Resonant feedback at ADMX

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Axions are of particular interest because the Peccei-Quinn (PQ) mechanism remains perhaps the most credible scheme to preserve CP-symmetry in QCD. Moreover, the cold dark matter (CDM) of the universe may well consist of axions and they are searched for in dedicated experiments with a realistic chance of discovery.

Originally it was assumed that the PQ scale to one fermion line as in axion emission by nucleon bremsstrahlung was very large, \( \approx 10^{13} \text{GeV} \), the tree-level coupling coefficient was essentially fixed by the energy scale that characterizes the CP-violating term, and the axion mass, \( m_a \), was related to the electroweak symmetry-breaking scale, \( \sim 100 \text{GeV} \). That was before the DFSZ model \[ g_{A W}(\text{fit}) = 5 \times 10^{-10} \text{GeV}^{-1} \]

was related to the electroweak symmetry-breaking scale, \( \sim 100 \text{GeV} \). That was before the DFSZ model.
The ADMX bit

Accepted by PRD
Disadvantages of cavity axion detectors

• The form factor for axion to photon conversion means that in practice only the TM$_{010}$ cavity mode is useful.
• This mode must be tuned so that the averaging of the measured power spectrum at each tuning rod position is sufficiently long to achieve sensitivity to QCD axion models.
• The tuning mechanism is one of the most complex detector components, causing more problems as you go to lower temperatures and to higher frequencies.
• Conducting wall boundary conditions limit the mode frequency range. In practice, tuning of around +/- 15% is possible, then you need a different cavity or tuning rod configuration.
Figure 5 shows the ranges of axion mass $m_a$ and coupling to photons $g_{a\gamma\gamma}$ covered in our experiment. Also shown is the relationship between $m_a$ and $g_{a\gamma\gamma}$ predicted using several theoretical models, and regions where the axion has been excluded by previous searches. 5.6. Our present experiment is sensitive to KSVZ axions. The upgrade of the first stage cryogenic amplifier discussed in the next section, will allow us sensitivity beyond the DFSZ limit.
A violin string analogy.

The frequency of oscillation of a violin string is set by the boundary condition that the string has a node at each end.

Other boundary conditions could be imposed. For example, you could install a controller so that the two ends of the string have equal magnitude, opposite sign displacements at any given time.

This arrangement would allow the string to support waves of any frequency, since the two ends of the string are neither nodes nor antinodes.

Now add a resonant circuit in the feedback path so there is a preferred frequency. You can choose the mode frequency by adjusting the resonant circuit.
Resonant feedback concept

Cavity

Resonant feedback

Figure 4: On the left, a cross section through a right circular cylindrical conducting wall resonant cavity excited in the $TM_{010}$ mode. The vertical arrows indicate the electric field lines, and the circles with dots (crosses) indicate magnetic field lines directed out of (in to) the plane of the diagram. Half a period later the direction of both electric and magnetic field lines reverses. The electric field lines terminate on charge distributed on the inner wall of the metal ends. Currents flowing in the side walls, the charges on the ends, and the time rate of change of the displacement current, $\partial \mathbf{E}/\partial t$, completes the electrical circuit.

In the case of the capacitor, the electric field is more uniform (we have exaggerated the distance between the capacitor plates relative to the plate size for clarity), and the circuit is completed by the external wire that passes through the resonant electronics.

We show semi-quantitatively that the proposed resonant feedback scheme should achieve similar enhancement in signal power by a factor of $Q$, previously demonstrated both experimentally and theoretically for the cavity case in both the classical and single quantum limits [8, 43, 44]. Figure 4 shows a cross section through a right circular cylindrical metal wall resonant cavity with the $TM_{010}$ mode excited on the left, and a capacitor of similar geometry connected to a simplified resonant feedback circuit on the right. In the cavity case, the high $Q$ resonance is due to boundary conditions on $\mathbf{E}$ and $\mathbf{B}$ at the cavity walls. As with all resonators, fields circulating in the cavity form closed circuits, with power building up when the phase shift in the round trip is such that constructive interference occurs. In the case of the $TM_{010}$ mode, the magnitude of the electric field is given as a function of...
Realisation with a capacitor-like structure instead of a cavity

Figure 1: A schematic of the concept for a modified Sikivie-type axion detector utilizing resonant feedback. The resonant mode of the cavity is replaced by an external resonant circuit, and the cavity itself is replaced by a parallel plate capacitor coupled to the external resonator by transmission lines connected to the capacitor plates.

In practice, the capacitor plates would be separated by insulating spacers and small microwave substrate circuit boards mounted on the back of the plates would be used to attach the connectors to coaxial transmission lines and the resistive terminations. The volume of a magnet bore could be filled with a stack of capacitors connected in parallel, thereby decreasing the reactive impedance presented to the electronics by a factor of the number of capacitors. Figure 3 is an illustration of such a parallel capacitor stack; 4 parallel capacitors combined in-phase shown, but the idea could be expanded to, for example, 64 capacitors each of diameter 25 cm and plate separation 1.5 cm yielding a total stack height of 1 m, the same geometry as 5c.
Realisation with Heterodyning Electronics

Figure 4: A schematic of the practical implementation of feedback electronics, showing ultra-low-noise receiver electronics common to this proposal and more conventional cavity searches, as well as the feedback path to and from the capacitor, operated far below cut-off, threaded by a large static magnetic field. MSA and HEMT are acronyms for 'microwave squid amplifier' and 'high electron mobility transistor', respectively. The noise performance of MSAs, critical to these searches, are discussed in [20, 21]. HEMT amplifiers for ultra high frequency, low noise applications are discussed in [22, 23].

Temperature $T$ of a source of Johnson noise in a bandwidth $B$ emits noise power $P$ into a balanced sink given by

$$P = kB_T B.$$  \(5\)

At a mode frequency of 700 MHz corresponding to an axion mass of $2.9 \mu eV$, assuming a magnetic field of 6.8T, and other experimental parameters corresponding to the ADMX2 experiment configuration [15], the signal power expected from a KSVZ [16, 17] model axion converting to photons is $2 \times 10^{-22} W$. $JPA/$

<table>
<thead>
<tr>
<th>JPA/ MSA</th>
<th>HEMT</th>
<th>HEMT</th>
<th>Room Temp</th>
<th>Digital Signal Processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 dB</td>
<td>20 dB</td>
<td>20 dB</td>
<td>70 dB</td>
<td>0 dB, 5V full scale noise: $1\sigma = 5V/2^9$</td>
</tr>
<tr>
<td>150 mK</td>
<td>2.5 K</td>
<td>2.5 K</td>
<td>100 K</td>
<td></td>
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</tbody>
</table>

The diagram shows a schematic of the practical implementation of feedback electronics, including amplifiers, attenuators, and cryogenic and room temperature components.
show that using existing amplifier technology it is possible nevertheless to
maintain a good signal-to-noise ratio for mode oscillations around the feed-
back loop. Figure 4 shows a more realistic arrangement of amplification
stages as implemented in a representative axion search. This noise budget is
approximate; in practice the a detailed noise model of the electronics must
be constructed to understand the spectral content of the noise background,
especially in the vicinity of sharp features such as high Q resonances. The

\[
\text{Noise in 15MHz bandwidth [dBm]}
\]

<table>
<thead>
<tr>
<th>Location</th>
<th>Total summed noise into 750Hz bandwidth [dBm]</th>
<th>Noise from local component into 750Hz bandwidth [dBm]</th>
<th>Signal power [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-175</td>
<td>-178</td>
<td>-190</td>
</tr>
<tr>
<td>B</td>
<td>-155</td>
<td>-166</td>
<td>-170</td>
</tr>
<tr>
<td>C</td>
<td>-135</td>
<td>-166</td>
<td>-150</td>
</tr>
<tr>
<td>D</td>
<td>-115</td>
<td>-150</td>
<td>-130</td>
</tr>
<tr>
<td>E</td>
<td>-45</td>
<td>-76</td>
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</tr>
<tr>
<td>F</td>
<td>-45</td>
<td>-178</td>
<td>-60</td>
</tr>
<tr>
<td>G</td>
<td>-175</td>
<td>-178</td>
<td>-190</td>
</tr>
</tbody>
</table>

At a mode frequency of 700 MHz corresponding to an axion mass of \(2 \times 10^{-9} \mu eV\), assuming a magnetic field of \(6.8 \times 10^4 \) T, and other experimental parameters corresponding to the ADMX2 experiment configuration [15], the signal power expected from a KSVZ [16, 17] model axion converting to photons is \(2 \times 10^{-18} \) W.
Feedback circuit analysis

\[ H(s) = \frac{\Gamma s}{s^2 + \Gamma s + \omega_0^2}, \quad s = i\omega = 2\pi if \]

\[ H_C(s) = \frac{\tilde{v}_o(s)}{\tilde{v}_i(s)} = \frac{G_C\Gamma s}{s^2 + (1 + AGCG_W)\Gamma s + \omega_0^2}. \]

\[ H_0(i\omega_0) = AGCG_W \quad \text{To make a resonator, Nyquist stability criterion implies} \quad AGCG_W = 1 \]

Feedback halves Q, rather like the critically coupled cavity.
Digital electronics
Mark 1. Installed in January 2020

Remote PYTHON interface by Chelsea Bartram

FPGA programmed by Ed Daw and Mitch Perry.

8 parallel resonant filters with configurable Q, gain and frequency coded in VHDL using Xilinx Vivado

On-chip Microblaze soft core for control interfacing.

BASYS3 student-grade FPGA prototyping board
Why Digital Filters?

• You can implement many resonant filters in parallel on the same me digital device - a large FPGA can accommodate at least 100. Each resonance is a detector.
• Resonant frequencies are adjusted parametrically - no need for mechanical tuning rods. Big experimental advantage.
FPGA feedback filter for mark 1 digibox at ADMX

Figure 4. Eight resonance filter output.
Early tests

- First tests using a homemade parallel plate capacitor in open loop showed that the transmission of a capacitor at GHz frequencies is very far from unity.
- Feedback control is needed to cause a parallel plate structure to behave as a capacitor. Causing the voltage on one plate to oscillate at 1GHz is not sufficient to cause the other plate to oscillate in anti-phase with the same amplitude.
- In addition, broadband (6GHz) loads expose you to RF punch-through of local oscillators used in the heterodyne electronics as well as any other out-of-band noise. In the long term this is soluble by using digital RF, but for now go with Gray Rybka’s suggestion and **start with a narrowband cavity load.**
Preliminary Test setup at ADMX

Collaborators:
- Vector Network Analyser
- Artix 7 FPGA
- Resonant Filters
- DAC

Processor core calculating filter coefficients

Control interface

Attenuators

2.4GHz

50kHz Bandpass crystal filter bank
Test setup in practice

From presentation by C. Bartram, December 2020
Chelsea Bartram added another port to the test cavity. Mitch Perry developed an FEM model for it.
Simulated TM$_{010}$ mode

Reflection off antenna, $S_{11}$

Reflection off antenna, $S_{21}$

FEM using Cadence Clarity, M. Perry
Results from the Test Stand

2.6GHz cavity in transmission, then through digibox. Open loop gain adjusted to just above 1.

Measurements by Chelsea Bartram, January 2021.

Now adjust phase in open loop to multiple of 2*pi, close loop and see oscillations, back gain off until they vanish.
...Here we hit a problem

The measured open loop phase delay is unstable. Why?

It turns out we stabilised all the oscillators except one.

Back of BASYS3 board
housing the Xilinx Artix7 FPGA

Micrel DCS1033
CMOS oscillator
(silicon MEMS)
50ppm stability, so
5kHz frequency noise!

Basys 3 reference oscillator

Neat device, but
too unstable for
our application.
Long term solution
Xilinx ZCU111 development kit for Zynq Ultrascale+ MPSoC

4GHz sampling rate ADC, 6GHz DAC, external clock reference. Much larger DSP slice count, 8 parallel analog inputs and outputs. Arrived today at Sheffield.
Short-term solution

Detach the MEMS oscillator from the BASYS3, solder in a cable to connect to an external 10MHz stabilised 100MHz oscillator.
Future plans

1. Close loop on feedback in the test stand.
2. Measure S-parameters of closed loop system.
3. Develop control servos to maintain resonance in feedback loop - stabilise open loop gain, phase at
4. Implement on the ‘sidecar’ cavity in the ADMX magnet.
5. Proof-of-principle run of resonant feedback system with the sidecar cavity with sensitivity to axions.
6. Develop a ‘capacitor’ like wideband RF structure for operation in ADMX using FEM to work out cable coupling into device and form factor for axion conversion. Fabricate and test prototype RF structure.
7. (aspirational) Deploy and test RF structure in ADMX.
Feedback control of loop gain

Any imbalance between the oscillating voltages on the two capacitance plates causes an oscillating potential difference between the sense plates. This signal is linear in the departure of gain from 1, and can therefore be used to stabilise the gain.

\[ +V_0 \cos(\omega t) \]

\[ -V_0 \cos(\omega t) \]

Differential signal feeds back to control resonant feedback gain
Many RF structures

Calculation of the speedup assuming 100 parallel resonances and a resonator stack filling the ADMX magnet imply coverage of the ADMX search band
Mass range

• High frequency limit imposed by bandwidth of the fastest phase coherent digital feedback loops. Around 10GHz is about as fast as you can go, which is an axion mass of $m_a < 40$ micro-eV. But, ever faster ADCs/DACs can push this up. This is likely because of mobile comms.

• Low frequency limit set by lowest frequencies where RF amplifiers are quantum limited. This is probably limited by the onset of 1/f noise effects, which is at around 100MHz, corresponding to an axion mass of $m_a > 0.4$ micro-eV. But, new lower noise amplifiers at low frequency could push this down.

• So, currently this technique could potentially cover 2 decades in axion mass if it is proved to work.
Summary

• Paper makes the case for replacing the cavity TM$_{010}$ mode with a parametrically controlled external resonant circuit.
• Removes link between geometry of resonator and tuning range - much wider band search.
• No tuning rods, so simpler cryogenics.
• Multiple modes in parallel, so faster scan rate.
• E mostly parallel to axis, so maximal form factor.
• Feedback needed to control loop gain, zero out the stray fields.
• Digibox installed at ADMX in Seattle - Chelsea.
• Testing underway on warm test cavity w/4 ports.
• Simulations of RF structures underway - Mitch.
• The UK has funded the **Quantum Sensors for the Hidden Sector** (QSHS) grant for at least the next 3.5 years.
• We intend to partner with ADMX and The Australian ARC centre of excellence for dark matter particle physics to deliver advanced quantum electronics and a new high mass search chain for installation in the ADMX target, targeting the 25-41 micro-eV mass range.
• Resonant feedback is within the funded remit of the grant.
• I am the principal investigator of the UK group - Institutions involved are **Sheffield, Cambridge, Oxford, RHUL, UCL, Lancaster, Liverpool** and the National Physical Laboratory.
• We will be hiring 6 more postdocs and a project manager. There are also strong possibilities for faculty positions via UK fellowship schemes. Contact me if interested - e.daw@sheffield.ac.uk
Coherence of the axion induced photon signal

Cavity • Bare ADMX cavity corresponds to 2 micro-eV axion. With rms axion velocity of 240km/s, De Broglie wavelength is 830m, so coherence time of axion is 3.4ms (time of flight of one De Broglie wavelength across cavity. Circulation time for TM_{010} mode in cavity is 1.7ns, so the axion field is coherent over 2 million cycles, therefore the maximum Q-enhancement of the signal is 2E6.

Feedback • Everything the same except for the circulation time, which is now the time around the feedback loop. Assuming 0.7c signal velocity and 250MHz sampling, plus a 20m long feedback loop, the circulation time is 103ns, so the maximum Q-enhancement for an axion signal is 34,000. This is comparable with loaded Qs in ADMX.
Where is the quantum limit?

At 1GHz, a single quantum is at

\[ hf = 6 \, \mu eV \]

The ADMX electronics has a noise temperature of 300mK, so that

\[ k_B T = 26 \, \mu eV \]

This is 4.3 quanta of oscillation. The state of this feedback circuit is that of a not-very-highly-excited, software configurable quantum harmonic oscillator.
Action of IWAVE digital filter on a simulated Glauber state

45Hz input - Phasor with unit amplitude + r.m.s. 0.1 gaussian displacement, phase randomised over 2pi. Response time of 1s Filter Q of 142.

Filter then attenuate: