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NbTi THIN FILM SRF CAVITIES FOR DARK MATTER SEARCH*

G. Marconato†1, O. Azzolini, R. Caforio, E. Chyhyrynets, D. Fonnesu, D. Ford, V. Garcia, G. Keppel, C. Pira, A. Salmaso, F. Stivanello
INFN, Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy
C. Braggio[2], INFN, Sezione di Padova, Padova, Italy
D. Alesini, C. Gatti, A. D'Elia, D. Di Gioacchino, C. Ligi, G. Maccarrone, A. Rettaroli, S. Tocci
INFN, Laboratori Nazionali di Frascati, Frascati (Rome), Italy
U. Gambardella, D. D'Agostino, Gruppo Collegato di Salerno, INFN Sezione di Napoli, Salerno, Italy
S. Posen, Fermi National Accelerator Laboratory, Batavia, Illinois, USA
[1]Also at Dipartimento di Scieze Chimiche, Università degli Studi di Padova, Padova, Italy
[2] Also at Dipartimento di Fisica, Università degli Studi di Padova, Padova, Italy

Abstract

The search for dark matter is now looking at ALPs (axion-like particles) as a very promising candidate to understand our universe. Within this framework, we explore the possibility to use NbTi thin film coatings on Cu resonating cavities to investigate the presence of axions in the range of 35-45 μeV mass by coupling the axion to a very strong magnetic field inside the cavity, causing its conversion to a photon which is subsequently detected. In this work the chemical treatments and DC magnetron sputtering details of the preparation of 9 GHz, 7 GHz, and 3.9 GHz resonant cavities and their quality factor measurements at different applied magnetic fields are presented.

INTRODUCTION

An outstanding result of modern cosmology is that a significant fraction of the universe is made of dark matter. However, the nature of such component is still unknown, besides its gravitational interaction with ordinary baryonic matter. A favored candidate for dark matter is the axion: a new particle introduced by Peccei and Quinn to solve the strong CP problem [1]. Axions and axion-like particles (ALPs) have extremely small coupling to normal matter and radiation.

The QUAX (QUaerere AXion) proposal [2] explores the possibility to study the interaction of the cosmological axion with the spin of fermions (electrons or nucleons). In fact, due to the motion of the Solar System through the galactic halo, the Earth is effectively moving through the cold dark matter cloud surrounding the Galaxy and an observer on Earth would see such axions as a wind. In particular, the effect of the axion wind on a magnetized material can be described as an effective oscillating RF field with frequency determined by axion mass. Thus, a possible detector for the axion wind could be a magnetized sample placed inside a microwave resonant cavity, both cooled down at ultra-cryogenic temperature to avoid the noise due to thermal photons. This setup will be called haloscope hereafter. Since the mass of the ALPs is unknown, many cavities have been fabricated to explore different frequencies within the calculated range of existence of the axions.

The work presented hereby focuses on the superconductive coating of 3 copper microwave cavities (6 half-cells) made in collaboration with different laboratories. The coatings were performed via DC magnetron sputtering (DCMS) by means of a 4 inches NbTi planar target. The first NbTi on Cu haloscope realized, was a 9 GHz cavity coated by DCMS using a $Nb_{0.38}Ti_{0.62}$ target in 2019 [3, 4]. The goal of this research was to improve the performance of this previous haloscope by changing the sputtering target from the $Nb_{0.38}Ti_{0.62}$ to a $Nb_{0.31}Ti_{0.69}$ since this particular composition of NbTi had been proven to have higher pinning for flux vortices due to precipitations of titanium particles, leading to theoretical better performances of the superconductive cavity, in particular higher quality factor in presence of high magnetic field [5]. We also studied the effect of introducing a Nb barrier layer between the copper substrate and the NbTi layer to prevent diffusion at the interfaces. This barrier layer is commonly used in NbTi superconducting magnets production [6].

EXPERIMENTAL PROCEDURE

After mechanical fabrication each cavity semi-cell needed to be chemically treated, in order to have a polished substrate for the deposition process (Fig. 1 A). The recipe for copper polishing involved several steps as follows:

1. Ultrasonic degreasing in GP17.40 soap at 40 °C for approximately 1 hour;
2. Ultrasonic in deionized water;
3. Electropolishing in H_3PO_4 (85 %): Butanol (99,9 %) at 3:2 volume ratio at room temperature with applied voltage 2-3 V for different times depending on the cavity shape and dimensions;
4. Ultrasonic, ethanol rinsing and drying with nitrogen.

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† giovanni.marconato@lnl.infn.it

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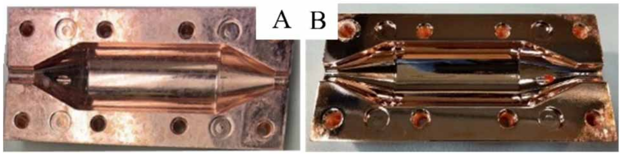

Figure 1: 9 GHz cavity half cell before (A) and after polishing (B).

After polishing (Fig. 1 B) we deposited the NbTi layer via DCMS on the first 9 GHz cavity (target composition $Nb_{0.38}Ti_{0.62}$). The sputtering parameters used were 24 h baking of the system at 600 °C, process 500 °C, process gas (Ar) pressure of $6\cdot10^{-3}$ mbar, 30 min sputtering time. The resulting NbTi layer showed thickness of ~2.5 µm (Fig. 2).

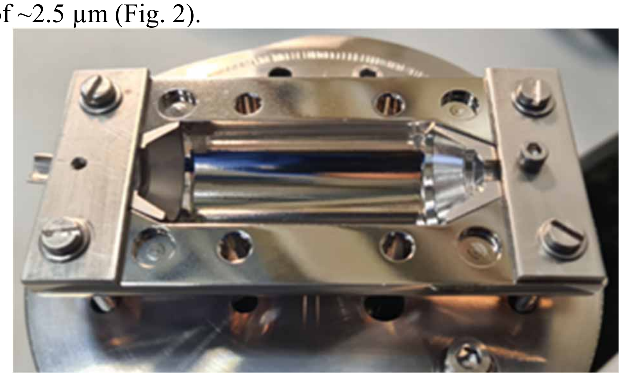

Figure 2: 9 GHz cavity half cell after NbTi deposition via DCMS.

As for the second 9 GHz cavity we followed the same polishing recipe and sputtering parameters, this time using a $Nb_{0.31}Ti_{0.69}$ target as previously explained. After characterizing the cavity, we proceeded to remove the NbTi film using a stripping treatment in order to add a Nb barrier layer. Stripping process involves the use of a HF:HBF_4 solution [7] to chemically dissolve the NbTi layer. Moreover, chemical polishing in SUBU-5 solution [8] was also done on this cavity.

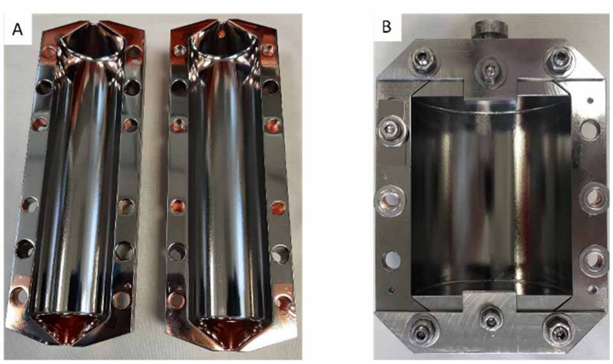

Figure 3: 7 GHz (A) and 3.9 GHz (B) cavities half cells after NbTi deposition via DCMS.

After the stripping process the 9 GHz half-cavity was coated with a Nb barrier layer of 1 µm via DCMS following a similar recipe to the previously described one, the half-cavity was subsequently coated with a $Nb_{0.31}Ti_{0.69}$ layer of again ~2.5 µm.

The other two cavities fabricated afterwards (7 GHz, 3.9 GHz) were made following the same recipe but without depositing the Nb barrier layer and using a $Nb_{0.31}Ti_{0.69}$ target (Fig. 3 A and B).

The two cone-shaped ends of each half cell were covered during sputtering process using two copper cones previously polished in SUBU-5 solution. This part of the cavities is where most of the dissipation takes place since the magnetic field is not parallel to the cavity surface. It was calculated that a superconductive film would dissipate more energy than the normal conductive copper surface due to flux vortices movement [3], hence the decision to not coat it. This represents one of the advantages of the use of NbTi coated copper cavities compared with bulk NbTi cavities, where the conical ends are superconductive and dissipate energy.

The first two 9 GHz cavities were made in collaboration with INFN Padova, the Physics Department of Padova University and Frascati National Laboratories of INFN, the 7 GHz cavity was made again in collaboration with Padova, and the 3.9 GHz cavity was fabricated by Frascati National Laboratories in collaboration with Fermilab (USA).

CAVITIES CHARACTERIZATION

Results for the first 9 GHz cavity quality factor as a function of the temperature are reported in Fig. 4.

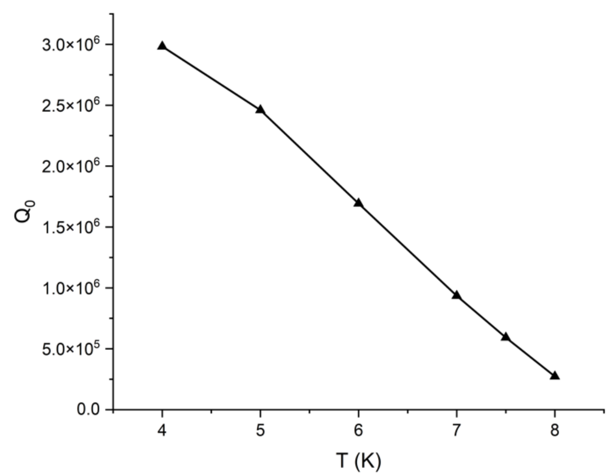

Figure 4: Quality factor versus temperature with no applied magnetic field for the 9 GHz ($Nb_{0.38}Ti_{0.62}$).

The results achieved using the 9 GHz cavity as a haloscope are reported in [3, 4].

The quality factor of the second 9 GHz ($Nb_{0.31}Ti_{0.69}$ layer) cavity was measured at LNF and returned a value of $8.5\cdot10^5$ at 4.2 K.

The quality factor of the same cavity with the Nb barrier layer was measured at LNF and returned a value of $8\cdot10^5$ at 4.2 K.

The quality factor of the 7 GHz cavity was measured at INFN Salerno, with the results shown in Fig. 5.

The dependency on the magnetic field of the different cavities' Q factor is shown in Fig. 6.

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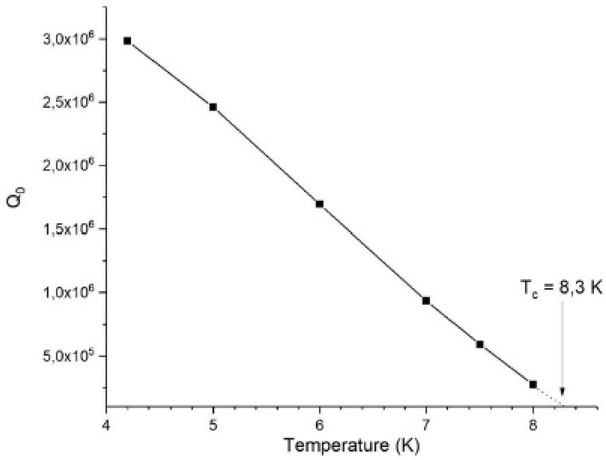

Figure 5: Quality factor versus temperature with no applied magnetic field for the 7 GHz cavity.

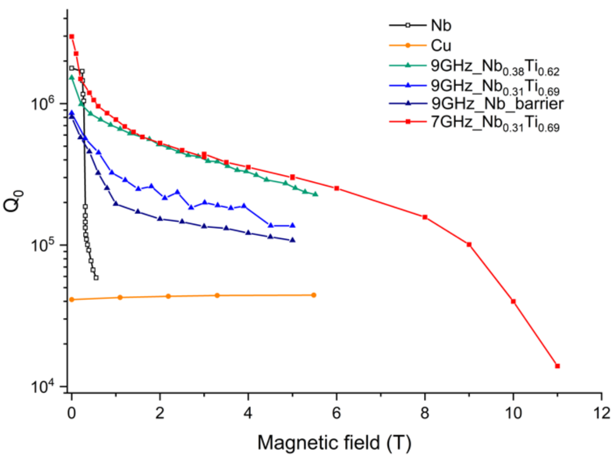

Figure 6: Quality factor versus applied magnetic field for different resonant cavities at 4.2 K. Typical values for Nb and Cu resonant cavities inserted for reference from [4].

The second 9 GHz cavity that we expected to perform better than the older one showed instead lower quality factor as can be clearly seen in Fig. 6. The barrier layer of Nb does not change the behavior of the resonator, which also shows a slight decrease in the factor of merit.

More surprising is the result on the 7 GHz cavity, which instead shows similar performance to that of the 9 GHz cavity made with the $Nb_{0.38}Ti_{0.62}$ target. In this regime, no change in surface impedance is expected at these frequencies, since the dominant loss mechanism, i.e., flux vortex motion, is blocked by pinning. Further investigation is needed to identify the reasons for the reduced performance of the $Nb_{0.31}Ti_{0.69}$ composition and the possible frequency dependence of the factor of merit. Interesting in this regard is the performance of the 3.9 GHz cavity, which has been sent to Fermilab and characterization of which is in progress.

FUTURE PERSPECTIVES

The rise of quantum technologies is opening up a new possible application for superconductive resonant cavities. Many studies have proven that inserting a qubit (be it a superconductive one or not) inside a resonant cavity in a 3D transmon geometry makes it possible to achieve longer lifetimes and much faster and more reliable gate operations [9, 10]. These results are exciting from a quantum computing and a quantum sensing point of view. In fact, qubits in general, but in particular a qubit inside a resonant cavity, can be used as a single-photon counter with extremely high performances [11]. Further tests of cavities for 3D transmon architecture qubits are currently ongoing using bulk ultrapure aluminum.

CONCLUSIONS

The first 9 GHz cavity and the 7 GHz cavity showed promising results as for haloscopes, while the 3.9 GHz one will be tested soon. Further samples are likely to be produced and characterized using the same procedure in order to look for ALPs of different masses, while also exploring the possibility to implement superconductive qubits inside the cavities to produce high precision single-photon counters.

Further studies on vortex pinning inside NbTi are likely to be carried out to understand the possible dependency of this phenomenon on the cavity's frequency as well as on NbTi alloy composition to explain the observed behaviour of the quality factor in the fabricated cavities.

A further improvement will be the replacement of NbTi with Nb3Sn thin films in order to be able to withstand higher magnetic fields and obtain higher values of the quality factor even at currently explored applied magnetic fields [12].

Studies on Nb3Sn DC magnetron sputtering deposition are currently ongoing, looking at best sputtering parameters with commercial Nb3Sn target while also exploring the possibility to produce targets via dipping of pure Nb targets in liquid Sn bath [13].

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