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# Surface resistance scanner of the irregular pipe structures

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***Abstract* – The surface resistance of the internal coating of pipes is an important characteristic which could indicate zones with the corrosion or leakages. In the particular case of particle accelerators, this parameter becomes even more important for the performance. We designed a scanning cell for the monitoring of the surface resistance along the whole pipe length. We show an example of the geometry optimization of the scanning cell for the octagonal shaped beam screen. Taking into account a $TE_{011}$ operating mode we determine the geometry of the cell from the point of view of sensitivity and the resonant frequency of the operation.**

## I. INTRODUCTION

The quality control of the new pipes and periodic monitoring of their health becomes more and more important within a more complex infrastructures. Corrosion significantly impacts the infrastructure operation, costs, transported gas or liquid quality. There is a wide range of methods to monitor corrosion, which are based on the measurements of the effects of the corrosion such as a weight loss, variation of the ultrasonic or electromagnetic responses [1]. One of the widely used measurement techniques is based on the monitoring of the resistivity of the pipe metallic surface [2, 3].

It is evident that pipes applications are not limited to industry only, it is fundamental also for scientific applications. A good example of such application is the Large Hadron Colliders (LHC) beam screens (the pipes surrounding the beam space), which are fundamental components of the accelerator magnets [4, 5]. It should support beam image RF currents up to 1 GHz generated by the bunches of particles. For this purpose a low impedance conducting film is deposited on the internal surface of the beam screen. Currently copper is used for covering, but recently also the possibility to use superconductors is in active discussion [6].

The most sensitive method for the measurement of the surface resistance $R_s$ is the high-frequency resonator approach [7]. This could be translated also in the resistivity ($\rho$) based on the relation $R_s = \sqrt{\pi f \mu_0 \rho}$ [8], where $\mu_0$ is the vacuum magnetic permeability and $f$ is the frequency.

Usually, resonant techniques are limited to the measurement of flat or small samples. In this article, we propose to use a resonator-based measurement cell for the characterization of $R_s$ of the curved irregular surfaces and its application for the quality characterization of the irregularly shaped pipes. First, we will discuss the $R_s$ measurement method and the proposed design of measurement cell. Then, the results of the measurement cell geometry optimization will be shown.

## II. SURFACE IMPEDANCE MEASUREMENTS

One of the most sensitive methods is a dielectric resonator (DR) approach. In the DR measurements, the use of the high permittivity dielectrics becomes important where high $Q$ and high sensitivity are needed. The electromagnetic mode of the DR is concentrated within the volume of the dielectric itself. For measurements of the metallic surfaces, the so-called surface perturbation approach is usually used. In this case, one of the metallic surfaces of the resonator is replaced by the sample.

Here we propose a method based on a cylindrical DR. The simple structure of the cylindrical DR consists of a dielectric puck placed coaxially in the cylindrical metallic cavity. Traditionally, for measurements of conducting samples one or both bases are replaced by metallic samples [9, 10]. Thus, only flat samples could be measured in this DR. Alternatively, small-sized samples could be placed in the volume of the resonant structure [11].

The resonator quality factor ($Q$) is used for $R_s$ measurements. The imaginary part of the surface impedance can be extracted from the resonator resonant frequency $f_0$. Nevertheless, its absolute value is difficult to extract [8], due to need of a proper reference. Hence, here we focus on the $R_s$ determination, which is much easier to determine. $R_s$ can be obtained from $Q$ by a simple relation [12]:

$$\Delta R_s = R_s - R_{s,ref} = G\Delta\frac{1}{Q} - background \qquad (1)$$

where $R_{s,ref}$ is the reference value, $G$ is a geometrical factor corresponding to the sample surface and could be estimated by electromagnetic simulation. The "background" contribution could be removed by a proper calibration procedure [12].

Here we aim to extend the limits of the traditionally used approaches of DR measurements to enable the characterization of *curved* surfaces. In particular, pipes with irregular section shape and inhomogeneities along the length of the pipe were taken into account. We designed DR for measurement of $R_s$ of the internal conducting wall of the pipe. It should be noted that the approach here described can be extended to measure not only $R_s$ but also changes in $X_s$, which could be fundamental for characterization of a superconducting covering.

In this article, we concentrate our attention on a particular case of irregularly shaped pipes. An excellent example of this kind of pipes, accelerators beam screens (BS), was taken as a base for our study. It should be noted that BS can have different dimensions and shapes; moreover they have inhomogeneities such as pumping holes along the length of the pipe, which must be taken into consideration. We leave issues regarding full $Z_s$ measurements, which becomes more important for the case of future BS with a superconducting covering, for future development.

## III. PIPE DR SCANNING SYSTEM

The proposed system is based on the following requirements: a) capability of the measurement cell to move inside the beam screen pipe along its axis; b) operation at or near 1 GHz, typical for BS applications [6]; c) room temperature operation and the possibility to extend to low-temperature measurements of superconducting covering; d) high sensitivity.

The measurement scanning cell (SC) should sense the whole curved internal surface of the pipe while simultaneously be free to move along the pipe. For this reason, a modification of the Hakki-Colemann DR was chosen due to its simplicity and expandability. The designed SC consists in two parallel cylindrical bases electrically disconnected from the wall of the pipe to ensure the free movement along its length. One could use low-loss non-abrasive dielectric separators (as PTFE) to ensure SC centering and to avoid internal surface scratching.

Figure 1a shows the concept of the assembly with SC inside the pipe. It should be noted that an axial centering of the SC is fundamental, but the design of the mechanical part to ensure it is outside the scope of this article.

Single-crystal sapphire was chosen for dielectric puck due to low dielectric losses (and so, high $Q$) and availability of relatively large crystals on the market. We propose $TE_{011}$ mode for DR as a good compromise between low $f_0$ and, usually, high $Q$. As a starting point we use previously designed non-gapped cylindrical DR. More details could be found in [13]. It was indicated that the range of the relation $r_d/h_d$ within which $TE_{011}$ is well separated from spurious modes. A minimum $f_0$ corresponds to the $r_d/h_d = 0.98$. In the following we will use this relation for dimensions of the dielectric puck.

Another advantage of $TE_{011}$ mode is that the e.m. field is concentrated within the volume of the dielectric puck. Thus microwave circular currents are induced on the pipe surface within the median plane of the dielectric puck. This type of electromagnetic mode allows to avoid inhomogeneity and spurious effects due to the gap between bases and pipe surfaces.

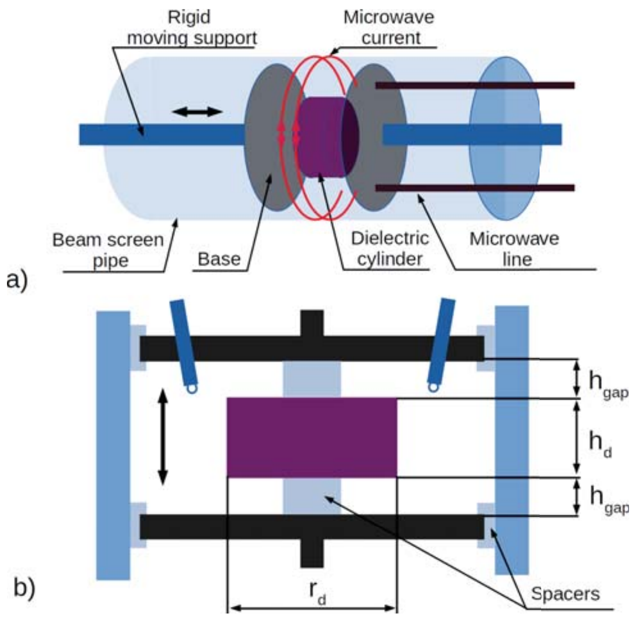


*Fig. 1. Representation of the SC positioned inside the pipe under study (a) and SC draft (b).*

We based our design on the optimization of the sensitivity on $R_S$ of the non-circular pipe wall. From equation 1 the sensitivity could be easily calculated as $|S| = |\partial Q/\partial R_s| = Q^2/G$. It is evident that not only high $Q$ but also the geometrical factor plays an important role in the sensitivity optimization.

To further increase $Q$ we used the configuration with two symmetrical gaps between the dielectric puck and the bases. Figure 1b shows a sketch of the proposed SC. To keep the dielectric puck fixed and centered, two dielectric supports with radius much lower than $r_d$ could be used to ensure mechanical stability without disturbing the e.m. mode.

In the following we present the study regarding the optimization of the geometry of the SC.

## IV. MEASUREMENT CELL PERFORMANCE OPTIMIZATION

An extensive study of characteristics of the resonator was performed to determine dimensions of the dielectric puck ($r_d$ and $h_d$) and gaps ($h_{gap}$).

It should be noted that beam screens have various dimensions and cross-sections for different magnets [14]. Different available internal volume for DR in the BS limits the radius of the dielectric puck. This, in turn, defines a range of the operating resonant frequency and dimensions of SC itself. Since the shape of BS is irregular, in the following we considered a small 5-mm gap between bases and nearest pipe wall element, which ensures free movement along whole pipe.

To further specify the size/shape constraints, we now focus the design of the SC for quadrupole magnets Q1 and Q2 octagonal beam screen [14]. More details about this SC design and applications could be found elsewhere [5, 15]

We extensively studied e.m. characteristics of DR-based SC using full-wave electromagnetic simulation. In order to reduce the computation time and the memory consumption which would have been needed for the simulation of a structure as near as possible to the real BS structures, we have taken advantage of the symmetrical design of the BS to create simpler models. To do so, we have simplified or removed from the model the parts not facing directly the DR puck and irrelevant in the determination of the e.m. response of designed DR cell: in this way we were able to reduce the portion to be simulated between proper simmetry planes. In Figure 2 a simulation model used in the study of the Q1 BS and the cross-sections of both Q1 and Q2 BS are shown. Along the four sides of both the Q1 and Q2 BS, adjacent to the a cooling tubes, a flux exchange grid of rectangular slots $8\times1$ mm$^2$ spaced by 1 mm is distributed linearly (see Figure 2). In the simulation, the position of the slots was kept fixed and their smallest dimension concurred in the determination of the maximum size of the mesh. We leave for a future study the simulation of the effect of the longitudial position of the slots and of their different distributions. The space of the parameters $r_d$ and $h_{gap}$ was studied keeping the relation $r_d/h_d = 0.98$ constant. The space between cylindrical base and BS wall was fixed in the simulation to be 5 mm. Radius of the base was chosen as $r_{base} = 95$ mm for Q1 BS (with minimum distance between walls 99.7 mm) and $r_{base} = 105$ mm for Q2 BS (with minimum distance between walls 110.7 mm).

A wide range of the dimensional parameters was studied. We vary the radius of the dielectric $r_d$ between 15 mm and 40 mm (near to $r_{base}$ value); symmetrical gaps with $h_{gap}$ up to 56 mm were used.

Figure 3a shows typical results regarding the dependence of the $f_0$ on the geometry of designed SC. Without gaps even the use of a large sapphire dielectrics does not allow to reach 1 GHz. Thus gapped DR is preferred. We illustrate that $f_0$ reach saturation at high values of $h_{gap}$ depending on the $r_d$. It was determined that for both BS under study $h_{gap} > 21$ mm does not lead to a visible reduction of $f_0$. Lowest values of $f_0$ correspond to the large dielectrics with $r_d$ near $r_{base}$ thus tending to fill whole section of the SC. As an example, for LHC beam screen, which has a smaller minimum distance between walls 36.9 mm[14], the DR fills the whole internal space of the pipe in order to obtain frequencies below 4 GHz (results not reported here).

Usually high $Q$ is associated with a high sensitivity of DR. We report in Figure 3 b and c a comparison of the $Q$ and sensitivity in the space of the parameters $r_d$ and $h_{gap}$. We observe an evident growth of $Q$ with an increase of the gaps. Thus we focus, mainly, on the region with a high gap size. We observed the presence of the maximum on the dependence $Q(r_d)$ near $r_d/r_{base} = 0.5$ for both Q1 and Q2 BS.

We determine that the growth of the gap size increases monotonously the sensitivity. Larger $r_d$ is characterized by smaller sensitivity growth than for smaller dielectrics tending to the saturation. We obtained that both BS presented in this study, despite different dimensions, are characterized by similar characteristics as a function of relative radius $r_d/r_{base}$. This weak dependence on the internal dimensions of the octagonal cross-section of the BSs allows to provide a generalized guide for the design of SC for others similarly shaped BSs. More complex crossections of BS could influence the SC responce and thus require further SC optimization.

It is evident from Figure 3 that the lowest $f_0$ corresponds to not optimal characteristics of the resonator. Even using a high $h_{gap}$ and low $f_0$ one should consider a reduction from the optimal value of more than 50 % on $Q$ and $\sim$30 % on the sensitivity.

In some cases high $Q$ could be preferred, thus relation $r_d/r_{base} = 0.5$ should be chosen. It was obtained that in this case only high values of $h_{gap}$ could correspond to both optimum $Q$ and sensitivity with the drawback of the higher $f_0$ near 2.5 GHz.

Based on sensitivity, one could estimate a minimum detectable variation of $R_s$ as $\Delta R_{s,min} = \Delta Q_{min}/|S|$. Taking into account that minimum variation of Q-factor which could be detected is $\Delta Q_{min} = 40$ and high $h_{gap} = 51$ mm, $R_{s,min} = 10\ \mu\Omega$ for $r_d/r_{base} = 0.5$ and $R_{s,min} = 13\ \mu\Omega$ for $r_d/r_{base} = 0.9$.

In this article, we focused on the issues regarding only the basic characteristics of the SC, keeping issues related to the real SC prototype design for future development. In practice, after the choice of the geometry of the dielectric to optimize the SC characteristics, one should presumably deal with lower Q-factors than those predicted due to the possible, lower conductivity of the metallic parts of a real BS. Moreover, the SC should be designed in order to minimize the effect of vibrations during the movement of SC along BS pipe, keeping its operation stable and reproducible. As far as the feeding microwave line is concerned, low-loss coaxial cables could be a good solution. Indeed, we exclude the use of waveguides because of their large size in the needed frequency range, comparable to the size of the BS itself. On the other hand, the larger losses of coaxial cables make the level of the coupling between microwave line and resonator an important design choice in order to preserve a good SNR value.

As a summary, we determine different geometry choices which could be adapted to the needs of the measurements performed with SC. It should be noted that the here presented measurement SC design could be easily applied for every metallic pipe $R_s$ characterization.

## V. CONCLUSIONS

We designed a measurement cell for surface resistance measurements of the internal covering of the metallic pipe with non-circular irregular cross-section. The cell based on the DR was proposed for the scanning of $R_s$ along the whole length of the beam screen. We performed e.m. simulations to take into account irregular cross-section of the beam screens. It was shown that by use of the gaped DR allows to decrease of $f_0$ and increase $R_s$ sensitivity level. We presented as an example of the results of the simulation of Q1 and Q2 beam screens. For this case, we use a sapphire dielectric resonator excited on $\text{TE}_{011}$ with $f_0$ near 1.5 GHz, including a gap larger than 21 mm. Further increase of the gap does not give an evident improvement in $f_0$ and sensitivity, and could even decrease $Q$. We determined optimum sensitivity $|S| = 4{\cdot}10^6\ 1/\Omega$ and minimum detectable $R_s$ $R_{s,min} = 10\ \mu\Omega$ at relative dielectric radius $r_d/r_{base} = 0.5$, while the corresponding $f_0 = 2.5$ GHz is not optimal. By analysing two distinct structures for the beam screens, having different sizes, we observed a weak dependence of the DR design on the on the actual internal dimensions of the octagonal cross-section. This allows to provide a tentative generalized guide for the design of SC for others similarly shaped BSs.

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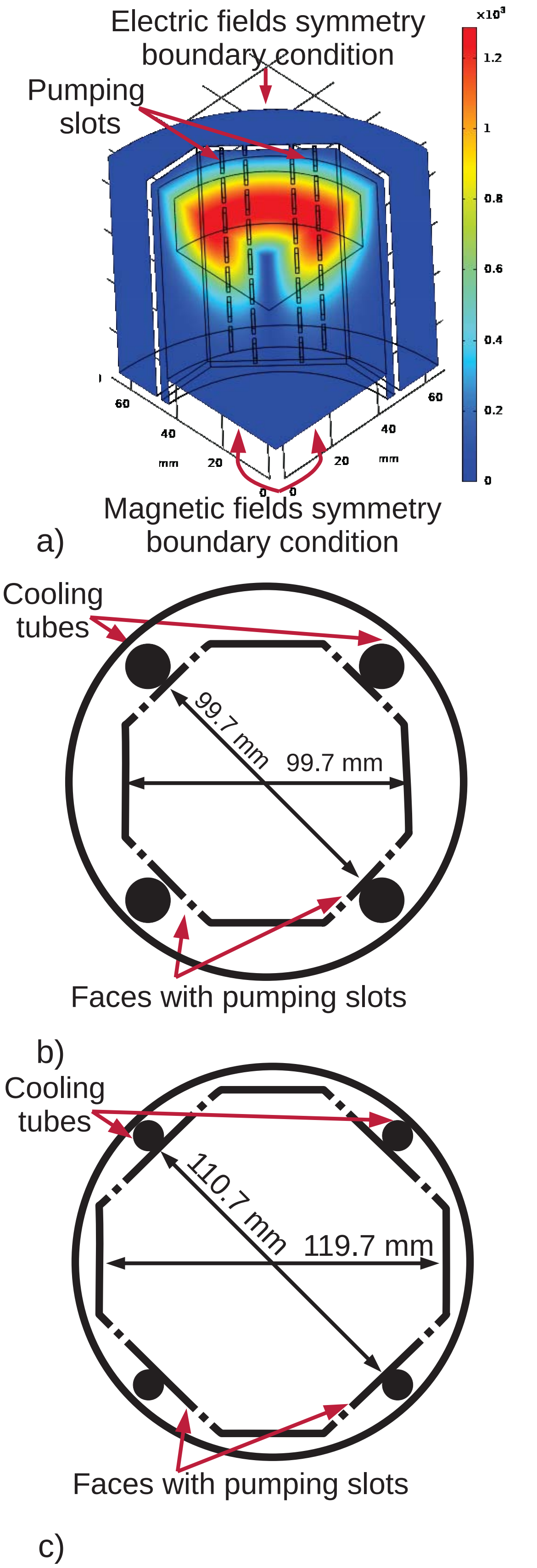


*Fig. 2. Electromagnetic simulation model of $TE_{011}$ mode (a), cross-section of the Q1 model (b) and cross-section of the Q2 model (c).*

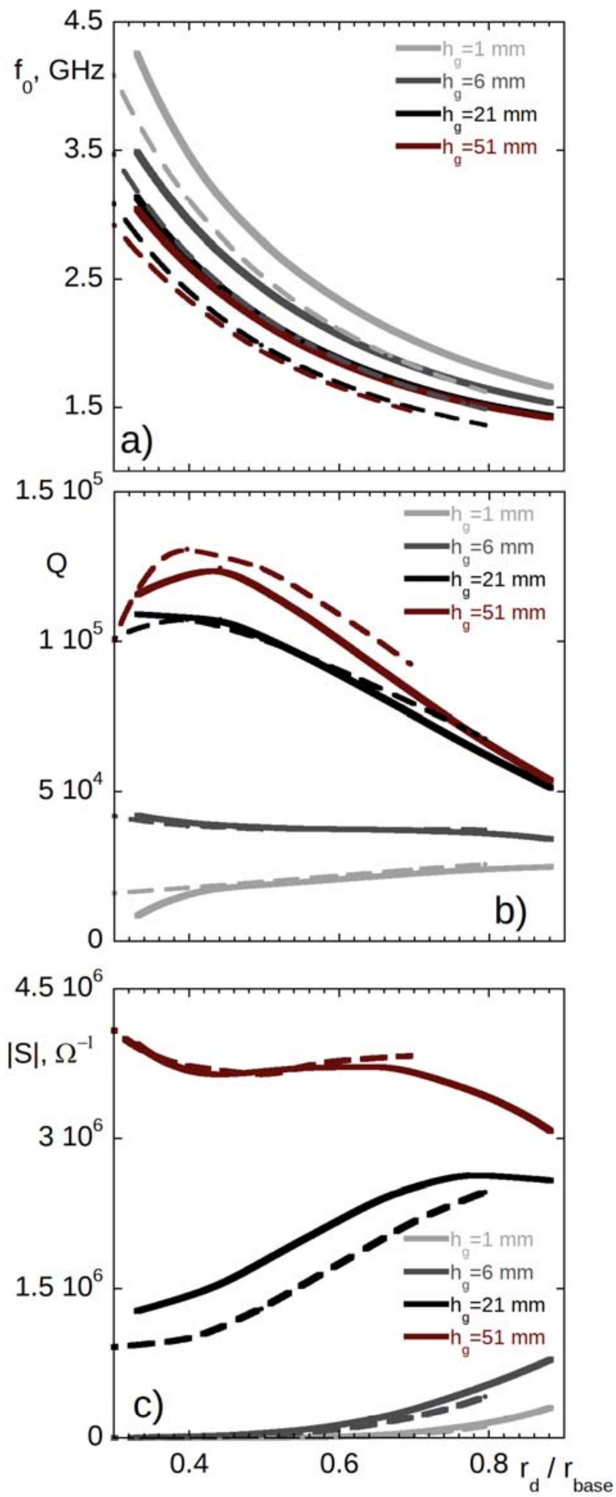


*Fig. 3. Resonant frequency (a), quality factor (b) and sensitivity (c) as a function of the reduced dielectric radius. Q1 BS results represented as solid lines, Q2 BS – with dashed line.*