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HIGH-PRECISION MEASUREMENTS OF THE QUALITY FACTOR OF SUPERCONDUCTING CAVITIES AT THE FREIA LABORATORY

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Abstract

The dependence of cavity quality factor Q_0 on accelerating gradient gives insight into the intrinsic limit of RF surface impedance that determines the cavity performance. In this paper we propose a high-precision method of measuring Q_0 of SRF cavities. A common way to study the performance of an SRF cavity is to build an oscillator around it that is referred to as a self-excited loop. In the standard approach, by tuning the loop phase for a maximum field level in the cavity and measuring forward and reflected waves, one finds the cavity coupling. Then, performing a time-decay measurement and finding the total quality factor, one gets Q_0. However, this approach suffers from a deficiency originating from a single data-point measurement of the reflection coefficient. In our method by varying the loop phase shift, one obtains amplitudes of the reflection coefficient of the cavity as a function of its phases. The complex reflection coefficient describes a perfect circle in polar coordinates. Fitting the overdetermined set of data to that circle allows more accurate calculation of Q_0 via the least-squares procedure. The method has been tested at the FREIA Laboratory [1] on two cavities from IPN Orsay: a single spoke and a prototype ESS double spoke.

INTRODUCTION

The quality of accelerated beams and overall efficiency of a superconducting (SC) linear accelerator depend on the performance of SC cavities and an extensive research and development program on the cavities has been undertaken during last decades. However, some aspects of the physics of SC RF cavities remain unclear and even controversial such as the so-called low-field Q-slope [2]. According to the classical BCS theory, the cavity quality factor, Q_0, is a monotonically decreasing function of the field created in the cavity whereas experimental observations strongly indicate that in the low-field region between a few mT and a few tens of mT, Q_0 increases as the field is raised, see [2] and references herein. A recent field-dependent model [3] of the RF surface impedance based of Mattis-Bardeen theory suggests that the positive low-field Q slope continues up to 100 mT. That has an important implication on the intrinsic limit of RF surface impedance that determines the performance of SC RF cavities.

Accurate measurements of intrinsic cavity characteristics such as the quality factor are indispensable for facilitation of understanding of the physics of SC RF cavities and the low-field Q-slope effect, in particular. In this paper we propose a high-precision method of measuring Q_0 of SC RF cavities. The method can also be used at accelerator test facilities for studying the cavity performance needed to ensure the proper dynamics of accelerated beams. Measurements of the pressure sensitivity, Lorentz force detuning and microphonics are presented in the conference proceedings, TUPB083.

There is a number of accurate methods of measuring Q_0 developed for normal conducting cavities [4–9]. However, these methods fail to work for SC cavities because of their ultra-narrow bandwidth, which is in the order of a Hz or even less, and large variations of the cavity frequency on a time scale required for measurements. The cavity walls are made thin for good heat transfer so that fluctuations in pressure of helium – the cavity is immersed to – can detune the cavity by many times of the cavity bandwidth.

A common way to circumvent the problem is to build an oscillator around the cavity that is referred to as a self-oscillating loop [10]. The loop tracks the cavity frequency and the field excited remains constant in time provided that the system reached a steady-state equilibrium. By tuning the loop phase for a maximum field level in the cavity and measuring forward and reflected waves, one finds the cavity coupling [11]. Then, performing a time-decay measurement [12] and finding the total quality factor, we can find Q_0. However, this approach suffers from a deficiency originating from a single data point measurement of the reflection coefficient. Here, we propose an extension of a high-precision method developed for normal conducting cavities to SC counterparts. By varying the loop phase, one obtains amplitudes of the reflection coefficient as a function of its phases. This overdetermined set of data allows more accurate calculation of the cavity coupling coefficient via the uncertainty minimization procedure.

THE CAVITY MODEL

An electromagnetic (EM) field of a closed metallic cavity is represented by a set of TE and TM eigenmodes corresponding to different spatial field distributions and being solutions to the source-free Maxwell equations. Each eigenmode is characterised by a quality-factor, Q_0, and a frequency of temporal oscillations, ω_c. In the presence of a source, the general solution for a field excited in the cavity can be represented as an expansion over the eigenmodes with unknown *scalar* field amplitudes [13]. If the modes are not degenerated, then the amplitudes in question evolve in time according to the second-order differential equation of the oscillator-type. The effective excitation source (driving force) in this equation is given by the overlap integral of the spatial distributions of a physical excitation source, for example, such as an antenna and the eigenmode. The over-

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lap integral is proportional to the strength of the excitation source and to the cavity coupling to the outside world. In what follows, the excitation source is referred to as a coupler. The coupler is usually a reciprocal element and characterised by the external quality factor, Q_{ext}, that is a figure-of-merit of energy losses by a cavity to the outside world in one cycle. It is also advantageous to describe the amplitude of a TM eigenmode – used for particle acceleration – in terms of a voltage, V, seen by a test charged particle traversing the cavity. Then, the equation for the voltage reads [14]

$$\ddot{V} + \frac{\omega_c}{Q_L}\dot{V} + \omega_c^2 V = \omega_c \frac{R_{sh}}{Q_L}\dot{I}, \tag{1}$$

where $Q_L = (Q_0^{-1} + Q_{ext}^{-1})^{-1}$ is the total quality factor, R_{sh} is the surface resistance and $I(t)$ is the excitation current. One must distinguish between the loaded Q_L and intrinsic Q_0 quality factors, and it is the latter that is of interest for characterisation of the RF surface impedance of SRF cavities. In general, Q_0 is a function of the cavity voltage.

An EM wave not only enters the cavity through the coupler but also leaks out through it forming a reflected wave. The reflection coefficient defined as the ratio of the reflected voltage to the incident one reads:

$$\Gamma = \frac{\kappa - 1 - iQ_0\Delta}{\kappa + 1 + iQ_0\Delta}, \tag{2}$$

where $\kappa = Q_0/Q_{\text{ext}}$ is the coupling coefficient and

$$\Delta = \frac{\omega}{\omega_c} - \frac{\omega_c}{\omega} \tag{3}$$

is the relative detuning of the excitation signal frequency, ω, with respect to the cavity resonant frequency. The complex reflection coefficient describes a perfect circle in polar coordinates as a function of detuning, as it is demonstrated in Fig. 1. This observation is the base for one of the most efficient methods of finding Q_0 and κ, [9]. In our approach we use a modified version of the method [9], so it is useful to recall briefly this method.

The measurement data of complex reflection coefficient Γ are fitted to the ideal Q circle specified by a Möbious transformation

$$\Gamma = \frac{a_1 t + a_2}{a_3 t + 1}, \tag{4}$$

where a normalized frequency variable reads $t = 2(\omega - \omega_c)/\omega_c$. The cavity parameters can be deduced as follows:

$$Q_L = \text{Im}(a_3), \quad \kappa = \frac{1}{2/d - 1}, \quad Q_0 = Q_L(1 + \kappa), \tag{5}$$

where d is the Q circle diameter given by

$$d = \left| a_2 - \frac{a_1}{a_3} \right|. \tag{6}$$

A measurement of Γ as a function of ω yields an overdetermined set of data, which allows to improve greatly the accuracy compared to a three points measurement [5] by making use of a least-squares fit to find the mean and variance of the cavity parameters. However, a direct extension of this method to SC cavities fails to work because fluctuations in time of the SC cavity frequency are as large as the cavity bandwidth so that the cavity becomes out of tune during the measurement. The cavity has to be operated in the self-excited loop enabling tracking of the cavity frequency.

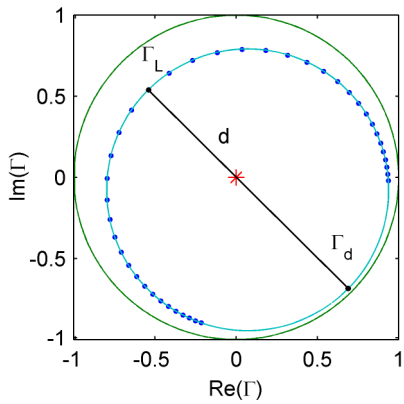

Figure 1: Typical dependence of the measured complex reflection coefficient Γ as a function of frequency ω for an ideal cavity.

SELF-EXCITED LOOP

A typical self-excited loop [10] shown in Fig. 2 includes an amplifier with a limiter, an attenuator, a phase shifter and the cavity itself. If the amplifier gain is greater than the overall losses in the rest of the loop, then any EM fluctuation gets amplified. In practice, a signal in the loop starts to grow from electrical noise of the amplifier but due to the resonant nature of the cavity the signal becomes quasi-monochromatic. The signal central frequency is determined by the condition of the round-trip phase shift being equal to a multiple of 2π, which can be recognised as a condition of constructive interference, and reads

$$\theta_c(\omega) + \theta_l(\omega) = 2\pi n. \tag{7}$$

Here, $\theta_c(\omega)$ and $\theta_l(\omega)$ are the phase shifts across the cavity and rest of the loop, respectively; n is integer and it is sufficient to consider $n = 0$.

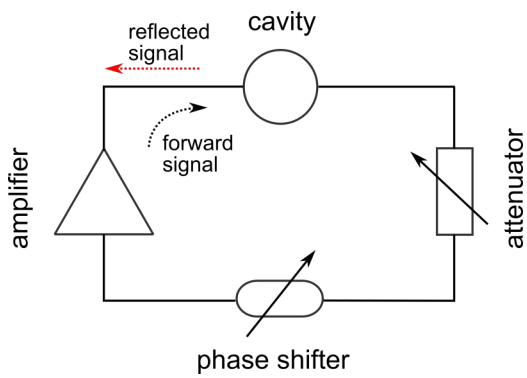

Figure 2: Schematic of the self-excited loop.

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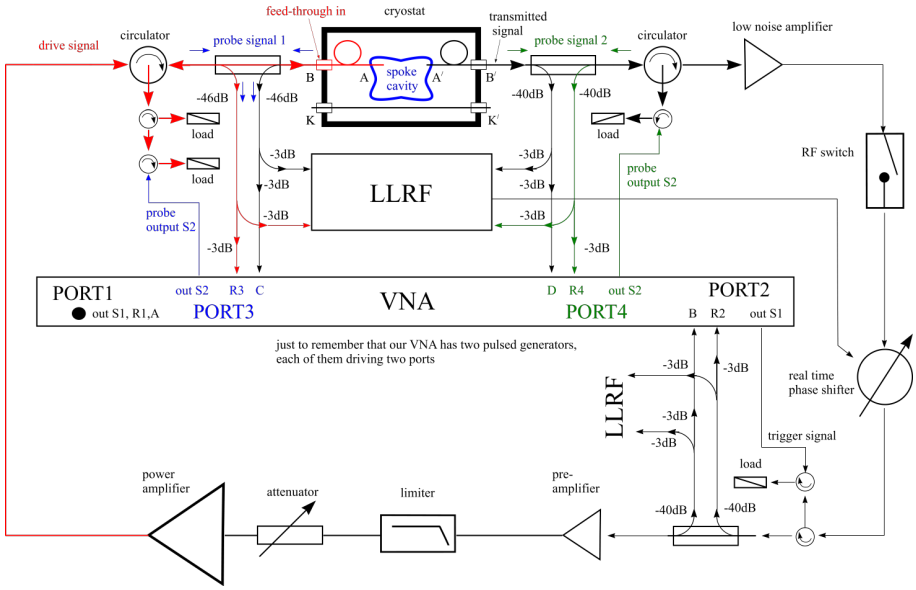

Figure 3: A schematic of the experimental setup for measuring the cavity S-parameters.

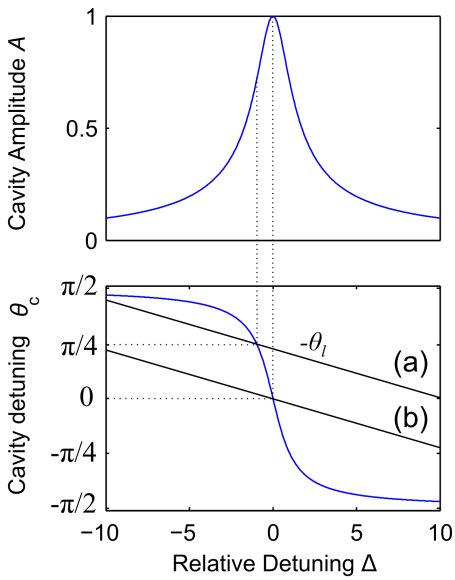

Figure 4: Operation of the cavity in the self-excited loop.

The graphical solution to Eq. (7) is shown in Fig. 4, where $\theta_l(\omega)$ is approximated by a straight line since it is dominated by the phase shift across the cables connecting the self-excited loop components and the cavity located in a cryomodule. When the phase shift across the loop $\theta_l(\omega)$ is equal to zero, the loop oscillates at the cavity central frequency $\omega_l = \omega_c$. That situation corresponds to the case (b) shown in Fig. 4. In the general case, the loop frequency is different from the cavity frequency, the case (a) in Fig. 4.

In the traditional approach of measuring the Q_0-circle, the frequency f of an input signal is swept over the cavity bandwidth and this gives the reflection coefficient as a function of f. However, in the self-excited loop, the frequency of oscillations is determined by the loop and we have no direct control of it. Instead, for given fixed input power to the cavity, we sweep the phase shift across the loop and that changes the frequency of the system. By sweeping the phase from $-\pi/2$ to $\pi/2$ around the cavity resonance, we can measure the amplitude of the reflection coefficient as a function of phase and find the Q_0-circle. However, for SC cavities, a measured Q_0-circle will be deformed because the cavity field changes during the phase sweep and so does cavity Q_0 because of the Q_0-slope. We will show how to deal with this deformation below, on the specific measured data.

THE SETUP AND RESULTS OF MEASUREMENTS

The schematic of our measurement setup is shown in Fig. 3. We use a Vector Network Analyser (VNA) as a calibrated heterodyne receiver to measure directly the cavity S-parameters, forward, reflected and transmitted signals. We first implemented the port extension technique, in which the VNA calibration plane is moved to external couplers (to the left and right w.r.t. to the cryostat in Fig. 3), then we applied de-embedding [15] of the cables connecting the extended VNA ports to the cavity. To this end, we installed in the cryostat an additional pair of back-to-back connected cables (KK' in Fig. 3) identical to the pair of cables connecting the cavity to RF feed-throughs (BA and A'B' in Fig. 3). Then, we connected the VNA extended VNA ports through this pair of cables and measured the S-matrix. Since, the cable connection is symmetrical, we can find the S-matrix of each chain of cables and de-embed them. Practically, we calibrated out the impedance of all cables connecting the extended VNA ports to the cavity so that we get directly true values of forward, reflected and transmitted signals, both magnitudes and phases.

In order to obtain the Q-circle, for fixed forward power to the cavity, we changed step-by-step the phase shift across

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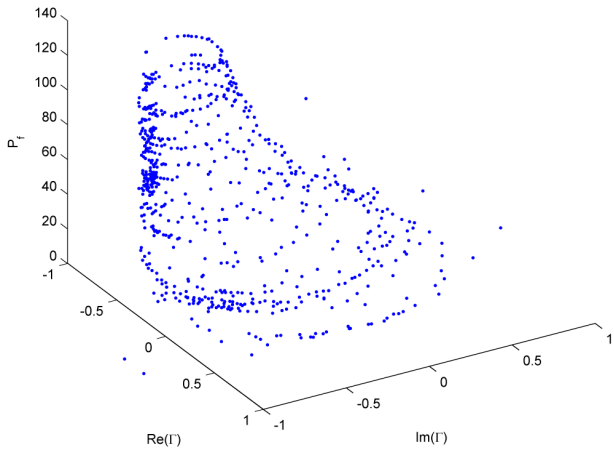

Figure 5: The cavity reflection coefficient as a function forward power for different phase shifts across the cavity.

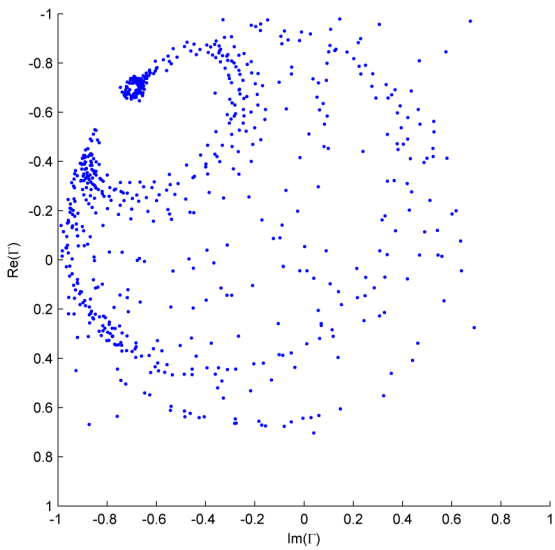

Figure 6: Projection of the cavity reflection coefficient on a 2D plane.

the cavity by tuning the phase shifter installed in the loop. This procedure is performed for each power level of interest, yielding the complex reflection coefficient of the cavity as a function of forward power and phase shift across the cavity. The raw data are shown in Fig. 5 as a 3D plot, and the projection of the reflection coefficient on a 2D plane is depicted in Fig. 6. One can see that at high power level, the Q-circles are deformed because as we sweep the phase, the cavity voltage changes and that results in change of the cavity quality-factor. By the moment of writing this paper, the data analysis was not finished because the cavity testing was delayed but the measured data look good and we will apply a nonlinear least-squares fit to find the cavity Q-slope.

SUMMARY

Using the self-excited loop and VNA as a calibrated heterodyne receiver, we measured the cavity reflection coefficient as a function of forward power for different phase shifts across the cavity. This overdetermined set of data allows more accurate calculation of the cavity coupling coefficient via the uncertainty minimization procedure.

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