Workshop on Microwave Cavity Design for Axion Detection

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Book of Abstracts
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Greetings and Welcome

Axion Dark Matter Detection with Microwave Cavities - Overview of Challenges
Dr. CAROSI, Gianpaolo

1 Lawrence Livermore National Laboratory

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In this talk I will present an overview of the axion dark matter haloscopes that use microwave cavities to resonantly enhance the conversion rate of axions to potentially detectable levels. I will layout the number of design challenges facing experimental efforts moving forward.

Cavity Design considerations for ADMX

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Here we will present a historical context for the design considerations that lead to the ADMX cavity system from Phase 0 - Phase I.

Introduction to RF-Structures and Their Design
Dr. KRAWCZYK, Frank

1 Los Alamos National Laboratory

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The numerical design chapter of the class addresses two topics: (1) Numerical Methods that include resonator design basics, introduction to Finite Difference, Finite Element and other methods, and (2) Introduction to Simulation Software that covers 2D and 3D software tools and their applicability, concepts for problem descriptions, interaction with particles, couplers, mechanical and thermal design, and finally a list of tips, tricks and challenges.

ACE3P for RF structure simulation
BOWRING, Daniel

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RF codes such as Comsol and CST Microwave Studio are powerful tools but they have some limitations. Most notably, simulation throughput is limited by the availability of expensive (and therefore typically scarce) solver seats. Furthermore, high-fidelity geometry meshing may be difficult. SLAC has developed ACE3P, a 3D parallel code for RF structure simulation that runs on the National Energy Research Scientific Computing Center (NERSC). Simulations may be run relatively quickly in batch mode with extremely high geometry fidelity. We present a brief
introduction to ACE3P, some example simulations from other experiments, and an assessment of its utility for ADMX.

Superconducting Microstrip Resonators - I / 50

Superconducting Microresonators

Prof. ZMUIDZINAS, Jonas

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Superconducting microresonators have attracted substantial attention over the past fifteen years due to a number of applications including photon detection, particle detection, and quantum devices. Our understanding of the behavior of these devices has advanced substantially during this period, particularly with regard to the influence of two-level systems on the dissipation and noise observed in these resonators, as well as nonequilibrium and nonlinear effects observed in the superconducting materials. Nonetheless, there are still significant gaps in our understanding in several areas, and there remains substantial opportunity for improvement and innovation as well as application to new problems. This presentation will outline both the recent developments and the remaining challenges in this field.

Superconducting Microstrip Resonators - II / 48

Simulation of Superconducting Qubit Devices Using COMSOL

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Over the last decade, superconducting qubits have emerged as strong candidates for a scalable quantum computing architecture. These devices deliver coherence times approaching milliseconds and basic coherent quantum logic operations have been demonstrated. First order models for superconducting qubits follow lumped circuit element representations, capturing a large portion of their behavior for practical operation. Despite their continued improvement in coherence times, quality factors, and measurement techniques, the qubits and their resonant readout circuitry still suffer from environment-induced noise. Current models of noise involve phenomenological explanations where uniformly distributed harmonic oscillators and two level systems simulate thermal excitations and intrinsic defects. To further investigate the microscopic sources of noise, we are developing simulations using COMSOL Multiphysics, a finite element solver with a broad range of capabilities including high frequency electromagnetics, thermodynamics, and any arbitrary physics described by differential equations. In this talk, we discuss some of the COMSOL modeling techniques currently applied in our study and the future direction of our larger qubit modeling effort.

Superconducting Microstrip Resonators - II / 64

Microstrip Resonator Design work at LLNL

Dr. HORSLEY, Matt

1 LLNL

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We will present initial simulation work for microstrip resonators at LLNL.

Quantum Limited Axion Cavity Amplifiers - I / 70
A Varactor Tuned Microstrip SQUID amplifier for axion searches

Mr. O’KELLEY, Sean¹

¹ UC Berkeley

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Here we will overview the SQUID amplifier that has been developed for the ADMX experiment.

Quantum Limited Axion Cavity Amplifiers - I / 49

Josephson Parametric Amplifiers: Theory and Application

EDDINS, Andrew¹

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Measurement of signals consisting of small numbers of microwave photons per unit bandwidth requires multiple amplification stages so the signal can be efficiently detected by room temperature electronics. However, even the lowest-noise commercially available microwave amplifiers add the equivalent of tens of photons of noise, making them insufficient for the amplification of single- or sub-photon signals. Recent interest in measuring photon-level signals from superconducting circuits has motivated the intensive development of Josephson parametric amplifiers (JPAs). Consisting of Josephson junctions shunted by a capacitor to form a nonlinear resonator, a typical JPA provides large gain (~20 dB) with nearly quantum-limited noise performance over instantaneous bandwidths of many MHz (depending on frequency band) that can be tuned over an octave. These devices have enabled a variety of experiments with superconducting qubits, including high-fidelity readout, quantum feedback, and observation of individual quantum trajectories. They also provide a valuable tool for the field of microwave quantum optics through their ability to generate squeezed states of the EM field. In this talk, I will discuss the operating principle and design considerations of a JPA circuit, their typical usage in qubit measurement, and their potential application to the detection of dark matter.

Microwave Cavity Motion Control / 77

Piezoelectric Tuning of Microwave Cavities for Axion Searches

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The Axion Dark Matter eXperiment (ADMX) searches for dark-matter axions by looking for their resonant conversion to microwave photons in a strong magnetic field. In the event that ADMX rules out axions in the 500MHz - 2GHz frequency range, new technologies and cavity geometries will need to be explored to find higher mass axions. ADMX Sidecar is a higher frequency pathfinder experiment that uses a miniature resonant cavity to search for axions in the 3.5GHz-6GHz frequency range. The Sidecar cavity sits on top of the main ADMX cavity and relies greatly upon piezo motors for tuning and for antenna coupling. Here I discuss the progress of this experiment and give an update on our success with piezoelectric tuning/coupling.

A Prototype Piezoelectric Drive System for ADMX

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Here we will present work on a prototype rotary piezoelectric drive system to adjust tuning rods in the ADMX experiment.
Microwave Cavity Axion Searches - II / 43

4-9 GHz Cavity Development at CAPP
Dr. THEMANN, Harry¹

¹ Center for Axion and Precision Physics

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I will present our experiences with developing expertise at cavity design. We were given a chance to run parasitically in an 8T magnet with a 60mm bore. This drove our choice of frequency regime. Because of the fixed geometry of the refrigerator and magnet we were required to have all mechanisms and actuators in close proximity to the dilution refrigerator and in a fringe field of 100-300G. We took this as an opportunity to also develop experience and expertise using piezo actuators.

Microwave Cavity Axion Searches - II / 62

The ADMX-HF Experiment
Prof. VAN BIBBER, Karl¹

¹ UC Berkeley

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Here we will present an overview of the ADMX-HF experiment at Yale University and discuss the lessons learned in the development of a 4-6 GHz microwave cavity which has recently gone through its first commissioning data taking.

Open Cavity Resonators - Project Orpheus
RYBKA, Gray¹

¹ University of Washington

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Overview and progress of the open cavity resonator concept.

Axion ( & Paraphoton) Microwave Cavity Searches - III / 56

Cross-spectral measurement techniques for axion cavity searches

Author(s): Dr. PARKER, Stephen¹
Co-author(s): Prof. TOBAR, Michael ¹

¹ The University of Western Australia

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The cross-spectrum of two measurements rejects uncorrelated signals, while retaining those that are correlated. Here we present some fundamental concepts of cross-correlation measurements and how they can be applied to axion cavity searches. One technique allows for improved resolution when observing the intrinsic thermal noise of cavities by rejecting uncorrelated amplifier noise. A different technique allows the spectrum outputs of two spatially well-separated cavities to be effectively combined.

We will also present a brief status report of a cavity-based search for ~26.6 GHz CDM axions.
Novel Microwave Cavities for Precision Measurement and Testing Fundamental Physics.

Prof. TOBAR, Michael

1 The University of Western Australia

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At the University of Western Australia we have a long history of developing high-Q cavities and transducers at microwave frequencies for applications for precision measurement, frequency standards, quantum information applications and testing fundamental physics. The latter includes hidden sector photon and axion experiments. Types of resonators include high-Q dielectric whispering gallery resonators, TE and TM mode resonators, reentrant cavity resonators, including new multi-post cavities. A broad overview of the cavity types and uses will be given, with particular focus on applications to axion and hidden photon sector experiments.

Searching for Hidden Photons

MARDON, Jeremy

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A “hidden photon” is a possible new particle, similar to the photon but with a small mass and with only a tiny coupling to electrically charged particles. Searches for hidden photons – whether as dark matter or as a new force carrier – have a great deal of overlap with corresponding axion searches. However, they tend to be significantly easier for two reasons: 1) static B-fields are NOT required, and 2) the astrophysical constraints are much weaker, making the allowed part of parameter space easier to reach. I will briefly review the landscape of hidden-photon theory and searches.

Slow Wave Cavity Axion Search

Dr. CAROSI, Gianpaolo

1 Lawrence Livermore National Laboratory

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Here we outline the concept of using reactive endcaps to lower the frequency of a cylindrical cavity.

LC Circuit Based Low Frequency Axion Search

Ms. CRISOSTO, Nicole

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A status update of prototype testing for LC circuit based axion searches will be presented. This will include initial results for various inductor geometries and tuning mechanisms.
Low Frequency Axion Searches / 79

Reentrant Cavity for Low Mass Axion Search

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Co-author(s): CHOU, Aaron ; Dr. SONNENSCHEIN, Andrew

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Simulations and initial measurements of a reentrant cavity designed to explore lower frequencies in a fixed magnet bore volume.

Increasing Cavity Quality Factor / 44

Novel Aluminum-based High-Q Cold RF Resonators for ADMX

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Improved aluminum refining techniques now provide high-quality, cost-effective high-purity aluminum samples. The high-purity aluminum will be better resonator material than copper because of its extremely low resistivity and high thermal conductivity at cryogenic temperature in strong magnetic fields. We will show material properties of high-purity aluminum and demonstrate possible improvement of the aluminum based ADMX resonator.

Increasing Cavity Quality Factor / 80

Primer on Superconducting Radiofrequency Cavities

BOWRING, Daniel

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This overview will outline the motivation and concepts behind superconducting radio-frequency microwave cavities, primarily in the context of accelerator cavities.

Increasing Cavity Quality Factor / 68

Magnetic Field Limits of SRF Cavities

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This talk will discuss the ultimate limitations for high Q0 operation of SRF cavities, including theoretical predictions and experimental measurements. Various SRF materials are considered and realistic expectations for maximum magnetic fields on the walls of the cavity are presented.

Increasing Cavity Quality Factor / 61
An RF sputtering system for thin film superconducting cavity R&D
SIMANOVSKAIA, Maria

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Here we will outline an RF sputtering system that has recently been installed at UC Berkeley with the goal of developing superconducting thin film cavities for axion searches.

Open Discussion & Presentation of New Ideas / 78

Electric Tiger

Author(s): Mr. SLOAN, James
Co-author(s): RYBKA, Gray; Mr. PATEL, Kunal; Mr. GARRETT, Daniel

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Electric Tiger is a project consisting of designing, building, and taking axion exclusion data with a prototype rectangular prism cavity. The cavity includes regions of dielectric to modify the shape of the resonant modes of the cavity in such a way that coupling to axions is enhanced. The motivation, design, and status of Electric Tiger will be presented and the outlook for the prototype and beyond will be discussed.

Active Microwave Cavities - I / 53

Cavities march in step

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To reach high frequencies while maintaining a good B^2V, the axion detector will require either a complex multi-cell structure or the operation of a number of cavities together. In order to employ a number of cavities that are power-combined in phase, the cavity resonant frequencies will need to be identical. This talk outlines a technique developed by Pound to lock a klystron to a resonator and elaborated by Drever and Hall for locking lasers to optical resonators. This Pound-Drever-Hall method is widely used, notably by LIGO, to maintain lock of up to five resonant lengths. It employs phase modulation of the electromagnetic waves incident on the cavity, followed by mixing of the generated sidebands with the reflected carrier, and then by phase-sensitive demodulation to generate an error signal. The error signal may be used in a servo loop to adjust the cavities’ resonant frequency.

Active Microwave Cavities - I / 57

Active Q Cavities

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An overview of the R&D on increasing the quality factor of cavities using active feedback will be given.

Microwave Cavity Geometries - I / 58

Photonic Bandgap Cavities
LEWIS, Samantha¹

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This talk will be a basic overview of Photonic Band Gap design.

Microwave Cavity Geometries - I / 74

Superconducting photonic bandgap structures for high-current applications

Author(s): Dr. SIMAKOV, Evgenya¹
Co-author(s): Dr. SHCHEGOLKOV, Dmitry ² ; ARSENYEV, Sergey ³

¹ LANL
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We report the results of recent design and testing of several 2.1 GHz superconducting radio-frequency (SRF) photonic bandgap (PBG) resonators. PBG cells have great potential for outcoupling long-range wakefields in SRF accelerator structures without affecting the fundamental accelerating mode. Here we describe the results of our efforts to fabricate 2.1 GHz PBG cells with round and elliptical rods and to test them with high power at liquid helium temperatures.

Microwave Cavity Geometries - I / 59

Directly characterization of cavities with a bead-pull technique

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This talk will present an overview of the bead-pull technique that is being used to characterize cavities for ADMX and ADMX-HF.

Microwave Cavity Geometries - I / 72

Progress on mode-locking cavties at U. of Florida

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Here we will discuss some of the work that has been done on mode-locked cavities at U. of Florida.

Quantum Limited Axion Cavity Amplifiers - II / 63

Accelerating cryogenic axion searches with one and two mode squeezed states.

Prof. LEHNERT, Konrad¹

¹ JILA, University of Colorado

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The search rate of cryogenic axion cavity search will soon be limited by fundamental quantum fluctuations of the microwave field. In this talk, I will describe how this noise can partially be overcome using quantum squeezing of the microwave field. In contrast to what is often thought to be the case, I will show that it is in principle possible to measure both quadratures of the axion induced microwave field without adding measurement noise.
Quantum Limited Axion Cavity Amplifiers - II / 75

Generation and Reconstruction of Propagating Quantum Microwaves
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Propagating quantum microwave signals are promising building blocks for quantum communication and quantum computation. In particular, such itinerant quantum microwaves can be generated by Josephson parametric amplifiers (JPAs) in the form of squeezed states. At the same time, JPAs are widely used as low noise amplifiers for the detection of microwave signals on the single photon level. In this work, we characterize the basic properties of flux-driven JPAs at millikelvin temperatures. We investigate the squeezed states generated by the flux-driven JPAs with a dual-path setup. Squeezed coherent states could be generated by sending coherent states into a JPA. Alternatively, displacement operations can be applied to squeezed states using a directional coupler. We discuss our experiments in the context of remote state preparation and quantum teleportation with propagating microwaves.

Active Microwave Cavities - II / 66

Electronic Tuning with Non-Linear Dielectrics
Dr. SONNENSCHEIN, Andrew

1 Fermilab

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Since dielectric materials inserted into a resonator cavity cause a permittivity change, there are a number of dielectric materials which might be suitable for this application, but none have been sufficiently well studied in low-temperature, high magnetic field environments. The key issue is whether the necessary level of tunability can be achieved without prohibitively large energy dissipation. We are planning to test several materials and fabricate a prototype resonator.

Active Microwave Cavities - II / 71

Electronic Tuning & Coupling of Cavities
Dr. CAROSI, Gianpaolo

1 Lawrence Livermore National Laboratory

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We will present an overview of R&D efforts to employ electronic tuning and coupling of microwave cavities.

Microwave Cavity Geometries - II / 47

University of Florida High-Frequency Microwave Cavity Research
Mr. STERN, Ian

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The axion is now by far the most promising candidate for the constitution of cold dark matter and this has generated a proliferation of searches around the world. While almost all CDM axion experiments use the Sikivie haloscope method, it is clear that to reach cosmological sensitivities
at higher masses, new RF techniques that go beyond the current microwave cavity designs must be advanced. The University of Florida has been conducting research to extend the usefulness of haloscope detectors to higher axion masses. Computer simulations and analytical studies have validated the theory of using periodic post arrays and regulating vanes for tuning cavities at higher frequencies. A 12-vane cavity prototype is currently under development. Mode search schemes, necessary for scanning highly crowded frequency ranges, are being explored. The Pound-Drever-Hall frequency locking technique is also being investigated using a 2-cell segmented cavity prototype. Results of the studies and status of prototype testing will be presented.

Microwave Cavity Geometries - II / 65

Resonator design strategies for high and low mass axion searches

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TBD

Microwave and Millimeter-wave Cavity Research and Development at SLAC

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1 SLAC National Accelerator Laboratory

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We present ongoing research and development in advanced microwave and millimeter-wave cavity design and fabrication at SLAC National Accelerator Laboratory. This research is primarily focused on improving the performance of accelerating structures with optimized cavity design for reducing breakdowns and increasing Q-factor, distributed coupling and improved fabrication with micro-machining and diffusion bonding. Future areas of interest will also be presented.

End of Workshop Discussion & Open Floor to New Ideas / 81

Lattice QCD Input to Axion Cosmology

Dr. EVAN, Berkowitz

1 LLNL

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Here we describe recent work to place a lower bound on the axion mass from lattice QCD calculations.

End of Workshop Discussion & Open Floor to New Ideas / 82

Workshop Close-Out

Dr. CAROSI, Gianpaolo

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End of the workshop discussion.