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STATUS OF THE NEW QUADRUPOLE RESONATOR FOR SRF R&D

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Abstract

A basic understanding of the properties of SRF samples after being exposed to surface treatments will aid in the development of consistent theories. To study the RF properties of such samples under realistic superconducting-cavity-like conditions, a test device called Quadrupole Resonator (QPR) was fabricated. In this publication we report the status of the QPR as a joint project of Universität Hamburg and DESY. Our device is based on the QPRs operated at CERN [1] and at Helmholtz-Zentrum Berlin (HZB) [2]. Its design will allow for characterizing samples at temperatures between 2 K and 8 K, under magnetic fields up to 120 mT and with operating frequencies of 433 MHz, 866 MHz and 1300 MHz. Fabrication tolerance studies on the electromagnetic field distributions and simulations of the static detuning of the device, together with the commissioning report and the ongoing surface treatment, will be presented here.

INTRODUCTION

Niobium (Nb) is the material of choice for the construction of superconducting radio frequency (SRF) cavities in modern particle accelerators. Since the accelerating fields in these SRF cavities are reaching their theoretical limit, materials such as Nb_3Sn [3,4], multilayer structures (SIS) [5], and treatments like N-doping [6], N-infusion [7] and mid-T bake [8] of bulk Nb cavities have been shown to increase quality factors and the maximum fields they can achieve. However, further research is required before cavities made of these materials can be used to equip complete accelerators. An improved version of a sample characterization device called Quadrupole Resonator (QPR), originally developed and operated at CERN and HZB, has been further developed and built in a cooperation between Universität Hamburg and DESY. The measurement capabilities of the QPR will be discussed in the following sections.

THE QUADRUPOLE RESONATOR

The Quadrupole Resonator was developed at CERN in 1998 [9]. In the mid-2010s, the results of an optimized QPR were reported by Helmholtz-Zentrum Berlin [10]. A redesign of the CERN QPR was announced in 2017 [11] and new results were reported in 2019 [12]. In a collaboration between Universität Hamburg and DESY and Universität Rostock [13], an improved version of the resonator has been further developed and recently built. SRF sample properties will be measured with this device in the parameter space defined by the resonance frequency f, LHe bath temperature T, and applied magnetic field B. It will allow for systematic investigations of the sample's surface resistance R_s, critical magnetic field H_c, and superheating magnetic field H_{sh}. The previously mentioned data make it possible to determine the following material properties: London penetration depth λ_L, mean free path ℓ, critical temperature T_c, and the superconducting gap Δ.

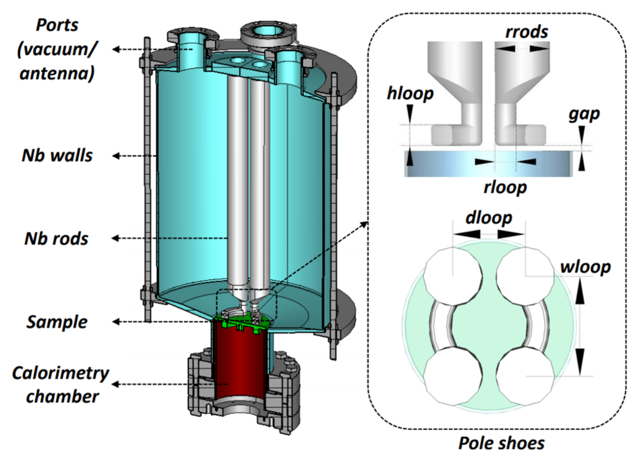

Figure 1: Cross-sectional view of a QPR (left) with the parametrized model of the pole shoes (right) [14].

The basic functionality of the QPR (Fig. 1) is as follows. RF fields enter the test cavity through the input antenna, which is situated in one of the ports on the top of the device. These fields resonate in the walls producing monopole-, dipole-, or quadrupole-like mode distributions of the electromagnetic field. The pole loops, formed by the rods and pole shoes, are employed to focus the magnetic field onto the sample surface, which reaches its maximum when only a quadrupole mode (operational mode) is excited. A probe antenna measures the energy of the RF field stored in the QPR, and this information is later used together with a calorimetric technique (Fig. 2) to determine the surface resistance of the sample [1,2].

The QPR has the following operational range specifications: temperatures between 1.5 K and 8 K, maximum applied field on sample $H_{sample,max}$ up to 120 mT, and the

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resonant frequencies $f = 433$, 870 and 1310 MHz. The investigated samples are disc-shaped and 7.5 cm in diameter.

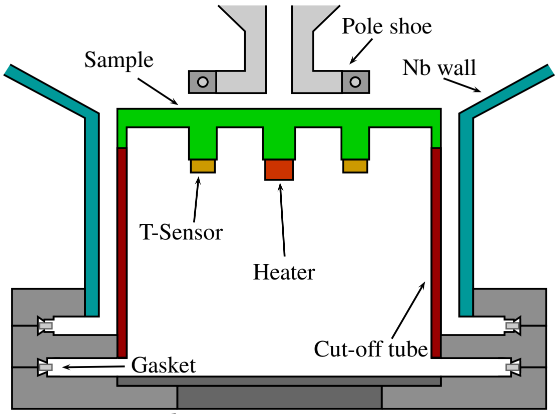

Figure 2: Cross-sectional view of the calorimetry chamber [15].

Advantages of the QPR

The SRF community has developed a variety of devices for the characterization of superconducting samples. Since testing of new materials in coated cavities can be expensive and time consuming, it is preferable to study small samples with a controlled set of parameters. For example, TE Host cavities, Sapphire Loaded Cavities, and Hemispherical cavities require mounting samples between 5 cm and 13 cm in diameter [16]. The QPR offers the following advantages over other sample characterization systems: It allows for a direct measurement of the surface resistance, while other devices measure relative to a reference sample. The measurements can be performed at RF frequencies f and cryogenic temperatures T typical for SRF cavities. For example, in the QPR the surface resistance of samples can be studied at 1.3 GHz, which is the operational frequency of Nb SRF TESLA-shaped cavities in XFELs. An easier sample preparation and exchange with turn-around time at a lower cost are possible. The device can operate in the low frequency domain (first two subharmonics) to study the contributions of the residual and BCS resistance [17] or to study frequency-dependent effects [18]. Finally, there is the capacity to add a magnet system to study flux pinning effects, since material properties such as the efficiency and sensitivity to trapped flux of a sample are also important to determine.

STATIC DETUNING SIMULATION STUDY

The resonator and the calorimetry chamber form a coaxial gap below the sample (the space between the cut-off tube and the Nb wall in Fig. 2) that damps the electromagnetic fields for the quadrupole modes. Therefore, defects that modify the symmetry of the resonator (detuning) may excite unwanted neighboring modes, such as monopole or dipole modes, which then travel into the coaxial gap, leading to an unaccounted heating of the sample. This effect causes an overestimation of the residual resistance since the auxiliary devices used in the calorimetric technique need to further compensate this additional heat source.

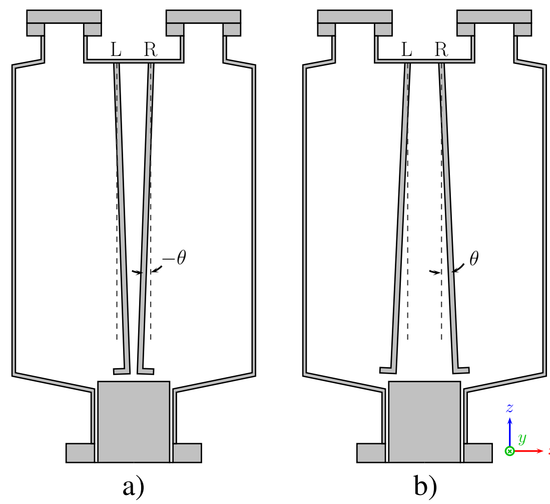

Figure 3: Schematic diagram of the angle variation of the Nb rods. The rotation of the rods was done around the y-axis with an angle θ that is a) negative when the rods get closer and b) positive when the rods draw apart.

In practice, static detuning of the QPR occurs because fabrication errors and/or deformations after pumping down induce angle deviations of the Nb rods. This issue could result in a shift of the operational frequencies or even in a place swap between two neighboring modes.

To study such a phenomenon in our device, simulations of the static detuning were carried out using CST MICROWAVE STUDIO® varying the angle of the right rod, both rods (Fig. 3), and both pole shoes. In the case of the symmetric bending of both rods at an angle between -0.4° and 0.4° around the y-axis (a tilting of 0.4° of one rod is equivalent to a displacement of 2.28 mm in the x-axis), a shift of the quadrupole modes' eigenfrequencies was observed (Fig. 4). This phenomenon might explain the differences in the operational frequencies of the HZB QPR compared to our simulated values [19].

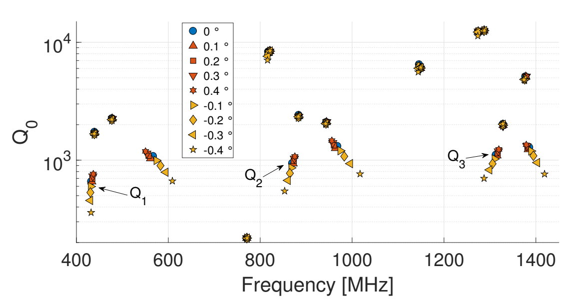

Figure 4: Quality factor vs. Frequency of the QPR at room temperature with a rotation of the rods around the y-axis at an angle θ between -0.4° and 0.4°.

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It was also observed that an exchange between the third quadrupole mode and the previous dipole mode happened for a -0.4° tilting of both rods (when the rods get closer). These simulations served as a control during the fabrication and commissioning phase.

COMMISSIONING OF THE QPR

The construction of the QPR was finalized in April at Zanon Research & Innovation Srl, and it was delivered in the beginning of May. A series of post-production tests were performed at Zanon R. I. to ensure the parallelism of the parts and the same were carried out at DESY. The following tests were done for the commissioning: 1) Ultrasonic wall thickness measurements of the vessel and pole shoes, which is an important preparation measure for the chemical surface treatment of the QPR. 2) Bridge coordinate measurement, to check the parallelism of the QPR vessel and the sample holder. 3) Spectrum of response to mechanical excitations. 4) RF spectrum and other properties like the antennas' coupling. Later, test number four was repeated after evacuating the QPR to check for deformations of the structure.

In the following subsections only the results of tests number two and four are presented since the data was recently taken and is being processed at the moment.

Mechanical Resonances

Microphonics, introduced by vibrations or RF noise, can trigger a dynamic detuning of the QPR. At HZB, a 100 Hz modulation on top of the driving RF signal was observed. Since the mechanical eigenmode of the Nb rods also lies at 100 Hz (see Fig. 5), they were excited, causing a build-up of the detuning until the measurement system lost the resonance. To mitigate this problem in our QPR, a redesign of the inside of the Nb rods was done to improve their stiffness and consequently shift the resonance frequency.

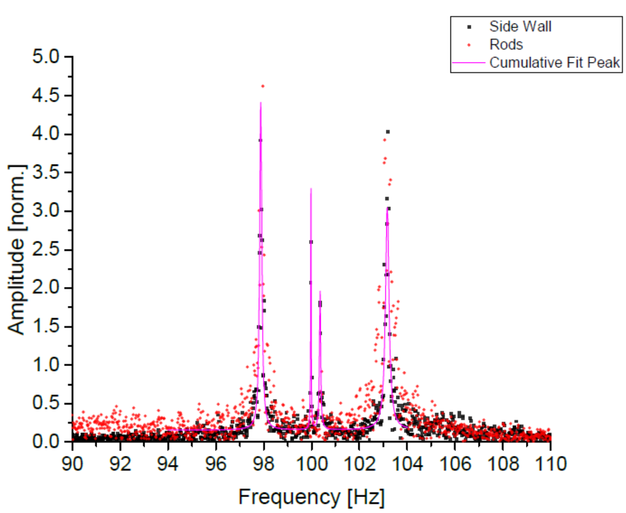

Figure 5: Normalized fast Fourier transform vs. Frequency. Mechanical spectrum of HZB's QPR measured with the geophone. Vibrational eigenmodes at and around 100 Hz are observed [14].

Figure 6: Mechanical resonances setup: four piezoelectric accelerometers mounted on the QPR's surface to measure vibrations in the x, y, and z axes.

To identify the mechanical spectrum in our resonator, several piezoelectric accelerometer sensors were mounted and stimuli were produced on it (Fig. 6).

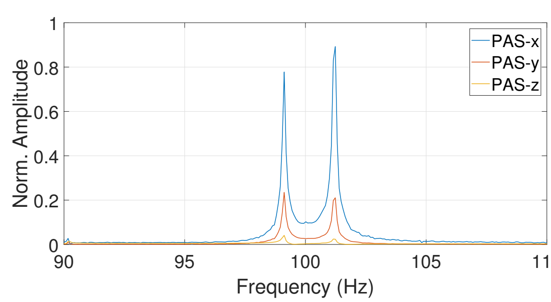

Figure 7: Normalized fast Fourier transform vs. Frequency. Three piezoelectric accelerometers (PAS) mounted on the top part of the QPR measured vibrations in the three dimensions when hitting it in the vicinity of the sensors.

As was expected from our modified design, when hitting the resonator on the top part, where the rods are connected to the vessel, the mode at 100 Hz is not present (see Fig. 7). This proves that the QPR is more stable against microphonics compared to HZB's design. The previous test represents a major success of the design and manufacturing processes at DESY and Zanon R. I., respectively.

RF Spectrum Measurements at Room Temperature

In addition to the mechanical spectrum, the RF spectrum was measured and the results were compared to simulated values. For the measurements, the input antenna (Fig. 8) loop area was oriented perpendicular to the magnetic field

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(a condition only valid for the quadrupole modes), while the pick-up antenna was oriented at 45° to couple to different monopole, dipole, and quadrupole modes (Fig. 9). For the simulations, a model with 10^6 hexahedrons was employed considering the geometrical information of the QPR after fabrication, i.e., a test at Zanon R. I. showed each rod bending at an angle of approximately 0.05° around the y-axis. This corresponds to a displacement of 0.285 mm in the x-axis. Additionally, an inclination of the sample with a maximum displacement of 50 μm in the z-axis with respect to its nominal plane was observed.

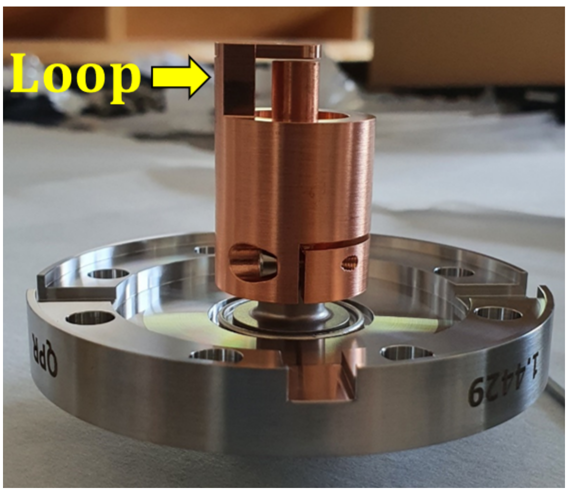

Figure 8: Input antenna: the coupling is controlled via the angle between the loop area and the field orientation.

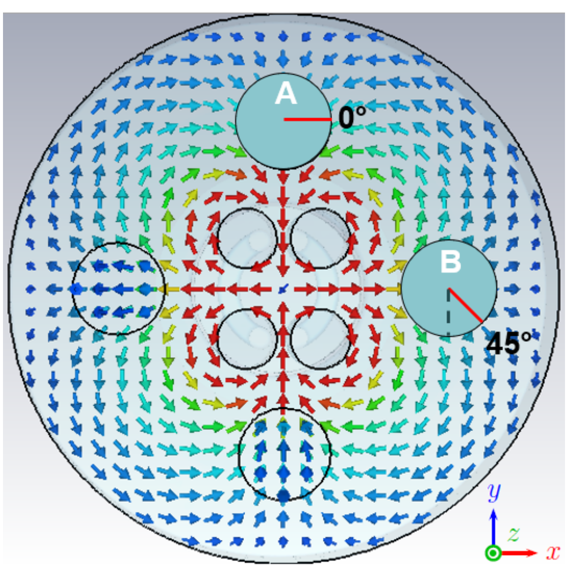

Figure 9: Cutting plane of the QPR normal to the z-axis. The input antenna loop area was fixed at 0° in port position A and the probe oriented at 45° in B. The magnetic field distribution corresponds to a quadrupole mode.

The simulated frequency values were found to be within a 4% deviation with respect to the real measurements and no dynamic mode order swapping was observed. Although a good agreement between the simulation and the measurement was observed, a significant deviation was found for some dipole modes (Fig. 10). These modes are more prone to mechanical fluctuations, breaking the symmetry of the resonator. Further analysis of this discrepancy is needed to understand the shortcomings of the RF model.

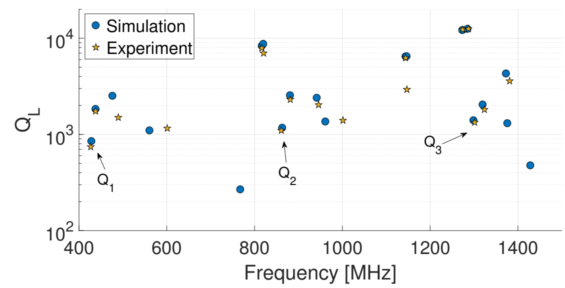

Figure 10: Loaded quality factor vs. Frequency of the QPR at room temperature. Comparison between simulation and experiment.

NEXT STEP: SURFACE TREATMENT

After the previous measurements, the QPR was sent to Zanon R. I. to undergo a standard surface treatment typical for Nb SRF cavities to ensure both high quality factors and high magnetic fields. The treatment will consist of the following steps: *i*) Coarse buffered chemical polishing (BCP) to remove 150 µm from the damaged inner layer of the Nb walls due to the mechanical preparation. *ii*) An 800 °C bake for 3 hours to avoid a quality factor degradation phenomenon named “Q-disease”. *iii*) A fine BCP to remove an extra 20-40 µm from the Nb wall's surface. Finally, *iv*) a 120 °C bake for 48 hours that will lead to a reduction of the QPR's surface resistance and to the disappearance of the sudden drop of the quality factor (Q-drop) at high fields [14].

Subsequently, the resonator is going to be tested at cold temperatures throughout the operation phase.

SUMMARY

Sample characterization is important as a step before coating an entire cavity and to assist the development of the theory of new materials and treatments. A test cavity called Quadrupole Resonator, further developed and built in a collaboration between Universität Hamburg and DESY, will allow for systematic studies of superconducting samples in the frequency f, temperature T, and magnetic field B space.

The QPR was expertly manufactured at Zanon R. I. and successfully commissioned at DESY, where its mechanical and RF spectra were identified. As was expected from its design, no mechanical mode at 100 Hz is detected, and the simulated RF modes are within a 4% deviation with respect to the measured values.

Now, the QPR surface is going to be chemically treated like a Nb SRF cavity, and the tests at cold temperatures will be performed afterwards during the operation phase.

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