Development of an Optimized Quadrupole Resonator at HZB

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Abstract

Current superconducting cavities are generally made of solid Niobium. A possibility to reduce cost as well as increase the quality factor and/or accelerating fields is to use thin film coated cavities. Apart from Niobium thin films, other substances such as Magnesium diboride, Niobium nitride and Niobium-tin are promising candidates. Measuring the RF-properties of superconducting thin films, specifically the surface resistance, with a high resolution at frequencies, magnetic field levels and operating temperature as realized in RF cavities, is needed to drive forward this development. Presently, only few setups exist capable of measuring the surface resistance of thin films samples with a resolution in the nano-ohm range at RF frequencies below 3 GHz. A dedicated test stand consisting of a quadrupole resonator is therefore being constructed at the Helmholtz Zentrum Berlin. Starting with the 400 MHz quadrupole resonator developed by CERN, the design was adapted and optimized to 433 MHz (making available the higher harmonic mode at 1.3 GHz for RF characterization of samples in the L-band) using simulation data obtained with CST Microwave Studio. A number of relevant figures of merit have been improved to provide a higher resolution, a lower peak electric field and less sensitivity to microphonics, enabling measurements with high resolution at high magnetic field levels.

INTRODUCTION

A method of measuring the surface resistance of samples uses a Quadrupole Resonator, pioneered at CERN in the late 1990's [1]. It consists of a pillbox-like niobium cavity which acts as a screening cylinder. Four rods are supported from the top-plate of the cavity and are short circuited pairwise by two loops just above the bottom plate. As can be seen in figure 1, the screening cylinder has a opening below the two loops from which the calorimetry chamber is mounted, thermally isolated from the screening cavity. Thus the RF power dissipation in the sample can be measured calorimetrically, which is far more accurate than that by RF power measurements. When RF power is coupled into the resonator, the magnetic fields focused onto the sample cause power dissapation which is measured by temperature probes inside the calorimetry chamber. A compensation heater attached to the bottom of the sample is powered such that the sample temperature remains constant when RF is turned on, yielding a very accurate means of determining the dissipated power. The coaxial gap between the calorimetry chamber and the screening cylinder is small enough that the first quadrupole (and dipole) modes are below the cutoff frequency. This means that the electromagnetic fields decay exponentially in this gap and are sufficiently small at the lower flange that they do not interfere with the dissipation measurement. The quadrupole resonator gets its name from the fact that it is a screened four wire transmission line, excited in a quadrupole mode.

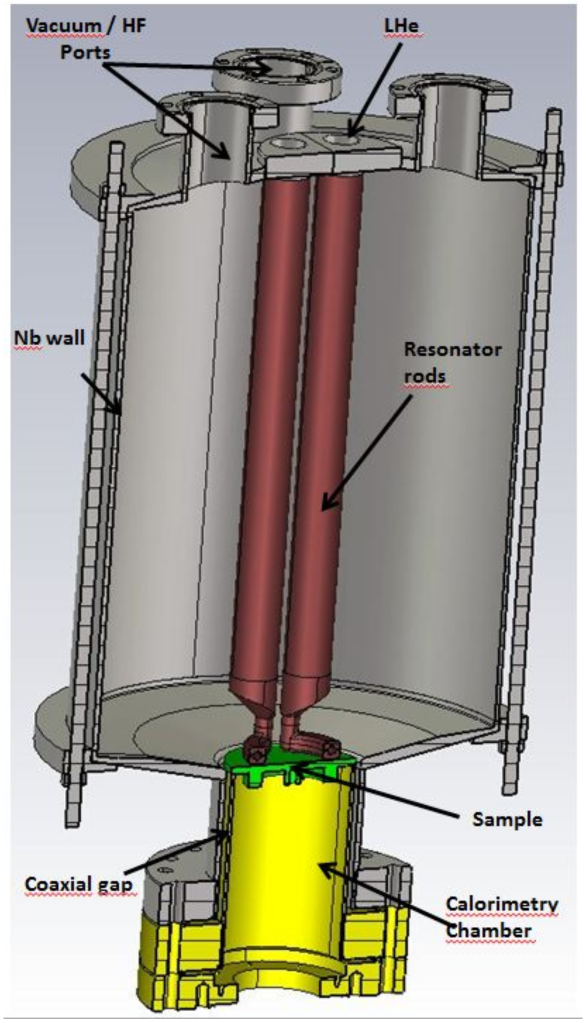

Figure 1: Cross section view of the quadrupole resonator. The screening cylinder is coloured in grey. It is isolated thermally from the calorimetry chamber (yellow) by a coaxial gap of $1\,\mathrm{mm}$. The sample, coloured in green, is welded on to the top of the chamber. The rods (red), connected by two crescent shaped loops, focus the magnetic fields on to the sample

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OPTIMIZING THE QUADRUPOLE RESONATOR

Using as a baseline the design of the Quadrupole Resonator at CERN we set out to create a new version of the Quadrupole Resonator for use at HZB. The target frequency of the first quadrupole mode was changed to 433 MHz. The third harmonic can then be used to measure the sample properties at 1,3 GHz, a frequency commonly used in superconducting accelerators.

The resolution with which the surface resistance of a sample can be measured is given by:

$$\Delta R_S = \frac{2\Delta P_{DC}}{\int_{Sample} \mid H \mid^2 dA} \tag{1}$$

where ΔP_{DC} is the minimal detectable heating resolvable by the temperature controller. [1] CST can be used to calculate the electromagnetic fields of the resonant eigenmodes. It normalizes the fields to a mode energy U of 1 J and can thus be used to calculate:

$$c = \frac{\int_{Sample} \mid H \mid^2 dA}{U} \tag{2}$$

A high value of c means that the magnetic fields in the resonator are concentrated strongly on the sample and thus increase the resolution of the measurement.

Apart from measuring with a high resolution, measuring at high field levels on the sample is also very interesting for future research. For example, current CW accelerator apllications require acceelerating fields of order $20\,\mathrm{MV/m}$ which translates to peak magnetic fields of around $85\,\mathrm{mT}$. To characterize new materials, the RF measurements should at least reach such field levels. The level of fields attainable in the resonator can be limited by:

- Thermal Quench, related to the peak magnetic surface field.
- Field Emission, related to the peak electric surface field.
- Multipacting, in which resonant electron trajectories cause the emission of large numbers of electrons.
- Mechanical oscillations (microphonics) causing the RF control system to lose its lock on the resonance frequency.

Experience at CERN has shown that more than one of these issues can limit the performance of the Quadrupole Resonator.[2] It is suspected that field emission or multipacting are the likely candidates causing the cavity to quench at a peak magnetic field of 60 mT on the sample surface. Mechanical oscillations of the quadrupole rods have been a strong concern when the cavity was operated at higher harmonics of 800 and 1200 MHz.

This leaves us with several figures of merit for the optimization:

- Maximizing the focusing factor c for high resolution
- H_{Sample}/E_{Pk}, where H_{Sample} is the peak magnetic field on the sample surface and E_{pk} is the peak electric field on any surface within the resonator. Ideally this value should be high to limit field emission.
- H_{Sample}/H_{pk}, where H_{pk} is the magnetic field on any surface within the resonator. Ideally this value should be high to limit the danger of quenches.
- An ideal design also takes into considerating multipacting as well as reduces the impact of microphonics by shifting mechanical resonances to high frequencies.
- Attention must also be given to the heating caused by fields leaking into the coaxial gap separating the resonator and the calorimetry chamber. It was decided that the ratio of power dissipating on the sample to power dissipating through the side of the calorimetry chamber was to stay below 1%, resulting in a negligable influence of this heating on the actual measurement.

RF Optimization

For the optimization, a fully parameterised model of the quadruople resonator was created, starting with the CERN geometry with shortened rods (to adjust for the new target frequency). In the first step, a suitable meshing needed to be found. As the field distributions of the quadrupole modes are shaped by the geometry of the rods, this was reflected in the mesh as well. A particularly fine mesh was selected for the gap between the loop and the sample surface. Next the mesh density was increased, noting the influence of the mesh on the figures of merit. With a suitably diverse meshing, the variations in the figures of merit stayed below 5% when 2.5 million cells or more were used.

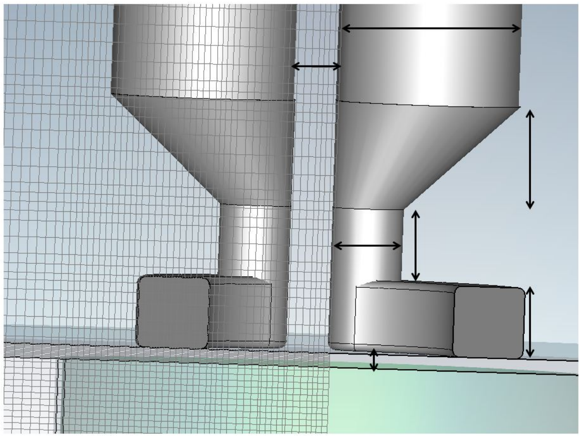

Figure 2: Parameterized model of the quadrupole resonator with typical meshing

With confidence in the meshing established, the next step was to perform a scan over all the free parameters and assess their influence on the figures of merit. Two examples of this can be seen in figures 3 and 4. One can see that the gap width between the loops and the sample have a large

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[1] A description of the calorimetric measurement system deployed can be found in [3]

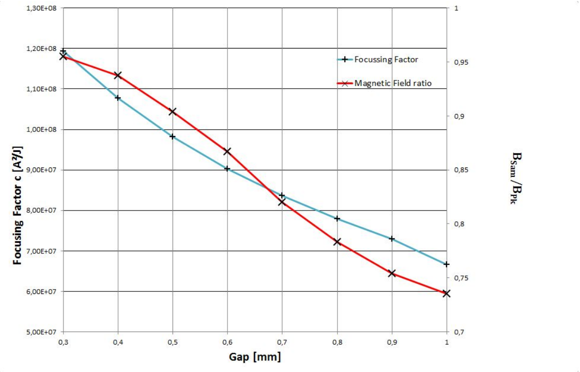

Figure 3: Focussing factor and ratio of magnetic field on sample to peak magnetic field plotted against gap width.

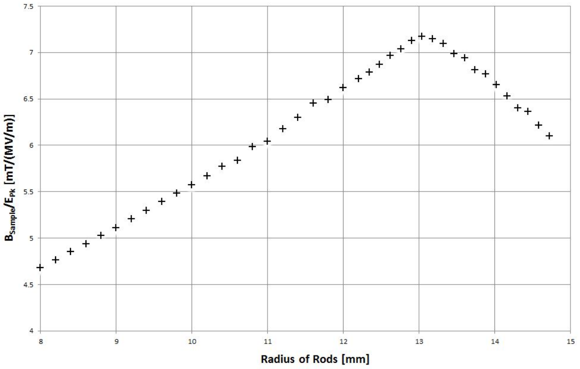

Figure 4: B_{Sample}/E_{Pk} plotted against radius of rods The maximum occurs due to the reduced peak electric fields on the rods, the magnetic fields on the sample only being influenced slightly.

effect on the magnetic fields concentrated on to the sample (i.e on the focusing factor c). The resonant frequency of the quadrupole mode also depends strongly on the the gap ($\sim 1\,\mathrm{MHz}/100\mu m$). This is a nice tool to enable a precise determination of the gap when actually mounting a sample.

The radius of the rods also had a strong effect, particularly on the peak electric field. Increasing the radius at first reduces the peak electric fields as the field lines running between the rods are diluted across a larger surface. A further increase will cause the rods to be in close proximity and thus increase the peak electric field. A minimum was found at a radius of $13\,\mathrm{mm}$. Compared to the rods of the CERN design (with a radius of 8mm), this is a considerable increase, additionally improving both the cooling through the liquid helium channels in the rods as well as the mechanical stiffness, which, in turn, improves the microphonics.

Other parameters such as the transitional elements between the the thick upper rods and the narrower loops were shown to have little influence on the figures of merit. These parameters were used later on for frequency tuning, as the power amplifiers and RF components for $433\,\mathrm{MHz}$ and $1300\,\mathrm{MHz}$ system had already been acquired.

Once the effects of all the free parameters were understood, an iterative process was used to find an optimized geometry.

Results of RF Optimization

The result of the optimization is displayed in the table below:

	Baseline	Optimized
c	$5.15 \cdot 10^7$	$1.12 \cdot 10^8$
B_{Sample}/E_{Pk}	$4.68\,\mathrm{mT/(MV/m)}$	$7.44\,\mathrm{mT/(MV/m)}$
B_{Sample}/B_{Pk}	0.81	0.89
1st mechanical mode	69 Hz	172 Hz

One can see, that in the modified design the peak electric fields are strongly reduced and that the magnetic fields are concentrated on to the sample more efficiently. The peak magnetic field occurs on the rods in both cases, a more favorable ratio was obtained by decreasing the distance between the loops and the sample from $1\,\mathrm{mm}$ to $0.5\,\mathrm{mm}$. The peak electric fields on the rods are also significantly lower in the HZB design, due mainly to the increase of the rod radius. The thicker rods also have the additional benefit of being less susceptiable to mechanical vibrations, the resonance frequency of the lowest mechanical mode being increased from $69\,\mathrm{Hz}$ to $172\,\mathrm{Hz}$.

CONCLUSION AND OUTLOOK

Following the RF optimization, we are now in the process of producing the cavity together with Niowave. Some additional modifications regarding the screening cylinder and the support fixtures were incorporated into the design. Construction is currently in an advanced state, we hope to present first measurement results in Spring 2014.

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