The QUAX R&D at LNF

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1 Photonic cavity

We designed a novel type of distributed Bragg resonator working on the TM010-like mode at about 13.5 GHz. The choice of the frequency was mainly given by the possibility of incorporating the resonator in the detection chain developed for the QUAX experiment. The main idea was to design a pseudo-cylindrical cavity realizing an interference pattern to confine the TM010 through long dielectric rods placed parallel to the cavity axis. These types of cavities are also known as photonic band gap cavities [1, 2]. The dielectrics, commercially available, were in the form of long sapphire cylinders of 1 mm of diameter. Sapphire was choosen for its very low loss-tangent, going from about 10^{-5}, at room temperature, down to a fraction of 10^{-7} at cryogenic temperatures [3].

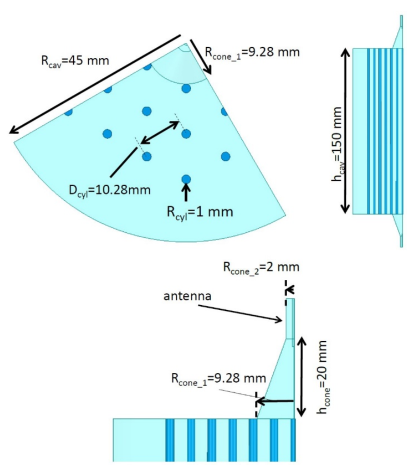

Figure 1: Final design of the cavity with its main dimensions.

We did the electromagnetic simulations using the code ANSYS Electronics Desktop [4]. Because of cylindrical symmetry we simulated only one quarter of the structure with perfect magnetic boundary conditions. The final designed cavity with main dimensions is given in Figure 1. In the cavity 36 sapphire rods of 1 mm diameter are positioned with the pattern shown in figure while the distance between the rods was chosen to have the resonant frequency of the confined mode TM010 at around 13.5 GHz. The number of rods was chosen to have enough attenuation of the electromagnetic field toward the cavity outer wall. Since the sapphire dielectric constant varies in a wide range depending on the crystal orientations, impurities and temperature, in the simulations we have considered a sapphire dielectric constant equal to 11.3 and a loss tangent at cryogenic temperature of 10^{-7} [3]. The copper surface resistance was set to about 5.5mΩ as expected in the anomalous regime at this frequency [5]. The two end plates, represented in the figure, were designed in order to reduce the power losses on the plates themselves. In particular, as already implemented and illustrated in [6, 7], two conical shapes were introduced. We chose the length of the cones to have enough attenuation of the electromagnetic field on the cones themselves thus reducing the losses on the copper endplates. To excite and detect the resonant modes, two coaxial antennas were inserted at the end of the cones.

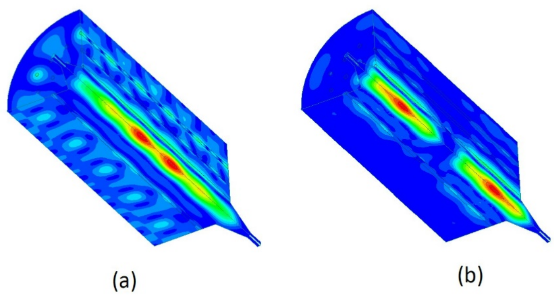

Figure 2: Magnitude of the electric field of the first two TM resonant modes: TM010 (a) and TM011 (b).

The magnitude of the electric field of the first two TM resonant modes, TM010 and TM011, is given in Figure 2. The first mode is expected to have a Q-factor of about 3×10^5 at cryogenic temperature, essentially limited by the losses on the cavity walls and endplates. Figure 3 shows the simulated transmission coefficient between the two coupled antennas whose peaks correspond to the resonant modes TM010 and TM011, respectively. In the plot are also visible two spurious peaks corresponding to mode configurations weakly coupled to the coaxial antennas.

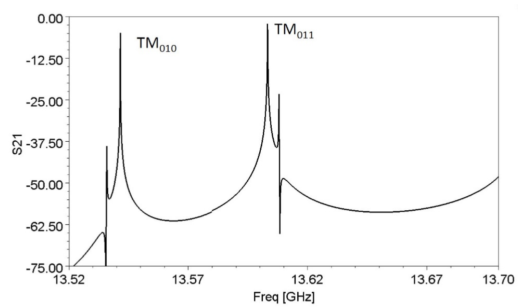

Figure 3: Simulated transmission coefficient between the two coupled antennas. The peaks correspond to the resonant modes TM010 and TM011.

The resonant cavity was assembled and tested at LNL. In figure 4 we show a detail of the cavity and in figure 5 the lineshape of the mode TM_{010} measured at a temperature of 5.5 K with a Vector Network Analyzer. We measured $Q_0 = 290,000$ for the mode TM_{010} at 13.6 GHz and $Q_0 = 520,000$ for the higher mode TM_{011} at 13.7 GHz.

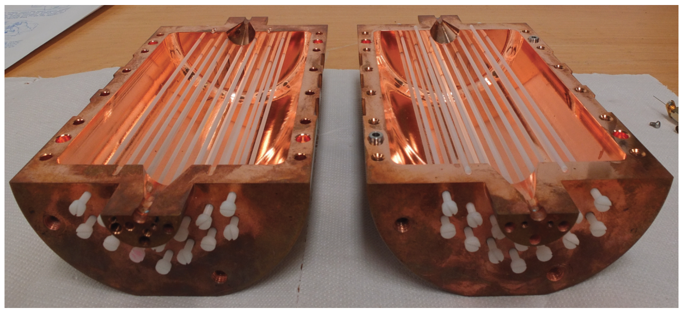

Figure 4: Photograph of the cavity opened in two halves.

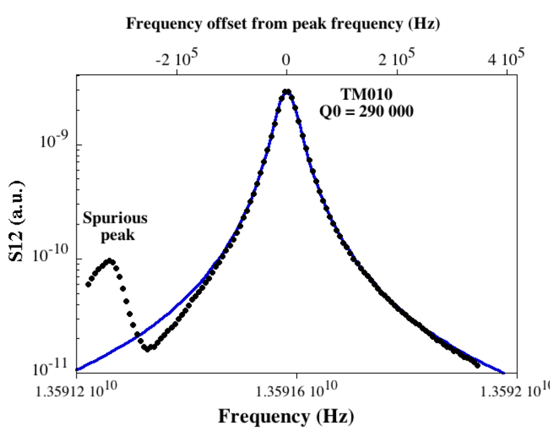

Figure 5: Measured S12 spectra (black dots) of the TM_{010} mode at liquid Helium temperature, superimposed with a fit (blue line) made with a Lorentzian function.

2 Characterization of a MgB_2 resonant cavity

We investigated the microwave properties at 14 GHz of a cylindrical resonant cavity made of bulk MgB_2 with copper end-caps. MgB_2 is a type II superconductor with critical temperature $T_c = 38$ K and higher critical field $B_{c2} = 15$ T. The material from which the cavity is made has been produced by the reactive liquid MgB_2 infiltration technology (RLI) [9, 10]. The RLI process consists in the reaction of pure liquid Mg and boron powder, sealed in a stainless steel container with a weight ratio Mg/B over the stoichiometric value (0.55). A cylindrical cavity fabricated with this technology was tested in [11] in the range 5-13 GHz otaining quality factor up to 10^5 at 4 K. We inserted the MgB_2 cavity inside a LHe cryostat at the center of an 8 T superconducting magnet. Two tunable antennas were inserted inside from the upper cavity endcap and connected to a Vector Network Analyzer. Countinous measurement was performed during cooldown. In the left panel of figure 6 we show the measured quality factor as a function of the temperature for the mode TM_{110} at 14 GHz and with no applied magnetic field. The quality factor saturates at about 30,000 probably limited by RF losses at the connection between cylinder wall and endcaps. After cooling the cavity at a temperature of 4.3 K we turned on the magnetic field. The field was increased up to 1 T and then decreased back to 0 T while measuring the quality factor. The result is shown in the right panel of figure 6. The quality factor rapidly deteriorates as the field increases indicating a depinning frequency lower than 14 GHz and a large loss due to vertex motion in the superconducting material dominating over the large RF losses caused by the bad connection between cylinder walls and endcaps. This large loss makes MgB_2 unsuitable for axion searches with a haloscope.

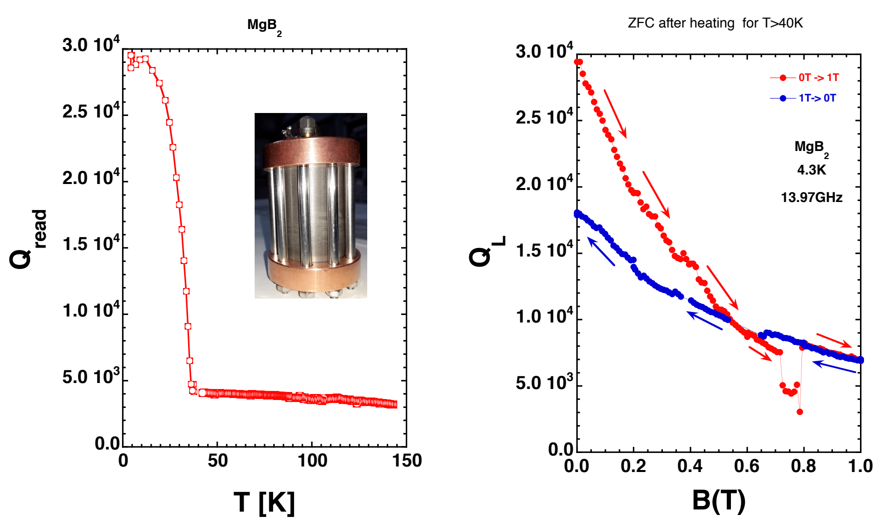

Figure 6: Left: Measured quality factor as a function of the temperature. Right: Measured quality factor at 4.3 K as a function of the applied magnetic field.

3 Magnetic field screening

Cryogenic linear amplifiers with noise at the quantum limit are based on superconducting Josephson-junction technology. When operating close to a magnet, as in the case of haloscope experiments, amplifiers must be placed inside a magnetic screen made both of high permeability and superconducting material. We tested a triple screen on Nb3Sn in a LHe cryostat at 4 k. A cryogenic hall probe was inserted inside the triple screen and put inside the cryostat in correspondance to the center of a 8 T superconducting magnet (figure 7). After cooling the system to 4 K, the magnet was turn on, increasing the B field up to 1 T. In figure 7 we show the measured field inside the Nb3Sn screen as a function of the applied magnetic field. High screening is observed up to a field intensity of 0.8 T. A more detailed study is described in [12].

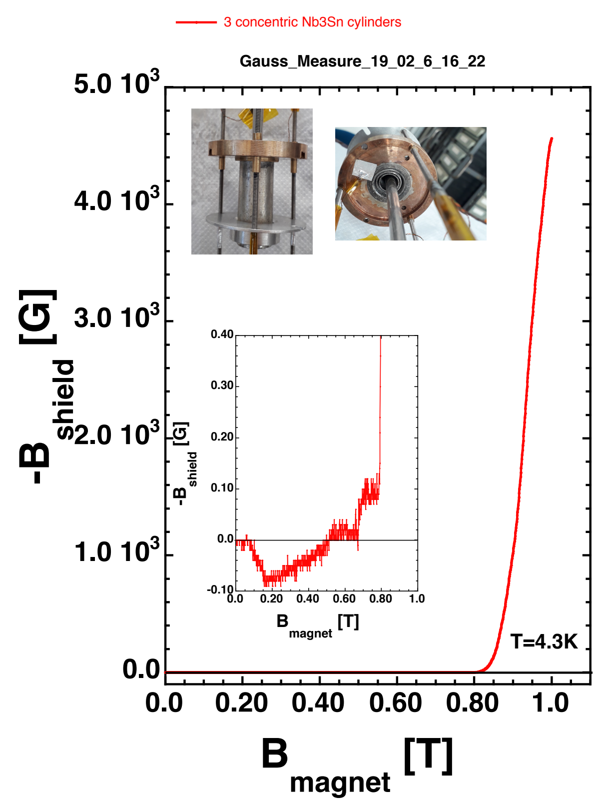

Figure 7: Measured field inside the Nb3Sn screen as a function of the applied magnetic field

4 List of Conference Talks by LNF Authors in Year 2019

1. A. Rettaroli, "First QUAX galactic axion search with a SC resonant cavity," IFAE - Incontri di Fisica delle Alte Energie 2019.

2. A. Rettaroli, “First QUAX galactic axion search with a superconducting cavity,” INVISIBLES2019 Workshop Neutrinos, Dark Matter and Dark Energy Valencia, Spain.

3. C. Gatti, ”Galactic axions search with a superconducting resonant cavity”, 15th AxionWIMP conference (Patras workshop) Freiburg, Germany.

5 Publications

- D. Di Gioacchino et al., “Microwave losses in a dc magnetic field in superconducting cavities for axion studies,” IEEE Trans. Appl. Sup. **29**, no. 5, (2019).
- D. Alesini et al., “Galactic axions search with a superconducting resonant cavity,” PHYSICAL REVIEW D, 99-10, 101101 (2019).

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2. N. Woollett, G. Carosi (2018), “Photonic Band Gap Cavities for a Future ADMX”. In: G. Carosi, G. Rybka, K. van Bibber (eds) “Microwave Cavities and Detectors for Axion Research”. Springer Proceedings in Physics, vol 211. Springer, Cham.

3. J. Krupka, K. Derzakowski, M. Tobar, J. Hartnett and R. G. Geyer, “Complex permittivity of some ultralow loss dielectric crystals at cryogenic temperatures,” Measurement Science and Technology 10 (1999), 387392

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7. D. Di Gioacchino , C. Gatti, D. Alesini, C. Ligi , S. Tocci, A. Rettaroli , G. Carugno, N. Crescini , G. Ruoso, C. Braggio, P. Falferi, S. Gallo, U. Gambardella, G. Iannone, G. Lamanna, A. Lombardi, R. Mezzena , A. Ortolan , R. Pengo, E. Silva, and N. Pompeo, “Microwave Losses in a DC Magnetic Field in Superconducting Cavities for Axion Studies,” IEEE Trans. App. Sup. VOL. 29, NO. 5, AUGUST 2019.

8. D. Alesini et al.,“High quality factor photonic cavity for dark matter axion searches,” arXiv:2002.01816.

9. EDISON, patent no. MI2001A000978.

10. G. Giunchi, Int. J. Mod. Phys. B 17 (2003) 453.

11. A. A. Gallito et al.,“Microwave response of a cylindrical cavity made of bulk MgB2 superconductor,” Physica C 468 (2008) 6671.

12. D. Alesini et al.,“The KLASH Conceptual Design Report,” arxiv:1911.02427.