05806`.

[9] Saptarshi Chaudhuri, Kent Irwin, Peter W. Graham, and Jeremy Mardon. ”Fundamental Limits of Electromagnetic Axion and Hidden-Photon Dark Matter Searches: Part I - The Quantum Limit”. *arXiv preprint arXiv:1803.01627*, 2018. URL `https://arxiv.org/abs/1803.01627`.

[10] Jonathan L. Ouellet et al. ”First Results from ABRACADABRA-10 cm: A Search for Sub-μeV Axion Dark Matter”. *Phys. Rev. Lett.*, 122:121802, Mar 2019. URL `https://link.aps.org/doi/10.1103/PhysRevLett.122.121802`.

[11] S. Chaudhuri et al. ”Radio for Hidden-Photon Dark Matter Detection”. *Physical Review D*, 92(7), OCT 8 2015. URL `https://link.aps.org/doi/10.1103/PhysRevD.92.075012`.

[12] Saptarshi Chaudhuri, Kent D. Irwin, Peter W. Graham, and Jeremy Mardon. “Optimal Electromagnetic Searches for Axion and Hidden-Photon Dark Matter”. *arXiv preprint arXiv:1904.0580*, 2019. URL `https://arxiv.org/abs/1904.0580`.