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Microwave dielectric resonator device concept for surface impedance measurement of rotating sample

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Abstract – **The surface impedance of superconductors in function of intense ($\sim$ 10 T) static magnetic field at varying orientations with respect to the crystallographic axes is of large interest for both characterization purposes, in view of the material engineering, and from the point of view of devices to be used in fundamental physics experiments. A varying field orientation is customarily obtained with mechanically rotating magnets, whose complexity limits the attainable maximum fields to a few T. Here we propose a special proof of concept design for a measuring cell in which the magnetic field orientation is fixed, while the sample orientation can be changed through its incorporation in a rotating portion of the cell. The main design choices are thus proposed for the measuring cell: a cylindrical dielectric loaded resonator, to be used within the surface perturbation approach for the measurement of the surface impedance of flat samples with typical size 10×10 mm^2. The main focus in this preliminary work is put on the sensitivity attainable on the surface resistance, i.e. the real part of the surface impedance.**

I. INTRODUCTION

Measurements of the surface impedance Z_s of superconductors in high magnetic fields with varying orientations are of specific but strong interest. Indeed, the most promising superconductors for the realization of next generation high field magnets, in applications such as high definition Nuclear Magnetic Resonance (NMR) [1] and future compact fusion reactors [2], are anisotropic. Hence, angle-dependent surface impedance is a useful characterization tool for the material engineering process. Moreover, large physics experiments, such as the Future Circular Collider [3] and the hunt for Dark Matter [4], require low surface impedance superconductors to be operated in high magnetic fields applied at various orientations with respect to the crystallographic axes. A standard approach in surface impedance measurements is based on the dielectric-loaded resonator (DR) [5]. Indeed, the dielectric loaded resonator method is the most sensitive technique for Z_s measurements in a wide range of temperatures and magnetic fields [5, 6, 7].

Usually, the measurement cell is a simple Hakki-Coleman DR [8], where a cylindrical dielectric puck is coaxially placed within a cylindrical conducting enclosure. In the commonly used surface perturbation technique, the sample replaces one of the conducting flat surfaces of the cavity. By changing an external parameter, such as the dc magnetic field intensity H, the induced variations "Δ" of the real (R_s) and imaginary (X_s) parts of Z_s with respect to a reference value $Z_{s,ref} = Z_s(H = H_{ref})$, can be derived from the measurement of the DR quality factor Q and resonant frequency f_0, respectively [9, 10, 11]:

$$\Delta R_s + \mathrm{i}\Delta X_s = G_s\left(\Delta\frac{1}{Q} - \mathrm{i}2\frac{\Delta f_0}{f_0}\right) - \text{background} \quad (1)$$

where the geometrical factor of the sample G_s is a constant analytically computed or determined through electromagnetic simulations; the term "background" refers to other DR contributions that can be removed by a proper calibration procedure [10]. Performing simple calculations, the sensitivity on R_s and X_s can be obtained:

$$S_{R_s} = \left|\frac{\partial Q}{\partial R_s}\right| = \frac{Q^2}{G_s}, S_{X_s} = \left|\frac{\partial \Delta f_0}{\partial X_s}\right| \propto \frac{1}{2G_s} \quad (2)$$

In standard configurations the static magnetic field is applied parallel to the resonator axis, and hence normal to the sample surface (see Fig 1a). In order to study the material anisotropic response to the *orientation* of the applied magnetic field, two possible approaches can be used: either rotate the magnet around the measuring cell or rotate the whole measuring cell within a fixed magnet. In the first case, specific magnets must be used, rotating either mechanically or magnetically. The added complexity makes them more expensive and limited in the maximum field attainable. The rotation of the whole cell, on the other hand, is hindered by the connection cables, given mainly by the microwave (mw) lines connecting the resonator to a microwave source and detector, which must be fixed.

Here we present a proof of concept based on a third path: a DR based measuring cell designed with a mobile part hosting the flat sample to be measured in various field orientations. To this purpose, the sample would replace a portion of the lateral (curved) cavity wall. Indeed, the measurement of Z_s on curved surfaces is more complex and seldom dealt with [12]. Thus, in the proposed design we postpone the optimization for the measurement of both R_s and X_s for future developments.

II. DESIGN

The here presented concept is based on the standard approach for the Z_s measurement by means of DR, whereas several additional constraints are taken into account to pursue the stated goal.

First, the measuring cell with all its components and connectors should be accommodated in the bore of a standard cryomagnet, which in high field magnets has typical radii R_{cr} no larger than 32.5 mm. Second, the DR must be able to operate in the $\leq$30 GHz range, where both the characteristic frequency of the materials to be studied and the operating frequencies of the mentioned applications are located [13, 14].

A. *Definition of the DR geometry*

The small sample space and the necessity to insert moving parts and cables are the main limiting factors for the DR cell size. A small cell size in turn leads to the higher resonant frequencies of DR.

In order to define the design framework, we first choose the DR resonant mode as a Transverse Electric TE_{0m1} mode, where $m = 1, 2....$ Indeed, it is well-known that the TE_{011} mode has one of the lowest resonant frequency with good frequency separation from other modes [6]. Moreover, the TE_{011} modes induce circular currents both on the bases and on lateral wall of the cylindrical cavity. Hence, no current paths cross the base-wall boundary allowing to physically separate the bases from the wall without disrupting the resonance. This feature will prove extremely valuable in the forthcoming design process. Moreover, the TE_{011} mode induces the maximum current density at the middle plane of the dielectric puck.

The draft of the DR cell is shown in Fig. 1b. The main idea is to conceive the the DR cell as composed by two parts. The fixed part consists of the dielectric puck and flat circular bases, while the lateral wall of the resonant cavity becomes a moving, rotating part. The sample is fixed on the moving part, at the dielectric puck's mid-height level, where the induced currents are maximum. This positioning allows obtaining maximum sensitivity on Z_s and, moreover, linear microwave currents on the sample surface. This is opposed to the circular current pattern encountered in the standard DR setup which, once used with tilted fields, determine non-homogeneous angles between field and currents on the sample surface and ultimately hindering an anisotropy investigation [15].

To place the sample in the rotating part, a recessed blind hole, covered by a thin metallic mask with a rectangular

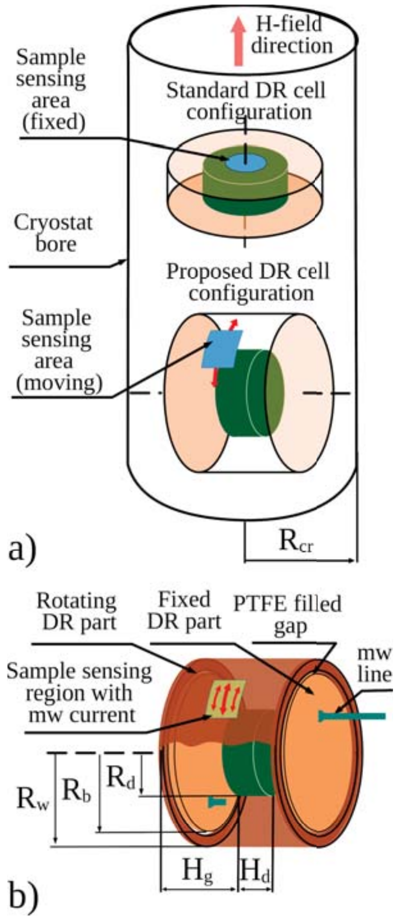

Fig. 1. Draft of the DR cell. a) sketch of the DR cell inside a magnet bore. b) Draft of the DR cell with the two parts, the fixed one with the dielectric puck and the rotating one with the sample holder.

slot, can be made in the lateral wall. In this way, the sample would not protrude in the cavity interior, and only a regular portion of its surface would be exposed to the microwave electromagnetic fields. In this preliminary design, we do not consider the details of mechanical supporting parts. To maintain a constant distance between the fixed resonator bases and the freely rotating lateral wall, we incorporate a thick PTFE layer between the parts. This gap does not affect the TE_{011} mode electromagnetic fields, which are concentrated near the dielectric puck, nor the current pattern induced in the enclosing surfaces, and thus minimally influences the characteristics of the DR cell.

The main components of the DR cell are represented in Fig. 1b: the dielectric puck is placed coaxially to the cavity, between the two flat bases, and has radius R_b smaller than the wall radius R_w.

We put (symmetrical) gaps H_g between the dielectric puck and the bases, so that power dissipation on the bases is reduced. The coupling ports between the DR and microwave lines are placed on the fixed bases (see Fig. 1b), instead of the more often used lateral wall, since the latter is a moving part in the present design.

B. *Definition of the size ranges*

We performed an optimization of the size of the DR cell focusing on the sensitivity of the resonator response on R_s of the sample. The size starting value is given by the cryomagnet bore: considering the smaller values - encountered in high ($\sim$ 10 T magnets), we set an upper limit for the external size of the whole cell to R_{cr} =22.5 mm. Considering that the main part of the DR cell volume will consist in structural supporting parts, together with semi-rigid cryogenic coaxial cables, basic estimations yield the maximum external size of the cylinder, 31 mm. Indeed, the structural cavity parts should be at least 5 mm thick. Adding the space needed for coaxial cables ($\sim$5 mm), the internal cavity wall radius R_w is $\leq$10 mm, and analogously the corresponding maximum cavity height is $\leq$20 mm.

A first simulation of the simple Hakki-Coleman DR structure [16] allowed determining the optimal ratio 0.98 between the dielectric puck radius R_d and height H_d to yield a TE_{011} mode well isolated in frequency from spurious modes. For the present design, which involves a gapped structure a possible different optimal value for R_d/H_d as been sought in a range centered in 0.98 mm.

The choice of the dielectric puck material is of paramount importance. Dielectrics with high relative (real) permittivity ε_r are preferable, since they concentrate more the electromagnetic field within the dielectric puck and thus minimize the disrupting effects of the DR inhomogeneities and gaps. At cryogenic temperatures, single crystal sapphire is usually chosen due to its relatively high ε_r (11.58 and 9.40 parallel and normal to the crystal main anisotropy axis, respectively) and one of the lowest dielectric loss tangents ($\tan\delta$=2.0 $\times$ 10^{-5} at room temperature [17]), enabling high Q factors. Other higher ε_r materials, such as rutile, could be used to reduce the cavity size and/or resonant frequency, but with the drawback of a decreased Q and corresponding sensitivity. Specific studies in this direction could be considered in future studies.

Since DR operates in the high magnetic field in cryogenic environments all metallic parts of DR should be nonmagnetic and should have a high thermal conductivity. For the following, we considered a medium-quality copper with R_s=42 mΩ for all metallic parts of DR. To investigate the capabilities of the proposed DR cell we performed a full-wave Finite Element Method (FEM) simulation. A 3D simulation of the detailed resonator structure needs large calculating power and thus is inefficient in the initial stages of the design process. Hence, in the following we present the results of a 2D (axisymmetric) model, made possible by the axisymmetry of both the DR structure and of the chosen TE_{011} mode.

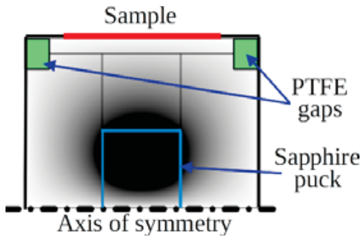

Fig. 2. An example of the simulated TE_{011} mode, in terms of its electric field spatial intensity (darker regions correspond to higher intensity). The red line represents the sample sensing area.

III. DISCUSSION

The FEM simulation performed taking into account the material properties, for both dielectrics and conductors, at room temperature. The extension to cryogenic temperatures will be considered in future works.

In Fig. 2 we illustrate a representative example of electric field distribution corresponding to TE_{011} mode under study. For this 2D axisymmetric model, the sensing area is represented as a 10 mm-wide strip along the whole cavity wall circumference. For future 3D simulation and real DR, samples will be only a portion of this strip as shown in Fig. 1b.

As anticipated in the previous Section, the optimization of the DR cell size is done by taking a fixed ratios R_d/H_d in the range near 0.98 . The symmetrical gap between dielectric puck and bases H_g is varied in the range 0.1 mm–9 mm. Since a small cavity radius is preferable, we studied also the effect of the cavity wall radius R_w by varying it between 6 mm and 12 mm. Given the circular shape of the magnet bore, analogous limits hold also for the longitudinal direction of the DR cell, being $H_d + 2H_g$ its total height (see Fig. 1b). As a result, the investigated parameters space is: R_d/H_d=0.8 –1.2 , H_g=0.1 mm–9 mm, R_w =6 mm–12 mm. Since this multi-variable space of parameters is large, here we focus on selected results.

For each parameters set, the resonant modes were calculated. The TE_{011} mode was identified from other modes using an automatic script which detects the maxima, minima and lobes in the field spatial distributions to identify the mode type and indexes. Upon increasing the dielectric puck size R_d/R_w from 0.2 to 0.8 , the Q factors exhibit a maximum whose position slowly shifts to higher values by increasing the gap H_g (see Fig. 3). Independently from the dielectric puck size R_d/R_w and from the cavity size R_w, even for small gaps H_g above 2 mm, the maxima of $Q(R_d/R_w)$ are in the same R_d/R_w region $R_d/R_w = 0.3 - 0.5$.

Although Q is an important parameter for the sensitivity on R_s, also the geometrical factor of the sensing region (G_s) contributes (see Eq. 2). Analysing the sensitivity,

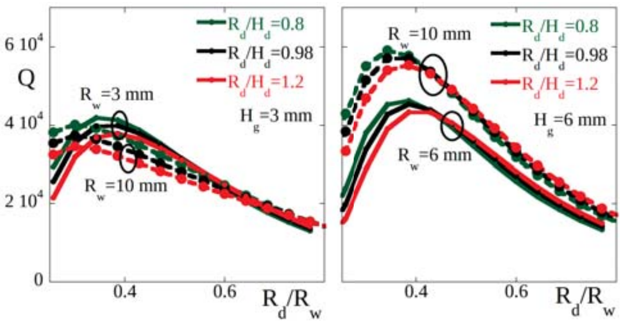

Fig. 3. Q-factor vs the normalized size of dielectric puck R_d/R_w, for TE$_{011}$ mode, different R_d/H_d, R_w and H_g.

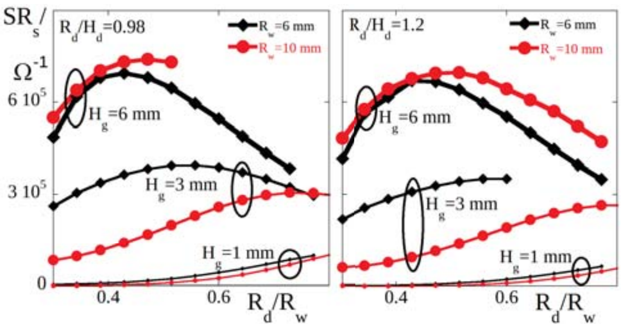

Fig. 4. Sensitivity of the resonator on R_s as a function of dielectric puck size for TE$_{011}$ mode, different R_d/H_d values, varying R_w and H_g. Cavity height is kept below 20 mm.

it can be seen that $S_{R_s}(R_d/R_w)$ is also characterized by a peak (see Fig. 4). As in the case of Q, by increasing the gap, the S_{R_s} maximum moves to lower R_d/R_w values and does not change visibly above H_g=6 mm. Maximum sensitivity at large gap can be obtained for dielectrics with R_d/R_w=0.45 .

Summarising, the DR geometry yielding an optimal sensitivity is: R_d/H_d=0.45 , H_g=6 mm and R_w=6 mm. An estimation of the minimum detectable R_s variation ($\Delta R_s = \min(Q)/S_{R_s}$) can be done considering a minimum detectable $\min(Q)$=40 and a realistic size for the sample. Taking for the latter a rectangle 10 mm wide and ℓ=6 mm long, it would cover a fraction $\ell/(2\pi R_w)$=0.16 of the lateral wall circumference, with a proportional reduction on the sensitivity. Thus, for TE$_{011}$ mode one obtains ΔR_s=0.36 mΩ.

IV. CONCLUSIONS

We have proposed a concept of a DR-based measuring cell for the measurement of the surface impedance of superconducting samples in a magnetic fields with varying orientations. The proposed measuring cell consists in a DR divided in two parts. A fixed one includes the dielectric puck and the bases. The second one, given by the lateral wall, is conceived to accommodate the sample and to be able to rotate within a fixed magnetic field. The main design goals and constraints have been identified and tackled with. A preliminary study, with FEM simulations, allowed to identify the ranges for the resonator dimensions needed to optimize the sensitivity on R_s measurements. A potential minimum detectable ΔR_s for measurements on 10 mm-wide and 6 mm long samples at 16 GHz is expected to be ΔR_s=0.36 mΩ.

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