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Calibration procedure for RF test

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Abstract

Precision measurements of quality factors of superconducting resonators are desired in the determination of ESS superconducting cavities. Components of the measurement setup, such as interconnecting cables and adapters, introduce variations in magnitude and phase that can mask the actual response of the device under test. In order to have an accurate measurement, calibration becomes the first and most important step. FREIA has developed a test stand based on a self-exited loop for demonstrating the performance of superconducting cavities at low power level. So far, a single spoke cavity Hélène and a double spoke cavity Germaine from IPNO have undergone a cold test with FREIA SEL. Several calibration procedures are studied in these tests. Similar test results as IPNO's previous test were obtained with the FREIA system, which means the accuracy control fulfills the requirements.

This report presents the calibration procedure of the FREIA SEL test.

Table of Contents

1. Introduction 4

2. SEL test stand 4

3. Calibration procedure 5

3.1 Using VNA de-embedding 6

3.2 Traditional calibration 7

Reference 9

1. Introduction

Precision measurements of quality factors of superconducting resonators are desired in the determination of accelerator facilities. At several-kelvin temperatures, the quality factor is generally determined by measuring and fitting the transmission data over the relatively narrow bandwidth defined by the response of a resonator. Components of the measurement setup, such as interconnecting cables and adapters, introduce variations in magnitude and phase that can mask the actual response of the device under test. The accuracy of the calibrated measurements is dependent on the quality of the standards in the calibration kit and how accurately the procedures are performed. One can choose from different calibration types, depending on the measurement and the level of required accuracy.

The FREIA laboratory (Facility for Research Instrumentation and Accelerator Development) is developing the RF system for ESS superconducting spoke cavities. Since 2015, FREIA develops a test stand based on a self-exited loop for demonstrating the performance of superconducting cavity at low power level. A single spoke cavity Hélène and a double spoke cavity Germaine from IPNO have undergone a cold test with FREIA SEL. Several calibration procedures are studied in these tests. Similar test results as IPNO's previous test were obtained with the FREIA system, which means the accuracy control fulfills the requirements [1,2].

2. SEL test stand

The first SEL developed at FREIA is shown in Figure 2. In the loop, the cavity is a narrowband filter and starts from noise to oscillate by itself. In this way, the cavity field amplitude is unaffected by the ponderomotive instability and there is no need for an external frequency source and tracking feedback. Therefore, the self-excited loop is ideally suited for high gradient, high-Q cavities operated in CW mode [3].

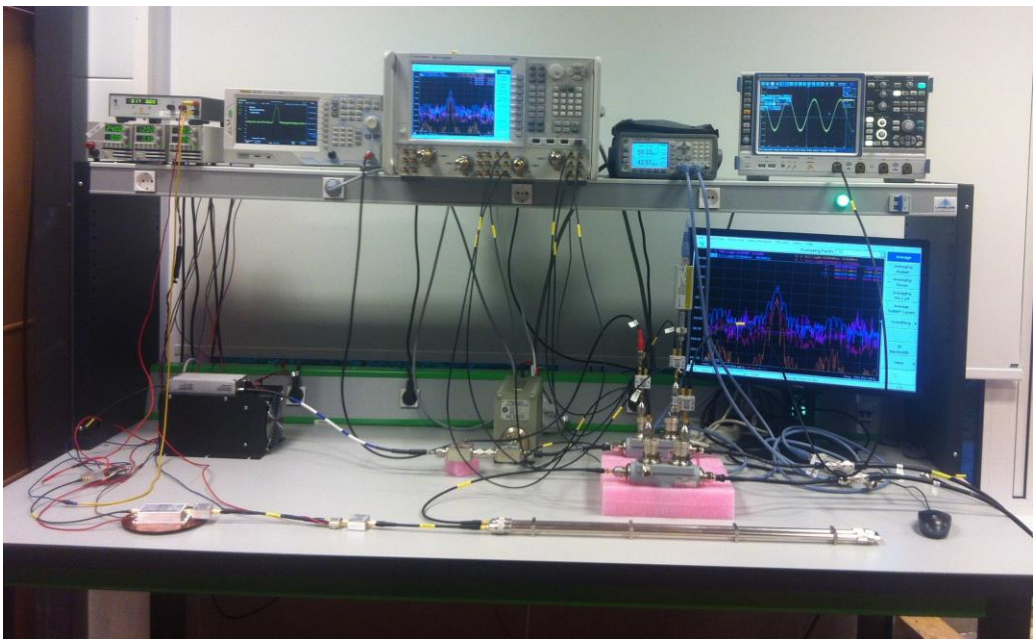

Figure 1 SEL setup at FREIA

We use a vector network analyzer (VNA) as receivers when running the SEL. To protect the system from radiation, the cavity is away from the control and measure system. The function of the VNA in this loop is double fold: it provides a convenient cable calibration and can also be used as receivers in the measurement. This way of using the VNA gives us both true power and phase information of signals even beyond the equipment limits. We also developed a digital phase shifter and gain-controller, based on NI FlexRIO FPGA and NI 5782R data acquisition modules. With this digital system, we can vary the loop delay with high-precision, from that we obtain the reflection coefficient as a function of loop delay.

So far, some key parameters of SEL at FREIA are listed below:

- The maximum power around 100 W by using one commercial amplifier, up to 1 KW by one 352 MHz single ended demonstrator amplifier module ;
- The maximum gain of the loop can reach 120 dB ;
- 40 dB variable attenuation range depending on control voltage;
- 270 degree delay by a trombone phase shifter;
- High-precision loop delay and loop gain control can be obtained by a digital phase.

3. Calibration procedure

Two methods, with both a power meter and a VNA, are used to cross check the accuracy of the measurement. During all these measurements, two cavities are set inside the new HNOSS horizontal cryostat system at the same time [4]. Six identical cryo-cables are installed inside the cryostat, four connect to cavities ports and cryostat flange separately, while the other extra two cables connect back to back with a through as reference. Corresponding to different method, two calibration procedures are presented. The block diagram of FREIA SEL is shown in Figure 2.

Considering of the attenuation of cables, especially cryo-cables, highly depends on the operating temperature, all calibrations should be done when the cavity is fully cooled down.

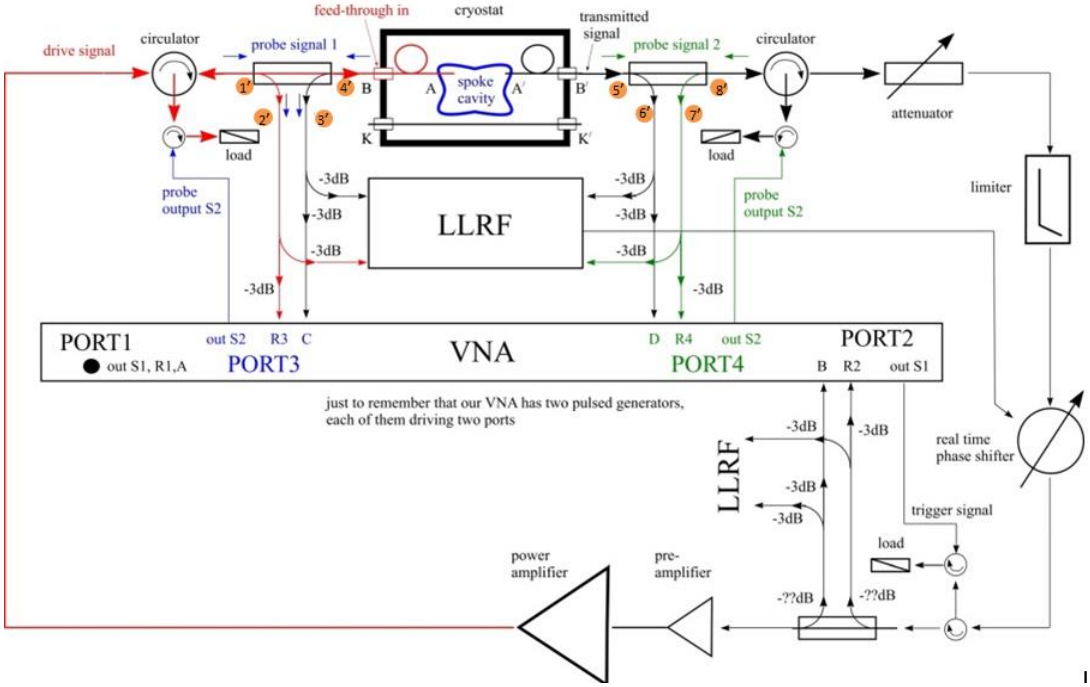

Figure 2: Block diagram of FREIA SEL

3.1 Using VNA de-embedding

In this way, we use a VNA to perform a convenient cable calibration and true power measurement. This way of using the VNA gives us both true power and phase information of each signal.

1) Check all the components, in instance, circulator, amplifier, directional coupler and VNA works well separately and connect them together as Figure 2.
   Here, the front panel ports of VNA will be used. The reference signal (R3) and measured signal (C) of port 3 of VNA should connect with forward directional coupler port 2' and 3', while port R4 and D connect with the port 7' and 6' separately. Actually, our VNA has two build-in generators, each of them drives two ports. In order to avoid an unexpected cross-couple, it is better to choose ports without sharing a same local source, like port 2 and 3.
   - Note that all VNA RF outputs should connect into the loop with a circulator and a load in order to protect from high level reflection.
   - Make sure all ports in the loop have been terminated by 50 Ω, especially when connect to the scope.
2) Run the SEL to find the resonant frequency.
3) Setting VNA parameters.
   - Set center frequency as the cavity resonant frequency.
   - Set 20 kHz to frequency span.
   - Set 100Hz to IF bandwidth.
   - Set the average number of 10 with ***point average*** option.
4) Power calibration procedure on VNA.
   - Calibrate the power meter.
     - ✓ Set 352MHz as a RF measured frequency of power meter Chanel A.
     - ✓ Choose ***Zeroing and calibration*** from the menu on the power meter to calibrate the power sensor at 0 dBm.
     - ✓ Note that the power meter should connect VNA with a GPIB cable.
   - Follow the guide on the VNA ***Calibation -- Cal wizard -- Use ECal -- two ports calibration*** and chose the corresponding ports of VNA **--** activate ***Source and receiver calibration.***
   - Connect power sensor to the output of forward directional coupler (port 4'). Here, take the port 4' as the first reference plane.
   - Carry out ***source and receiver calibration*** at this reference plane.
5) Two ports S parameter calibration on VNA.
   - Connect the electronic calibration kit to the VNA, wait until the light of Kit turns green, which means it is ready to work.
   - Disconnect power sensor and connect the electronic calibration kit with port 4' and port 5'.
   - Klick ***Continue*** to move on the two ports S parameter calibration by VNA.
6) De-embedding.
   - Connect cables to reference cables inside the cryostat at ports K and K'.
   - Get S parameters of the cable-cable system and save a sP2-type file with the data.

- Run Harald's code ***cablehalver*** in MATLAB and select that sP2-file when asked by the code. Calculate the effect of each cable separately by transfer-matrices (T-matrices), then convert T-matrices to S-matrices [5]. Save the output data file on the VNA in the same folder where the first sP2-file was taken from.

The chosen of T-matrices is driven by its connection with "input and output", which could be much easier to figure out the single effect of cable system. S-matrices could be obtained from equations (3.1) and (3.2).

$$T_{tot} = T_1 T_2 = T_2 \rightarrow T_{cable} = \sqrt{T} \tag{3.1}$$

$$\mathbf{S} = \begin{pmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{pmatrix} = \begin{pmatrix} \frac{T_{21}}{T_{11}} & \frac{\det(T)}{T_{11}} \\ \frac{1}{T_{11}} & -\frac{T_{12}}{T_{11}} \end{pmatrix} \qquad \mathbf{T} = \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} = \begin{pmatrix} \frac{1}{S_{21}} & -\frac{S_{22}}{S_{21}} \\ \frac{S_{11}}{S_{21}} & -\frac{\det(S)}{S_{21}} \end{pmatrix} \tag{3.2}$$

- In order to perform de-embedding goes ***Cal -- Fixtures – 2-port de-embedding*** on the VNA.
- Load the s2p-file produced by MATLAB.

7) Check the calibration, the S21 parameter should now be roughly zero and the S11 parameter should be as small as possible. After de-embedding, the reference plane has been moved to the feedthrough of cryo-cable. So the absolute power showed on the VNA is the true power out from antenna.
8) After VNA calibration, turn off the RF power of VNA and connect the loop to the cavity.

3.2 Traditional calibration

In this method, VNA will be used as an external source during the calibration.

Assume that the attenuation from the antenna to the measured plane is consists of two parts: attenuation of the directional coupling path (calibrated factors of forward, reflected and transmitted signal are C_f, C_r and C_t respectively) and attenuation of RF cables connecting the SEL with the cryostat (C_{cable_f} and C_{cable_t}).

The calibration procedure is listed as below. All signals have a unit of dBm. We define P_f, P_r and P_t as measured powers, while P_F, P_R and P_T are true powers from antenna.

3.2.1 Procedure one

1) Calibrate the power meter as 4) in 3.1.
2) Check all the components, in instance, circulator, amplifier, directional coupler and VNA works well separately and connect them together as Figure 2. Here, port 2', 3' and 6' connect to a power sensor separately.
    - Note that at least one extra circulator need to add between the coupler and the power sensor.
3) Run the SEL to find the resonant frequency.
4) Measure the attenuation factors of each coupling path.
    - Set VNA parameters and choose one point-frequency (or a narrow span) which is several MHz away from the cavity resonant frequency to detune the cavity.

- Use the VNA port 3 RF output (0 dBm for example) to feed in forward directional coupler at port 1', connect a power sensor to port 4'.
- Get the forward coupled power P_{f1} at port 2' and power P at port 4'. So the forward attenuation factor fulfills :

$$C_{f1}= P_{f1}-P \quad (3.3)$$

- Make port 4' open so that signal fully reflects back to the load. Define a reflected coupled signal at port 3' as P_{r2} and calculate the first part of reflect attenuation factor by equation (3.4).

$$C_{r1}= P_{r2}-P \quad (3.4)$$

5) Measure the attenuation factors of RF cables.
   - Connect the coupler with cavity by RF cables.
   - Re-measure the reflected coupled signal P_{r3} at port 3' , which relates to the attenuation of forward RF cable:

$$C_{cable_f}=(P_{r3}-P_{r2})/2 \quad (3.5)$$

- The relationship between measured and true power from the cavity fulfills:

$$P_F=P_f-C_{f1}+C_{cable_f} \quad (3.6)$$
$$P_R=P_r-C_{r1}-C_{cable_f} \quad (3.7)$$

6) With the same method at port 8', we could figure out the transmitted attenuation factors.

$$C_{t1}= P_{t1}-P' \quad (3.8)$$
$$C_{cable_t}=(P_{t3}-P_{t2})/2 \quad (3.9)$$
$$P_T=P_t-C_{t1}-C_{cable_t} \quad (3.10)$$

Here, P_{t1} is the coupled power measured at port 6' and P' is the power meter value at port 5', both of them are measured when disconnect the cavity. P_{t2} is the coupled power at port 6' while coupler connects with the cavity.

3.2.2 Procedure two

In this procedure, we introduce the VNA into the measurement of attenuation factors of RF cables. It provides an easier and more accurate way.

1) The some procedure as 3.2.1 1) to 4).
2) Set VNA parameters.
   - Set center frequency as the cavity resonant frequency.
   - Set 500 kHz to frequency span.
   - Set 100Hz to IF bandwidth.
   - Set the average number of 10 with ***point average*** option.
3) Perform the one-port S parameter calibration on VNA.
4) Connect the VNA to the forward RF cables and measure S11.
   - Note that the narrow bandwidth of superconducting cavity is beyond the test limit of VNA. Though the sweeping frequency range covers the resonant frequency, VNA is 'blind' of the resonant peak and 'jump over' it. So the S11 curve shows a straight line.

- S11 parameter contains the information of double-way power consumption of the forward power cable.

$$C_{cable_f}=S11/2 \qquad (3.11)$$

5) Connect the VNA to the transmitted RF cable and measure S11.

- With the same method to transmitted RF cable, we could figure out the transmitted attenuation factor.

$$C_{cable_t}=S11/2 \qquad (3.12)$$

6) The measured power and the true power from the cavity have a relationship as:

$$P_F=P_f-C_{f1}+C_{cable_f} \qquad (3.13)$$
$$P_R=P_r-C_{r1}-C_{cable_f} \qquad (3.14)$$
$$P_T=P_t-C_{t1}-C_{cable_t} \qquad (3.15)$$

Reference

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