The 3 cavity prototypes of RADES, an axion detector experiment using microwave filters

Sergio Arguedas Cuendis, on behalf of the RADES group

3rd Workshop on Microwave Cavities and Detectors for Axion Research

August 2018

Motivation

- For axion models with PQ transition happening after inflation, one can set a lower bound to the axion mass of at least $m_a^2 >$ 25 μeV.
- The RADES group is designing and constructing a haloscope type experiment to have competitive sensitivity to axion masses in the 10-100 μeV.

Measurement principle

- In the presence of a magnetic field, the conversion of axions into photons is triggered.
- A cavity resonating at the frequency of the expected axion mass will increase its output power.
- A figure of merit for our experiment is given by:

$$F \sim g_{A\alpha}^2 m_a^2 B^4 V^2 T_{sys}^{-2} G^4 Q \tag{1}$$

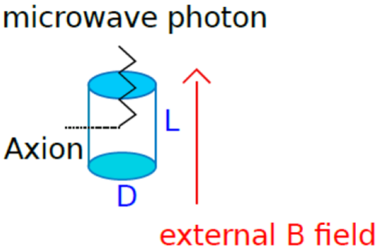

Figure 1: Standard haloscope experiment

Challenges of going to higher frequencies

- Increasing in mass means shorter cavities and smaller volume.
- Decreasing in volume will decrease the figure of merit of this type of experiment.
- To tackle this problem, RADES proposed, designed and built filters of 5 stainless steel sub-cavities joined by rectangular irises.

General Formalism

- In presence of a time-varying axion DM field, and a strong magnetic field, Maxwell's equations get an additional source

$$
\begin{aligned}
\nabla \cdot E &= 0 \\
\nabla \times B - \dot{E} &= g_{A\gamma} B_e A \\
\nabla \cdot B &= 0 \\
\nabla \times E - \dot{B} &= 0
\end{aligned}
\tag{2}
$$

General Formalism

- The electric and magnetic field can be expanded as a sum of orthonormal cavity modes. Using this, Ampere's equation gives the time evolution of the amplitude.

$$\ddot{E}_m + \omega_m^2 E_m + \Gamma_m \dot{E}_m = -g_{A\gamma} B_e \ddot{A} G \tag{3}$$

- Where the geometric factor G is define as:

$$G_m = \frac{1}{B_e V} \int_{V_c} d^3x B_e \cdot E_m \tag{4}$$

- The losses are parametrized by the factor Γ_m which is defines as:

$$Q_m = \frac{\omega_m}{\Gamma_m} \tag{5}$$

Multi cavity filter

- Consider a number of N cavities coupled through small irises.
- The cavities have very similar geometries and thus a similar fundamental mode at a common frequency.
- The coupling is linear and can be described with a coupling coefficient $K_{qq'}$

Multi cavity filter

- When excited by a monochromatic axion DM field, the system of coupled equations for the amplitudes of the fundamental mode is given by:

$$(\omega^2 \mathbb{1} - \mathbb{M})\bar{E} = -g_{A\gamma} B_e A_0 \omega^2 \bar{G} \tag{6}$$

- Where $\bar{E}$ is a vector containing the amplitudes and relative phase of the electric field in each cavity.

- The matrix $\mathbb{M}$ contains the natural frequencies, damping factors and coupling between the cavities.

Multi cavity filters

- $$\mathbb{M}=\begin{bmatrix} \Omega_1^2 & K_{12} & 0 & 0 & 0 & 0 \\ K_{21} & \Omega_2^2 & K_{23} & 0 & 0 & 0 \\ 0 & K_{32} & \Omega_3^2 & K_{34} & 0 & 0 \\ 0 & 0 & \ddots & \ddots & \ddots & 0 \\ 0 & 0 & 0 & \ddots & \ddots & \ddots \\ 0 & 0 & 0 & 0 & K_{N,N-1} & \Omega_N^2 \end{bmatrix}$$
- with $\Omega_q^2 = \omega_q^2 - i\omega\Gamma_q$
- The eigenvalues correspond to the square of the N resonant eigenfrequencies.
- The eigenvectors represent the E-field amplitude and phase of the fundamental mode of each of the individual cavities.

The 3 prototypes

- Inductive irises prototype (built in 2017)
- Inductive and capacitive prototype (built in July 2018)
- Inductive irises prototype with a vertical cut (built in July 2018)

Filter with 5 cavities and 4 couplings

- Let's emphasize that we can choose the design parameters Ω and K by altering the dimensions of the cavities and irises.
- For a given eigenvalue ω_i^2, the problem leads to the following system of linear equations.
- $$\omega_i^2 \begin{bmatrix} E_{i1} \\ E_{i2} \\ E_{i3} \\ E_{i4} \\ E_{i5} \end{bmatrix} = \mathbb{M} \begin{bmatrix} E_{i1} \\ E_{i2} \\ E_{i3} \\ E_{i4} \\ E_{i5} \end{bmatrix} = \begin{bmatrix} \Omega_1^2 E_{i1} + K_{12} E_{i2} \\ K_{12} E_{i1} + \Omega_2^2 E_{i2} + K_{23} E_{i3} \\ K_{23} E_{i2} + \Omega_3^2 E_{i3} + K_{34} E_{i4} \\ K_{34} E_{i3} + \Omega_4^2 E_{i4} + K_{45} E_{i5} \\ K_{45} E_{i4} + \Omega_5^2 E_{i5} \end{bmatrix}$$

Filter with 5 cavities and 4 couplings

- We have chosen to fix a desired characteristic frequency ω_i^2 and design a filter that maximizes the geometric factor for that frequency.
- The simplest solution is to take all coupling coefficients to be equal to a fixed value K, which gives the following solution for the individual cavity frequencies:

$$\begin{aligned} \Omega_2^2 = \Omega_3^2 = \Omega_4^2 = \omega_1^2(1-2K) \\ \Omega_1^2 = \Omega_5^2 = \omega_1^2(1-K) \end{aligned} \tag{7}$$

- All cavities must share the same resonant frequency, except the first and last one.

Inductive irises prototype

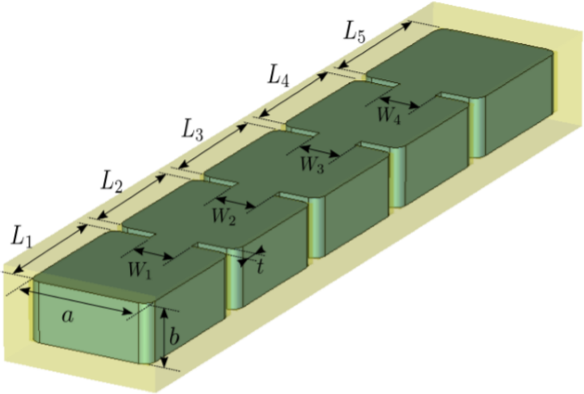

Figure 2: 3D model of the first prototype

Inductive irises prototype

- The frequency of operation was fixed to $\omega_1 = 8.4$ GHz.
- Using CST Microwave Studio the geometric parameters for this prototype were optimized:

Table 1: Dimensions of the cavity

Dimensions [mm]	T = 2 K
a	22.86
b	10.16
$L_1 = L_5$	26.86
$L_2 = L_3 = L_4$	25.00
$W_1 = W_2 = W_3 = W_4$	8.00
t	2.00

Electric field distribution of the 5 modes

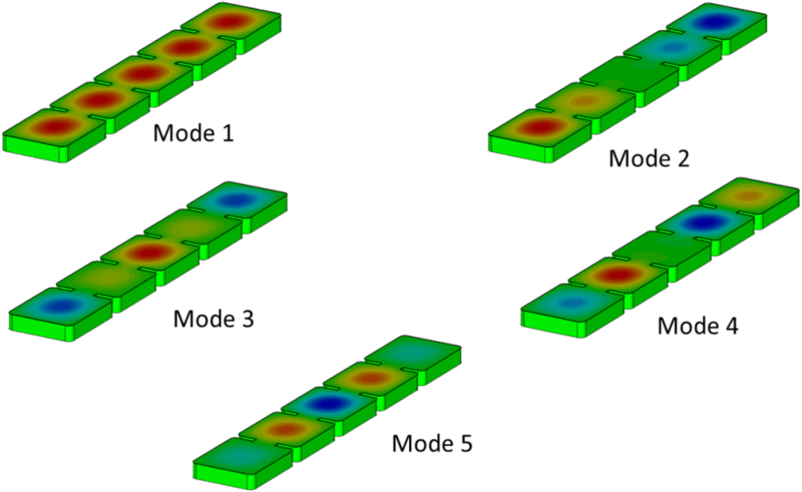

Figure 3: E-field distribution of the 5 modes

Electric field distribution of the 5 modes

Table 2: Frequencies and geometric factor of the first prototype

Mode	Electric field pattern	Frequency [GHz]	G
1	+++++	8.428	0.65
2	++0–	8.454	$3.2\ 10^{-7}$
3	-+++-	8.528	$8.1\ 10^{-5}$
4	-+0-+	8.625	$1.6\ 10^{-12}$
5	-+-+-	8.710	$6.4\ 10^{-6}$

RADES at CAST

- The prototype was fully installed at the CAST magnet in November of 2017

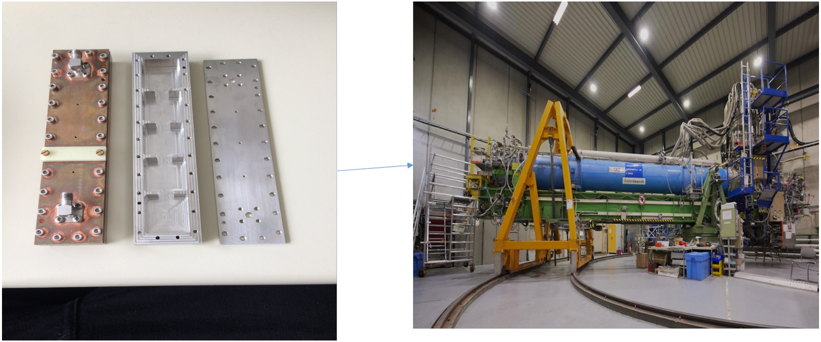

Figure 4: RADES cavity at CAST

Comparison between measurements and theory

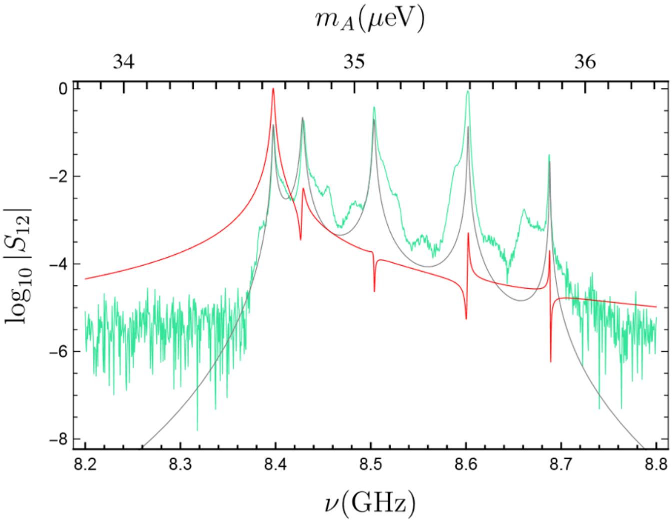

Figure 5: Transmission parameter: measurement (green) and theoretical model (gray). Red is axion coupling for the 5 modes.

Actual status

- RADES was taking data at CAST during the February-March campaign.
- This data is being analyzed at the moment.
- Some minor upgrades were done to the setup in the 2018 installation.
- Once the CAST magnet is ready, we will continue with the data taking.

Challenges for this prototype

- Improve the Q-value.
- Prevent the mode mixing when scaling in volume.
- Introduction of a tuning mechanism.

Inductive and capacitive prototype

- To grow in volume and at the same time having a working frequency higher than 8 GHz, one had to add more sub cavities.
- From the theoretical model we saw that the more cavities you have the more modes the filter will have.
- The issue with working with the lowest mode is that if we increase the number of cavities, there is a possibility of mode mixing.
- To tackle this problem, a new designed was studied and built in 2018.

Inductive and capacitive prototype

- The idea is to use inductive and capacitive irises.
- The coupling between the cavities is now alternating between negative and positive values.
- This time the mode coupling to the axion is not the first mode, but a higher mode.

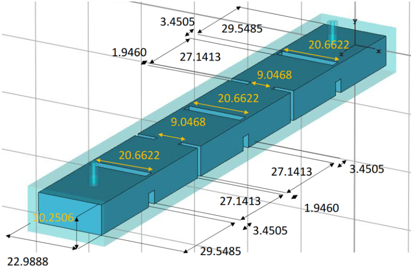

Figure 6: 3D model of the second model

Analytical model vs Simulations (Preliminary results)

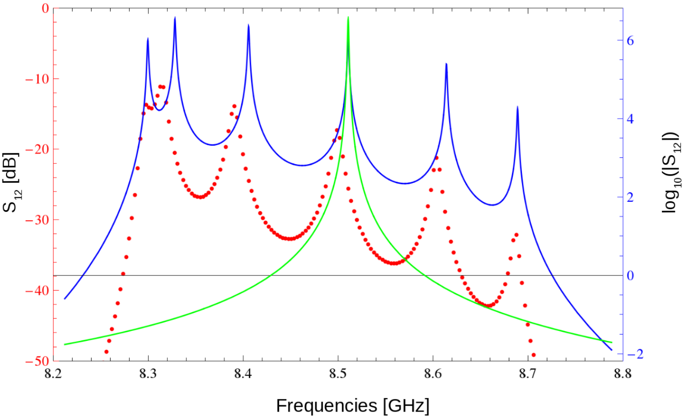

Figure 7: Transmission parameter for theoretical model (blue), axion coupling for the 6 modes (green), the results of the simulation with CST (red)

Electric field distribution of the 6 modes

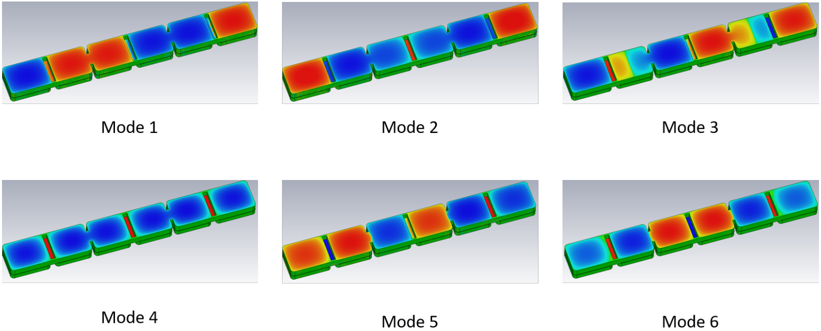

Figure 8: Electric field distribution of the 6 modes

Electric field distribution of the 6 modes

Table 3: Frequencies and geometric factor of the second prototype

Mode	Frequency [GHz]	G
1	8.29855	$3.9\ 10^{-9}$
2	8.3206	$1.1\ 10^{-3}$
3	8.39709	$2.7\ 10^{-9}$
4	8.51162	0.54
5	8.6159	$9.2\ 10^{-13}$
6	8.702	$3.6\ 10^{-5}$

Very preliminary results at the laboratory

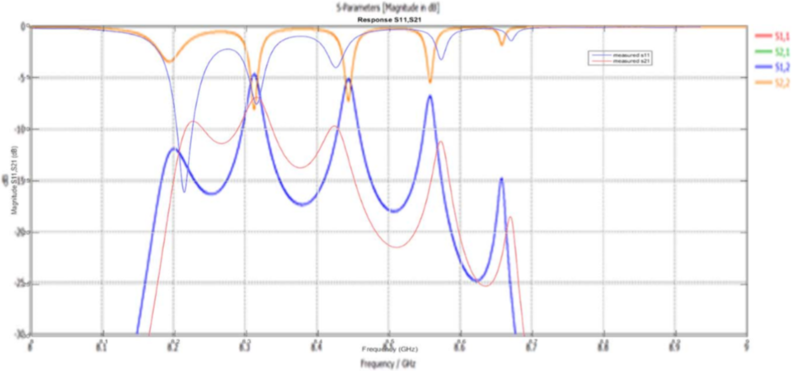

Figure 9: Transmission and reflection: Measurements vs Simulations

Future plans

- Full characterization of the S-parameters at the laboratory in Spain (from room temperature to $\sim$ 80 K).
- Characterization at 2 K in CERN cryogenic laboratory.
- Increase the number of sub-cavities for this prototype.

Inductive irises prototype with a vertical cut

- A new idea on how to increase the Q-factor for the first prototype wanted to be tested.

- By doing a vertical cut during the mechanization of the cavity. One cuts through the symmetry plane of the field lines. This cut affects less the path of the field lines, which increases the chances of getting a better Q-factor.

- Furthermore, it exits the possibility of tuning the cavity by moving the two parts away from each other.

Inductive irises prototype with a vertical cut

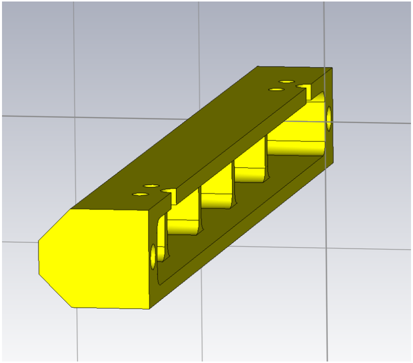

Figure 10: 3D model of the vertical cut model

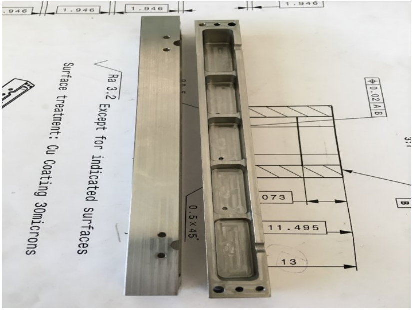

Figure 11: Stainless steel vertical cut cavity

Future plans

- Preparation are been made to set up a facility at CERN to test the prototypes at 2 K.

- Afterwards, a mechanical system has to be designed to move the two pieces and test the possible tuning of this prototype.

Conclusion

- The RADES group is aiming to develop a method for detecting axions in higher frequencies without losing in volume.
- The analytical model for a filter with multiple sub-cavities was developed.
- Following this model, the first prototype was designed, built and installed at the CAST magnet.
- New prototypes are going to be tested to improve the future performance of our detectors.

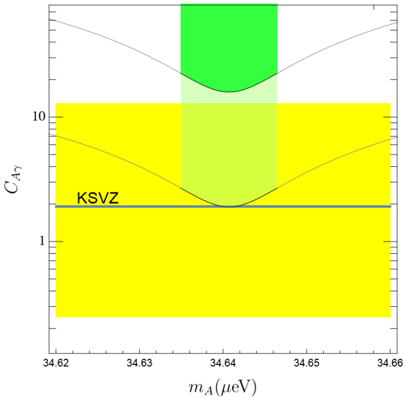

Figure 12: Sensitivity Plot

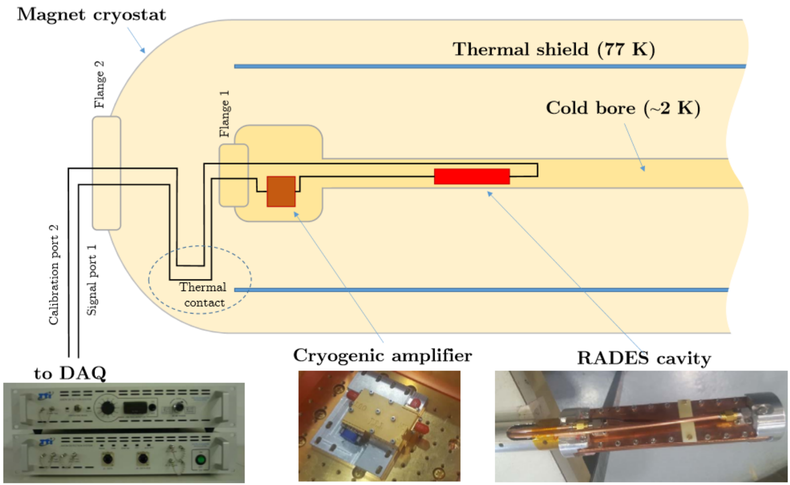

Figure 13: RADES-Setup