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DESIGN AND FABRICATION OF A QUADRUPOLE RESONATOR FOR SRF R&D

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Abstract

As Nb superconducting radio-frequency cavities are now approaching the theoretical limits of the material, a variety of different surface treatments have been developed to further improve their performance, although no fully understood theory is yet available. Small superconducting samples are studied to characterize their material properties and their evolution under different surface treatments. To study the RF properties of such samples under realistic SRF conditions at low temperatures, a test cavity called quadrupole resonator is currently being fabricated. In this work we report the status of the QPR at Universität Hamburg in collaboration with DESY. Our device is based on the QPRs operated at CERN [1] and at HZB [2] and its design will allow for testing samples under cavity-like conditions, *i.e.*, 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 a status report on the current manufacturing process, will be presented.

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 support. However, further research is required before a cavity made from these materials goes into operation. An improved version of a device called Quadrupole Resonator (QPR), originally developed and operated at CERN and HZB, has been further developed and built in a cooperation between Hamburg Universität and DESY. It will allow for the systematic study of small superconducting samples over a broad parameter space defined by the resonance frequency, cryostat temperature, and applied magnetic field.

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THE QUADRUPOLE RESONATOR

The Quadrupole Resonator (Fig. 1) 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 reported new results in 2019 [12]. In a collaboration between Hamburg Universität and DESY and Universität Rostock [13], an improved version of the resonator has been further developed and built. SRF sample properties will be measured in the parameter space defined by the resonance frequency f, cryostat temperature T, and applied magnetic field B. It will allow for systemic investigations of the sample's surface resistance R_s, critical magnetic field H_c, and superheating magnetic field H_{sh}. The previous data make it possible to determine the following material properties: London penetration depth λ_L, mean free path ℓ, and critical temperature T_c.

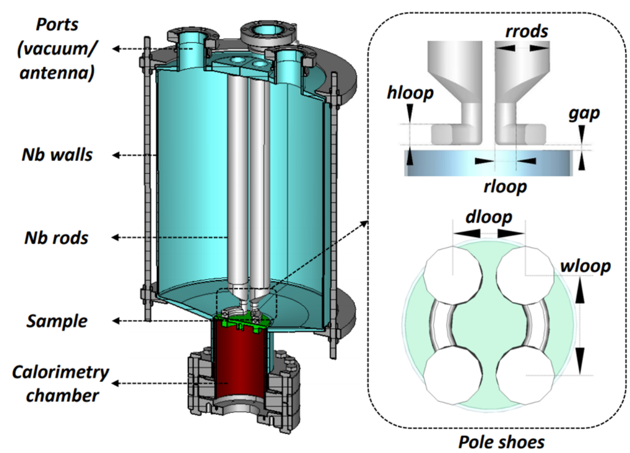

Figure 1: Cross-sectional view of a QPR (left) with the parametrized model of the pole shoes (right) [2].

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 resonant frequencies $f = 433$, 870 and 1310 MHz.

Calorimetric Measurement Principle

The calorimetry chamber (Fig. 2) has the functionality to thermally isolate the sample from the rest of the resonator to ensure the stable sample's temperature. Inside this chamber,

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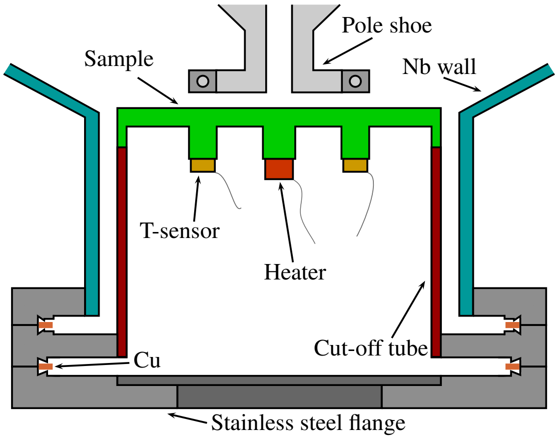

Figure 2: Cross-sectional view of the calorimetry chamber.

CERNOX T-sensors and a heater are placed at the sample's bottom surface. These auxiliary devices are connected in a closed-loop controller, which is driven to perform a DC power compensation measurement of the sample's surface resistance (Fig. 3). The technique is explained in the following steps:

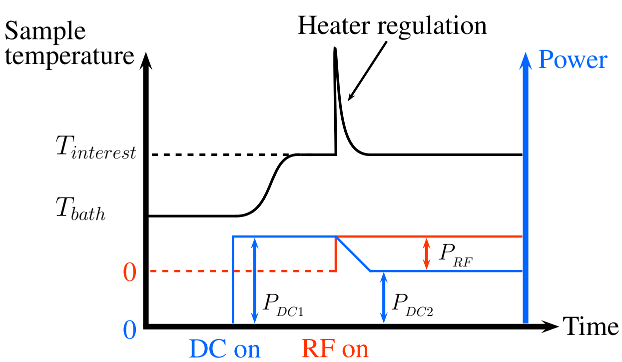

Figure 3: Illustration of the calorimetric measurement principle [2].

First, *a*) the heater increases the temperature of the sample from the temperature of the LHe bath T_{bath} to a desired value T_{int}<T_c. *b*) The required heating power P_{DC1} in the controller is recorded. Then, *c*) the RF system is turned on and RF dissipation leads to a further increase of the sample's temperature due to Joule heating. *d*) The controller decreases the power to compensate for this Joule heating until the temperature of the sample reaches T_{int} again. Finally, *e*) the changed heating power P_{DC2} is recorded.

Assuming a spatial constant R_s across the sample, the previous process can be summed up in Eq. (1):

$$R_s = \frac{2 * (P_{DC1} - P_{DC2})}{\int_{sample} |H|^2 \, dA}. \tag{1}$$

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, SIC, and Hemispherical cavities require mounting samples between 5 cm and 13 cm [14]. The QPR (Fig. 4) 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 frequency at what Nb SRF TESLA shaped cavities operate in XFELs. An easier sample preparation and exchange and 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 [15] or to study frequency-dependent effects [16]. 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.

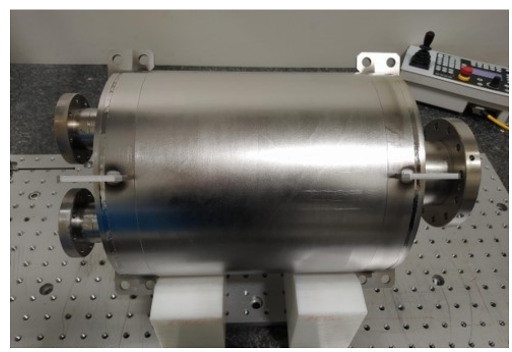

Figure 4: Finalized QPR at Zanon Research & Innovation Srl.

STATIC DETUNING STUDY

The resonator and the calorimetry chamber form a coaxial gap below the sample 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 the monopole or dipole modes, which might travel into the coaxial gap, leading to an unaccounted heating of the sample. This effect causes an overestimation of the residual resistance since P_{DC2} is lower to further compensate this additional heat source.

In practice, microphonics, deformations after pumping down, and/or fabrication errors induce angle deviations of the Nb rods which could result in a simultaneous excitation of more than one mode. For instance, a bridge coordinate measurement of the QPR performed at Zanon R. I. showed a deviation of the pole shoes with respect to the nominal design (Fig. 5).

To study such a phenomenon in our device, simulations of the static detuning were carried out using CST MI-

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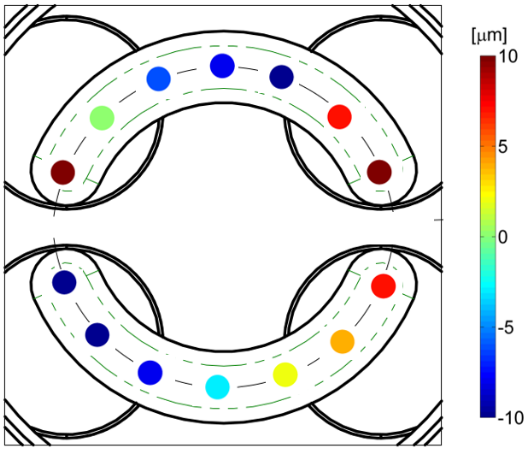
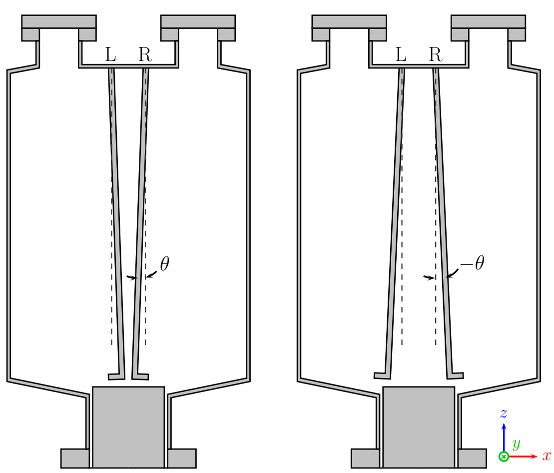


Figure 5: Parallelism of the pole shoes measured at Zanon Research & Innovation Srl. The deviations with respect to the nominal plane are within our tolerance values.

CROWAVE STUDIO® varying the angle of the right rod, both rods (Fig. 6), and both pole shoes. In the case of the bending of both rods, a spread of the quadrupole modes on the *f*-axis was observed. This phenomenon might explain the differences in the operational frequencies of the HZB QPR compared to our simulated values [17].



a) b)

Figure 6: 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) positive when the rods get closer and b) negative when the rods draw apart.

We observed that an exchange between the third quadrupole mode and the previous dipole mode happened for an angle deviation of 0.4° (Fig. 7).

COMMISSIONING OF THE QPR

The construction of the QPR was finalized in April at Zanon Research & Innovation Srl and 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 will be carried out at DESY. The following

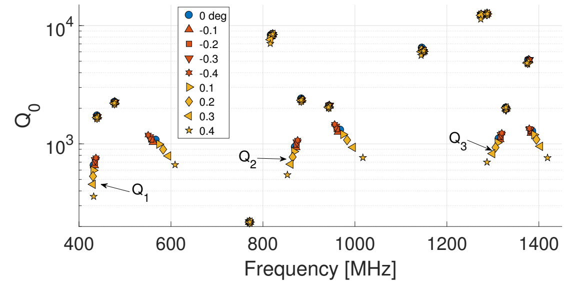


Figure 7: Quality factor vs. Frequency of the QPR at room temperature with a rotation of the rods around the *y*-axis with an angle θ between -0.4° and 0.4°.

tests are planned for the commissioning: 1) Wall thickness of the vessel and pole shoes (Ultrasonic measurements), which is an important preparation measure for the chemical surface treatment of the QPR (more about this below). 2) Bridge coordinate measurement, to check the parallelism of the QPR and the sample holder. 3) Spectrum of response to mechanical excitations. 4) RF spectrum and other properties.

Later, tests number two and four will be repeated after evacuating the QPR to check for deformations of the structure.

After the previous measurements, the QPR will undergo a standard surface treatment typical for Nb SRF cavities to ensure both high quality factors and high accelerating fields. The following surface treatment is going to take place at Zanon R. I.: *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 walls’ 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 [2].

CONCLUSION

The QPR at Hamburg Universität and DESY will allow for further studies of SRF properties of superconducting materials. 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.

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