ERROR ANALYSIS ON RF MEASUREMENT DUE TO IMPERFECT RF COMPONENTS *

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Abstract

An accurate cavity test involves the accurate power measurement and decay time measurement. The directional coupler in a typical cavity test llrf system usually has low directivity due to broadband requirement and fabrication errors. The imperfection of the directional coupler brings unexpected systematic errors for cavity power measurement in both forward and reflect power when a cavity is not considered a matched load as assumed in a cable calibration. An error analysis will be given and new specification of directional coupler is proposed. A circulator with a low voltage standing wave ratio (VSWR) creates a standing wave between the circulator and cavity. As long as the cavity phase is maintained, the standing wave of a non-matched cavity load will only change the input coupler coupling factor (Q_{ext1}), but not to the calculation of the cavity power loss that is independent of the Q_{ext1}.

INTRODUCTION

RF measurement has been used to determine the cavity gradient and unloaded quality factor (Q_0) since very early days in SRF [1,2]. RF measurement is nevertheless subjected to errors of power measurement and rf parameters. The error analysis has been described in earlier studies [2,3]. Lately, the additional errors caused by imperfect RF components have been studied experimentally [4]. The validity of the latest studies has been hotly debated. A careful study of these additional errors has to consider all the equations of the RF calculations and the practical procedures of RF measurement.

Considerable detailed RF measurement circuit diagram can be found in many references and text book [1,2]. A dramatically simplified RF measurement diagram is shown in Figure 1 which consists only a simple phase lock loop involving a RF power source, a circulator, a directional coupler and a RF cavity.

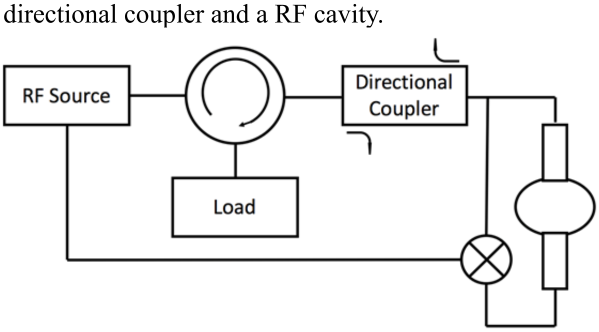

Figure 1: A dramatically simplified cavity test diagram.

The directional coupler allows the measurement of the forward power to the cavity (P_f) and the reflected power from the cavity (P_r). Measuring cavity transmitted power P_t allows one to derive the cavity power loss P_{loss}. Ideally, P_f is only proportional to the forward power from the RF source. However, due to design imperfections associated with broad band requirement and fabrication tolerances, the reflected power from the cavity can be slightly coupled into the P_f measured at the directional coupler forward coupling port. Equally, the P_r measured at the directional coupler's reflected coupling port includes the reflected power plus the coupled power from the forward power. Directivity represents how strong this unwanted coupling is in a directional coupler. Definition and measurement of the directivity is well discussed [5]. The higher the directivity, the weaker the unwanted coupling is. The unwanted coupling is also a function of the phase angle between the reflected power and forward power. The error analysis will be focused on the forward power and reflected power. The transmitted power is not affected by the imperfect directional coupler.

The circulator redirects the cavity reflected power to a RF load. Most commercial circulator does not have fully matched port where all the incoming power was fully cycled out. The standard VSWR is around 1.1-1.2. As such some power will be reflected and forms a standing wave in the line. The standing wave in the transmission line lead to cavity will modify the field at the cavity input coupler and cause the coupling factor of the cavity input coupler to change. This will change the external Q of the cavity (Q_{ext1}) and thus change the loaded Q (Q_L). The cavity decay time will change as the loaded Q changes. A misconception happens from time to time that the decay time changes means the cavity unloaded Q is also affected. In reality, cavity unloaded Q is not much affected by the standing wave in the forward power transmission line in most cases.

DIRECTIONAL COUPLER

Directional coupler is mostly characterized and used under matched load. Unfortunately, the load is mostly reflected or mixed for SRF cavities even with beam loading except the case for energy-recovered linear accelerators. All of the commercially available directional coupler has limited directivity (***D***). Power measured through directional coupler will be affected by its non-ideal directivity. Figure 2 illustrates the power measurement affected by directivity and non-matched load.

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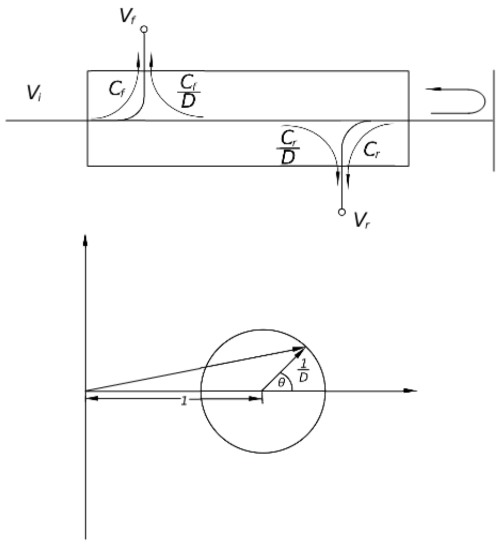

Figure 2: Voltage measured at one of the coupling port of a directional coupler.

To derive the power, one has to work with the voltage since only voltage can be calculated with the phase. An incident signal has V_i and C_f represents the coupling factor of directional coupler's forward port. Assuming the power is reflected partially (Γ) at certain termination point. The phase distance from the forward coupling port to the termination port is θ. One can derive the actual voltage measured at the forward coupling port as:

$$V_f = V_i\left(C_f + \Gamma\frac{C_f}{D}e^{-i\theta}\right) = V_i C_f\left(1 + \Gamma\frac{1}{D}e^{-i\theta}\right). \quad [1]$$

The power coupled out of the directional coupler's reflected port is negligible compared to the reflected power such as in a 20 dB or 30 dB directional coupler.

From the equation 1, one can derive the power coupling factor of the forward port as in Figure 3. A designed 20dB coupling factor is used. As one can see, with an almost fully reflected load, the actual coupling factor changes following the change of the termination point phase distance. The degree of the deviation varies for different directivity. Even with a high quality directional coupler (40dB), one can expect 0.14 dB peak to peak variation of the coupling factor. This variation is similar to the vendor provided frequency response typically attached to many directional couplers.

Figure 4 shows a measured coupling factors for a directional coupler which has a 25 dB directivity [6].

As the forward coupling port and reflected coupling port has a phase distance, one can look for a coupler that has both ports closely related to the each other and take advantage of the cancellation effect when one uses it to calculate the cavity power loss.

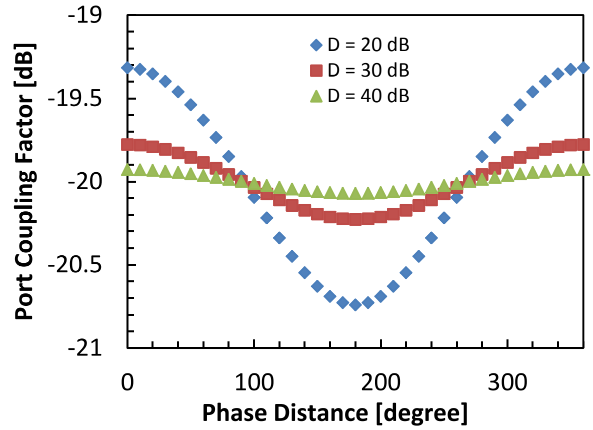

Figure 3: Calculated coupling factor variation of a 20dB directional coupler with different directivity (D).

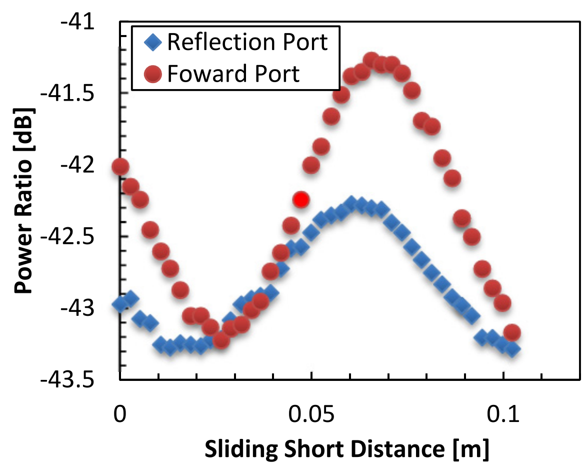

Figure 4: A measured coupling factor variation for a 40dB directional coupler (Courtesy of M. Middendorf).

CIRCULATOR

It is well known that circulator causes the standing wave in the transmission line between the circulator and the cavity. This is easily seen in the forward power during a cavity power switch off moment. As seen in the Figure 5, as the power was switched off from the rf source, the forward power did not switch to zero immediately, it actually followed the same decay curve as the cavity transmitted power which indicated there was an emitted power formed standing wave between the circulator and the cavity.

This phenomenon has been well explored in multiple stub tuners commonly used in waveguide coupler of superconducting cavities [7]. The tuning of the external Q is realized by changing both the standing wave ratio and phase through the stubs that strategically located in the waveguide.

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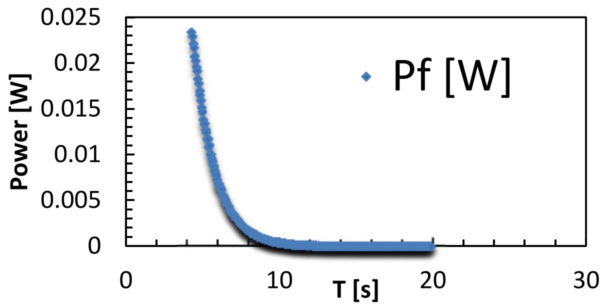

Figure 5: A forward power trace measured for a LCLS-II 9-cell cavity horizontal test.

Forward power and power coupler external Q has relation of

$$E_{acc} = \frac{1}{L}\sqrt{4P_f Q_{ext1}(\frac{R}{Q})}\frac{\beta}{\beta+1} \quad (2)$$

where β is the coupling coefficient of input coupler.

As Q_{ext1} changes, P_f and β will change accordingly to keep P_t the same. Following the standard equation [2], the Q_0 remains not much changed.

RF ERRORS EXAMPLE

A typical cavity measurement follows the following procedural sequence. One calibrates the power measurement system that includes the cable loss and the directional coupler coupling factor in the warm section. This calibration is then combined with the cold cable calibration. It is worth to note that depending on the calibration procedure, the calibration is usually conducted either under fully matched load or fully reflected mode. The termination point during the calibration is associated with certain phase distance to the directional coupler. This termination changes during the combining of the warm and cold calibration. It can also change from test to test or under different environment. Once the calibration is completed, one powers the cavity and measures the cavity decay time to determine the cavity loaded Q. As one measures the forward, reflected and transmitted power, one can determine the cavity power loss. Once the reflecting coefficient is determined from the forward and reflected power, the cavity stored energy is derived. At this time, the external Q of cavity power coupler, field probe and unloaded Q can be calculated. The accelerating gradient is then derived from the transmitted power. Follow up Q curve is determined based on the cavity transmitted power and the cavity power loss. Transmitted power measurement is not affected.

In Fermilab's vertical test setup, a Narda® directional coupler was used in RF circuit. The measurement of the coupling port is shown in Figure 6. Taking advantage of the two port's relative in sync phase angle (27-deg). One can calculate the true variation of the cavity Q_0 in a mismatched cavity power coupler with a coupling factor of 10. Table 1 lists the errors directly associated with the imperfect directional coupler using the following equation:

$$Q_0 = [1 + \frac{\sqrt{\frac{P_{in}}{P_r}+1}}{\sqrt{\frac{P_{in}}{P_r}-1}}(1+\frac{P_t}{P_{in}-P_r-P_t}) + \frac{P_t}{P_{in}-P_r-P_t}]\, Q_L \quad (3)$$

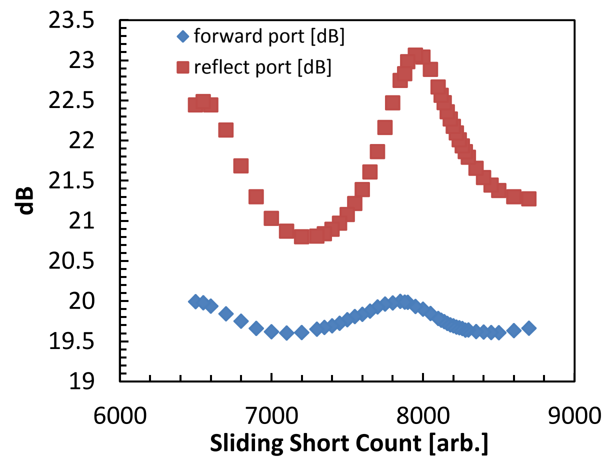

Figure 6: A non calibrated relative measurement of port coupling for a Narda® directional coupler.

Table 1: The additional measurement errors of Q_0 for a cavity coupler with a various coupling factor using a non-ideal directional coupler of 20dB directivity.

Coupling factor	Error of Q_0
10	±8.5%
5	±4.0%
1	0%

If a high directivity coupler is not available, one can place two identical directional couplers spaced at a quarter of the guided wavelength. The average reading of the two forward powers should be independent of the phase distance of the cavity.

CONCLUSION

The RF directional coupler is an important component in SRF cavity measurement. The high directivity is preferred to reduce measurement errors in non-critically coupled cavities. Broadband feature of the directional coupler is not recommended due to its generally poor directivity.

ACKNOWLEDGMENT

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