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THE CHALLENGE TO MEASURE nΩ SURFACE RESISTANCE ON SRF SAMPLES

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Abstract

Systematic research on fundamental limits of superconducting materials for SRF applications and their intrinsic material properties relevant for use in an accelerator requires studies in a wide parameter space of temperature, RF field and frequency. The Quadrupole Resonator at HZB enables precision measurements on planar samples at temperatures of 1.8 K to >20 K, RF fields of up to 120 mT and frequencies of 420 MHz, 850 MHz and 1285 MHz. In the past years, the capabilities of the setup were studied intensively and developed further. Sources of systematic errors, such as microphonics or misalignment have been identified and eliminated. In this contribution the current status of the QPR and its systematic limitations are discussed.

INTRODUCTION

To explore the fundamental properties of superconducting materials for SRF technology, high precision surface resistance measurements are essential. For systematic studies, a wide and easily accessible parameter space of temperature, RF field strength and frequency is desired. The Quadrupole Resonator (QPR) based on a design from CERN [1] is a sample test cavity for planar circular samples providing measurement conditions that are practically not accessible with single-cell accelerating cavities. A schematic view with special attention to the sample chamber is given in Fig. 1.

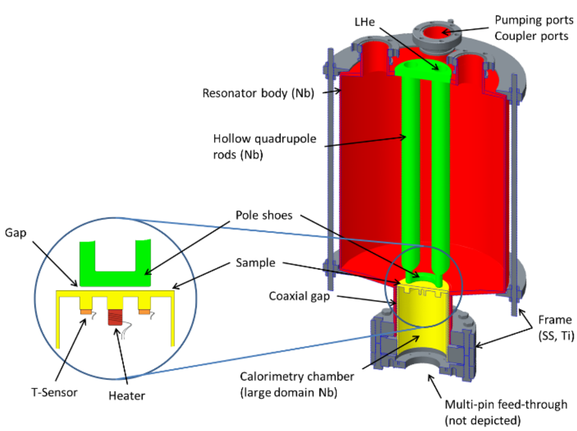

Figure 1: Schematic view of the QPR, taken from [2].

The calorimetry chamber (yellow) is mounted into the resonator as inner conductor of a coaxial structure. This design provides two important features:

a) Exponential damping of RF fields inside the coaxial gap when operated below cutoff frequency
b) Thermal decoupling of cavity and sample

The operating quadrupole modes have a cutoff frequency of about 2.5 GHz, hence only the upper planar surface of the inserted chamber depicts the actual RF sample. Four transmission lines (rods) are connected pairwise at short distance above the sample surface, focusing the RF magnetic field onto the sample. The length l of these rods defines the mode frequencies to be approx. $f = \frac{n \cdot c}{2l}$.

At the bottom of the sample diagnostics such as temperature sensors, heaters, coils and fluxgate probes are mounted. For detailed information on design and commissioning of the HZB QPR refer to [3, 4]. Stable sample temperatures of >20 K have been demonstrated, e.g. during a characterization of Nb_3Sn up to its critical temperature [5].

Surface Resistance Measurement

The RF surface resistance is measured via an RF-DC-compensation technique [6]. First, the sample is heated up to a temperature of interest $T > T_{\mathrm{bath}}$ by using only the DC heater. After recording the required heater power, the RF is switched on. The heater power is decreased by a PID controller such that the sample temperature stays constant. Assuming the surface resistance to be independent of RF field and constant on the sample, R_S is calculated from the difference in DC heater power according to

$$R_S = 2\mu_0^2 c_1 \frac{\Delta P_{\mathrm{DC}}}{B_{\mathrm{sample}}^2}. \tag{1}$$

c_1 denotes the ratio of peak over integrated magnetic field on the sample surface. It is derived from simulations and only slighty dependent on freqency. Using a numeric method, the result of Eq. (1) can be corrected to consider a field dependent surface resistance [7]. It is important to emphasize that the temperature of the liquid helium bath surrounding the QPR is kept constant at all times. This provides stable cavity conditions enabling CW measurements up to high RF fields – ultimately limited by the cavity quench field at 120 mT [4]. An exemplary measurement of $R_S(T)$ on a bulk niobium sample is shown in Fig. 2 for all three QPR modes and an RF field level of $B_{\mathrm{sample}} = 10$ mT. The unexpectedly high surface resistance measured at 1286 MHz is discussed in detail in a following section.

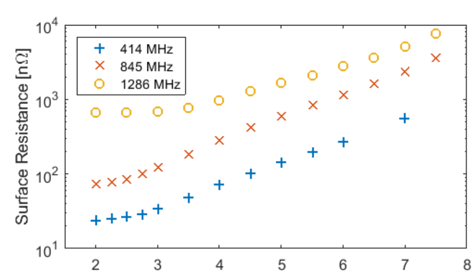

Figure 2: Surface resistance measurement on bulk niobium at all three QPR frequencies and $B_{RF} = 10$ mT.

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RESOLUTION AND FIELD LIMITS

The surface resistance is calculated from RF heating, compensated by a DC heater. The resolution limit is the minimum detectable difference in heater power at given values of temperature and field. Due to the exponential rise of surface resistance with temperature, this limit is physically most relevant at lowest temperature, i.e. close to the helium bath temperature. The pressure inside the cryostat is stabilized to ± 80 µbar, introducing temperature fluctuations of ± 1.4 mK. This limits the resolution to $R_{S,\,10\mathrm{mT}} = 0.35$ nΩ at an RF field of 10 mT, decreasing quadratically with field to $R_{S,\,120\mathrm{mT}} = 0.002$ nΩ at the quench limit of 120 mT.

The accuracy of the surface resistance measurement is dominated by the uncertainty in the RF measurement coming from cable calibration errors and power meter uncertainty. Except at very low field where heater and helium fluctuations play a role the surface resistance can be determined with an accuracy of 6.5 %.

Dependent on temperature a practical limit of useful RF fields for surface resistance measurements comes from RF heating of the sample. Since the RF-DC-compensation technique requires equilibrium states, RF heating has to be below the DC heater power at zero RF field. The achievable field and necessary pulse conditions therefore depend on the surface resistance itself. For details refer to [4].

PICKUP ANTENNA DEVELOPMENT

During operation a sudden decrease in measured R_S uncorrelated to any change of external parameters was sometimes observed, see Fig. 3. The DC heater power remained constant, pointing towards an error source in the RF measurement (see Eq. (1)). The QPR is equipped with two RF antennas, one overcoupled input antenna and a weakly coupled pickup probe. As forward and reflected power remained constant, the pickup antenna was identified as possible error source and studied in terms of multipacting and sensitivity to mechanical displacement. CST simulations showed no sign of multipacting at the field levels where R_S changes have been observed.

Given by the field configuration in the upper region of the QPR and the positioning of available vacuum ports,

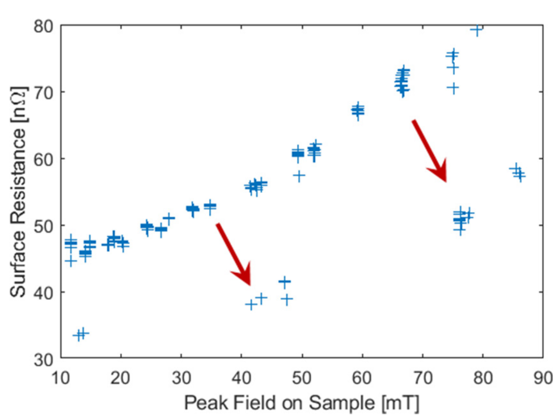

Figure 3: Surface resistance vs. RF field measured at 413 MHz and constant temperature of 3.5 K.

both couplers are loop-type. During commissioning two identical couplers were used (design "A" in Fig. 4), with the desired coupling adjusted by rotation. As shown in Fig. 5, the external quality factor Q_{ext} and hence the coupling is very sensitive to rotation at 87 deg, the design orientation of the pickup antenna. Regarding the "jumps" in Fig. 3, mechanical instability was identified to be likely the cause. Therefore, a dedicated pickup coupler ("B" in Fig. 4) has been designed. The previously difficult adjustment of rotation was especially critical at the third QPR mode (1285 MHz), since at higher frequency the coupling is stronger.

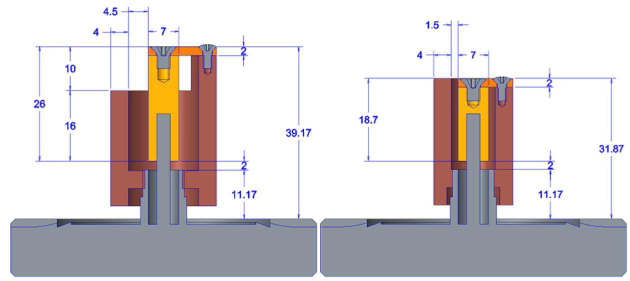

Figure 4: Sectional drawings of initial loop coupler A (left) and dedicated pickup coupler B (right).

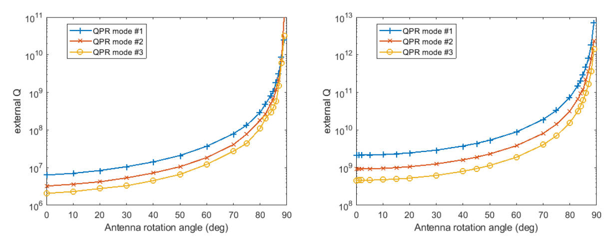

Figure 5: Q_{ext} of couplers A (left) and B (right) for all three QPR modes as a function of rotational angle.

OPERATION AT 1285 MHz

R_S measurements at the third QPR mode near 1285 MHz show unexpected behavior (see Figs. 2 and 6). First, the overall surface resistance seems too high compared to the other two modes and scales higher than quadratic as experimentally observed and theoretically predicted for the residual surface resistance [8, 9]. Second, looking in detail at data for $R_S(T)$ as shown in Fig. 6, the resistance rises when using pulsed RF at low temperatures.

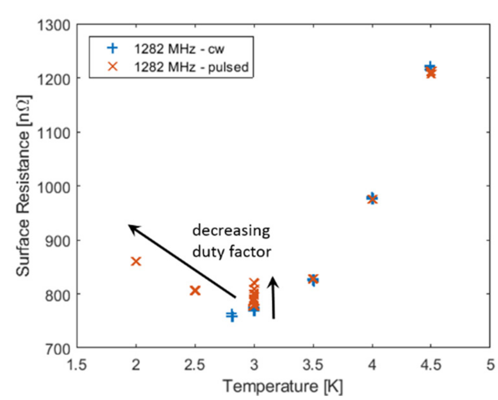

Figure 6: R_S data at 1282 MHz and 10 mT. At 3 K different duty factors are shown with rising R_S for lower DF.

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At 3 K the behavior of R_S vs. pulse duty factor was studied, yielding the lowest value for cw power and increasing systematically with decreasing duty factor (multiple data points at 3 K in Fig. 6). Referring to Eq. (1), three different classes of systematic errors resulting in too high R_S can be defined:

Calorimetry

Overestimating ΔP_{DC} leads to a too high value of R_S. Since temperature measurement and the heater control loop are both well separated from the RF system, a dependence of frequency can be excluded. Furthermore, the high surface resistance is indeed correlated to high ΔP_{DC} as expected, hence originating from RF heating of the sample.

Determination of B_{sample}

The RF field level inside the QPR is calculated from the power level measured at the pickup antenna and the corresponding coupling, very similar to cavity measurements. Measuring the critical field at different frequencies provides an independent cross-check of the RF field level. No suspicious behavior was observed, excluding a significant error of Q_{ext}.

RF Field Geometry

The calculation of the average surface resistance with Eq. (1) relies on the condition of dominant RF heating on the sample surface. Only in this case the simulation constant c_1 is valid. The sidewalls of the calorimetry chamber are made from niobium leading to a negligible contribution due to the reduced field level there. However, simulations of the coaxial structure yield significant heating at the bottom normal conducting flange. The non-negligible contribution of the quadrupole mode yields a bias of about 2.7 nΩ at 430 MHz [10].

During pulsed measurements at 1282 MHz simultaneous excitation of the neighboring dipole mode at 1287 MHz was observed (run#12 in Fig. 7). This can be triggered by dynamic Lorentz force detuning during the rise time of an RF pulse. Lorentz forces act on the quadrupole rods and lead to a bending or pendulum-like movement and corresponding microphonics. Assuming a slightly different behavior of the two pairs of rods leads to a geometrical deviation from the quadrupole symmetry. This deviation significantly increases the field penetrating the coaxial structure. A simulation of such asymmetric bending is shown in Fig. 8. For -0.4 deg of rotation the integral field at the end of the coaxial structure increases by a factor of 15, multiplying the RF losses with 225. This effect would be sufficient to scale the value of 2.7 nΩ expected at 433 MHz to about 1000 nΩ at 1.3 GHz.

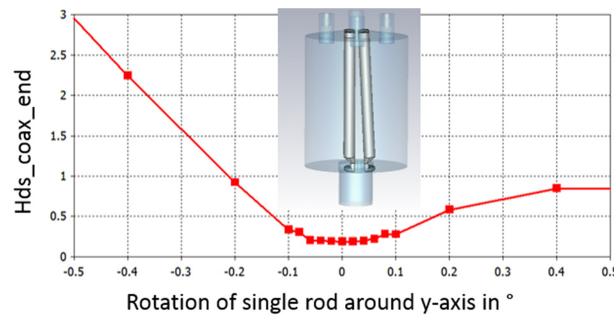

Figure 8: Simulation of the integral field at the lower end of the coaxial structure vs. bending angle of a pair of rods.

CONCLUSION

After successful commissioning, the QPR is now operational at its fundamental frequency of 420 MHz and two higher harmonics at 850 MHz and 1285 MHz. Resolution of sub-nΩ in surface resistance measurement has been demonstrated.

The high measured values of surface resistance especially at 1285 MHz point towards significant RF losses at the normal conducting bottom flange of the coaxial structure. In order to reduce those losses, copper and niobium coatings of the flange as well as using a bulk superconducting flange of NbTi will be employed in future tests.

For further design optimization for future devices, we advise to consider mode separation of quadrupole and cavity modes and to reduce the impact of broken symmetries.

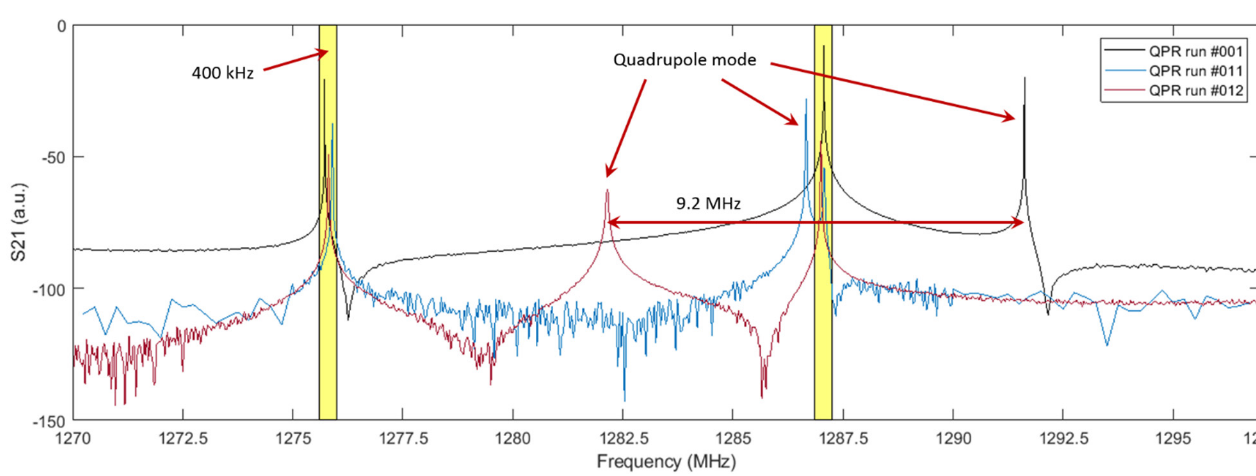

Figure 7: RF mode scans for three meas. runs with different samples. The resonant frequency of the third QPR mode changes by up to 9.2 MHz while the neighboring "cavity" modes stay within 400 kHz (span of highlighted areas).

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