SIMULINK ANALYSIS WITH NEW COUPLING BETA MEASUREMENT FOR VERTICAL TEST AT IRIS*

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Abstract

There have been concerns regarding the uncertainties of Q-factor measurements in vertical test system when the coupling beta is too low or too high. Forward and reverse power readings can be affected by cross-contamination in the bidirectional coupler and by re-reflection from the circulator, resulting in increased measurement uncertainty. This uncertainty becomes more significant when the cavity is far from critical coupling, because the dissipated power is determined from the difference between the forward, reverse, and transmitted powers.

To address this issue, we are recently developing a new method for measuring the coupling factor, β, based on the emitted power ratio between the input coupler and the pickup coupler. When the coupler geometry is mechanically fixed, the external quality factors (Q_e, Q_t) of each coupler remains constant. During cavity field decay, the emitted power ratio of the reverse power, P_r, and the pickup power, P_t, remains constant. this emitted power ratio makes it possible to calculate the coupling factors of both couplers with the transfer function.

This method reduces the sensitivity of coupling-factor measurements to RF power measurement errors. Simulink simulations were performed to evaluate the validity and accuracy of the proposed method. The Simulink model provides improved understanding and quantitative evaluation of measurement uncertainties in the vertical test system.

INTRODUCTION

HWR, QWR, SSR1, SSR2 cavities have been tested in vertical test facility at IRIS. HWR and QWR have been installed into the tunnel and are in operation [1]. We are in the second phase of SCL2 line, which is to use SSR1 for the former part of SCL2 line and SSR2 for the latter part. During HWR and QWR vertical tests, variable couplers have been used for the vertical test. It made it easy to do the vertical test. For we could adjust the position of the coupler, we were able to adjust the coupling between the coupler and the cavity well and do the conditioning for the cavity. But because of the complexity of the coupler, the multipacting and the outburst of outgassing took place in many cases. This was suspected to be the cause of the degradation of the performance of the cavity. We have changed the input coupler to the fixed type. The coupling coefficient of the fixed-type coupler had to be adjusted prior to the cleanroom assembly. We measured the external Q of the input coupler and the pickup coupler [2].

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We have been using the same Q calculation process as applied in the variable coupler use case for the fixed type coupler [3]. The variable coupler can move the position of the antenna tip freely within the mechanical limit so that we might be able to adjust the coupling to be critical because the reverse power which is composed of the vector sum of the reflected power at the input coupler and the emitted power from the cavity can be minimized, thereby reducing the error in the critical coupling.

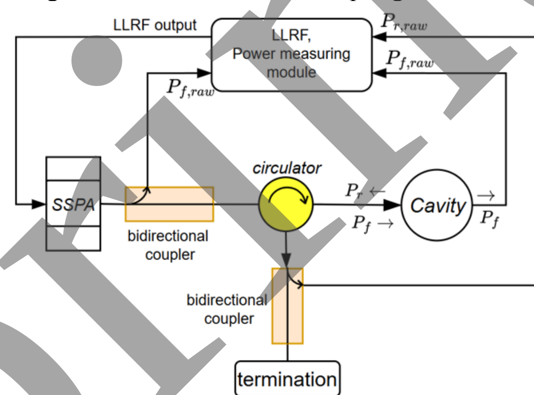

Figure 1: RF Diagram for Vertical Test at IRIS

Figure 1 shows the RF diagram for the vertical test of IRIS. We placed the directional couplers at the input port side of circulator and at the termination side to reduce the error term caused by the re-reflected power from the circulator. All calculations are using three powers, $P_{f,raw}$, $P_{r,raw}$, $P_{t,raw}$ which are each the uncalibrated forward, reverse, pickup power. P_f, P_r, P_t are the calibrated forward, reverse, pickup power at the input and pickup coupler RF plane. The reverse power is the vector sum of the reflected power at the coupler and the emitted power from the cavity [4, 5] and is expressed as:

$$P_r = \left|\sqrt{P_{ref}}e^{i\phi_{ref}} + \sqrt{P_e}e^{i\phi_e}\right|^2 \tag{1}$$

where P_{ref} is the power reflected at the coupler from the forward power and ϕ_{ref} is the phase thereof. If we knew Q_t and β_t. Then, Q_0 can be expressed as:

$$\mathrm{Q}_0 = \frac{P_t Q_t}{P_f - P_r - P_t} \tag{2}$$

where $P_f - P_r - P_t$ is the dissipated power at the cavity inner surface. The external Q-factor of a coupler does not change unless the structure of the coupler and the cavity is changed. If we knew β_t in any field level, then we could know Q_0.

Obtaining β_t using the above equation has a limitation that if P_0 approaches zero, in other words, if the coupling is too weak or too strong and the reverse power is increased, the denominator approaches to zero, then uncertainties can be increased.

We are developing new coupling beta calculation method using P_e/P_t ratio, where P_e is the emitted power at the input coupler. It makes it possible to calculate the intrinsic Q-factor of the cavity by adding one more parameter, the loaded Q-factor of the cavity that comes from measuring the decay time.

Simulink RF blockset is a tool for designing, modeling, and simulating high frequency RF systems. Simulink can be helpful to understand systematic RF behavior in the vertical test. Using Simulink model, we are trying to verify the method.

SIMULINK MODEL FOR VERTICAL TEST

We are developing a simulink model for vertical test for the systematic analysis of RF behavior. The model is illustrated in Fig. 2. The simulink model is composed of subsystem of cavity, S-parameter blocks that represent the cavity, a circulator and several bidirectional couplers, PID controller to maintain RF field level, cable block, etc. The cavity is modelled with SSR cavity of 325 MHz frequency. The cavity model in Simulink was implemented with series-connected R, L, and C elements coupled through transformers.

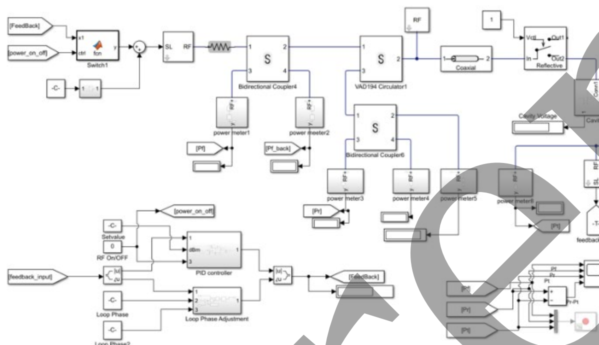

Figure 2: Simulink model for the vertical test.

The Simulink model uses RF blockset toolkit. It consists of mainly two parts. One is the normal Simulink model blocks, and another one is RF modelling block in which the actual RF simulation takes place. RF signals are simulated virtually between Inport and Outport block of RF blockset. Simulink RF mode that was used was circuit envelope Baseband simulation. All RF signals are expressed as the envelope complex signal with a modulation frequency. The input and the output were baseband complex ideal voltage. SSPA was not implemented in the Simulink model. Instead, the magnitude of the feedback signal was adjusted in PID controller. Loop phase control was realized by converting the complex baseband pickup signal to 'complex to magnitude and phase' block and adjusting the magnitude by PID controller and the phase by adding a certain value and then both PID controller output and the adjusted phase value are combined into the feedback complex signal by 'magnitude and angle to complex' block to the input to the Inport block of the RF system. The S-parameters of the circulator and bidirectional coupler were measured using a Vector Network Analyzer (VNA). For use in Simulink, three sets of Touchstone files (.s2p) were used to synthesize a 3-port Touchstone file (.s3p) for the circulator block, while six sets were used to synthesize a 4-port Touchstone file (.s4p) for the bidirectional coupler block.

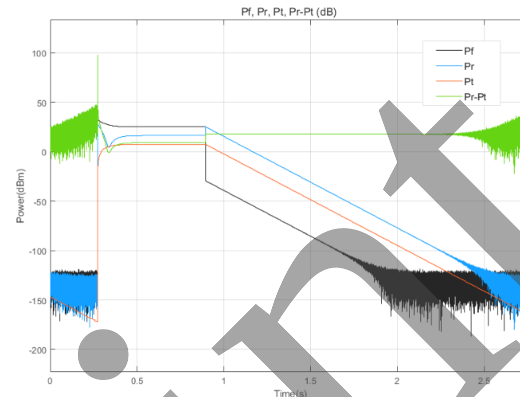

Figure 3: the output of the simulink model. The input coupler is over-coupled.

Figure 3 shows the constant ratio of $P_r - P_t$ in log scale after RF power is off. The Simulink model can be used later to simulate the RF behavior of the vertical test system.

NEW BETA MEASUREMENT METHOD

The coupling beta is a key role to calculate the intrinsic Q-factor of the cavity. Because it is the measure of how much the Q-factor of the cavity is related to the external Q-factor of the coupler. It means that knowing the coupling beta and the external Q allows us to determine the intrinsic Q-factor of the cavity. We usually measure the emitted power from the pickup coupler to measure the decay time in vertical test. The loaded Q-factor is shown by the derivatives of the pickup power change on a dB scale in Fig. 4. Additionally, we measured the emitted power from the input coupler and the pickup coupler simultaneously. As expected, the emitted power ratio was constant regardless of the field level and the loaded Q-factor of the cavity.

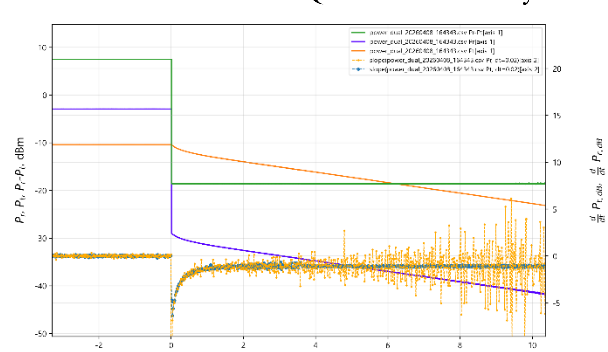

Figure 4: Power readings and their derivatives when RF was off in Vertical Test of SSR1 cavity. P_r(Violet),P_t(Orange), $P_r - P_t$ (Green), $\frac{d}{dt}P_r$ (Blue), $\frac{d}{dt}P_t$ (Orange with dash).

After the turn-off of the forward power, P_r is left with P_e only in the equation (1). We measured the decay time of the reverse power and the pickup power simultaneously. In one of the vertical tests for SSR1 cavities, we got the result of Fig. 4. And the ratio turned out to be almost constant as expected. Green line of Fig. 4 is $P_r - P_t$ in log scale. The fact that they are constant is the ratio of Q_e and Q_t is constant even if Q_0 is changing.

The derivatives of P_r shows a highly noisy pattern because of the noise in the power sensor at low power levels. To reduce measurement uncertainty, power measurements at excessively low levels should be avoided.

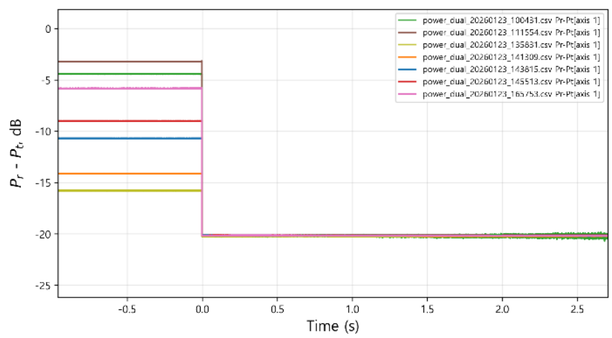

Figure 5: $P_r - P_t$ in log scale at various field levels. P_r, P_t are raw values.

Figure 5 shows that the difference in log scale was constant except for the noise increase in extremely low power. It means that P_e/P_t ratio is the same in any field level. P_e and P_t comes from the same stored cavity energy and are measured simultaneously. We can introduce the ratio k as follows:

$$k = \frac{P_e}{P_t} = \frac{Q_t}{Q_e} = \frac{\beta_e}{\beta_t} \tag{3}$$

The ratio k also has other physical meanings: it represents the external Q-factor ratio and the ratio of the coupling coefficients between the coupling ports.

If the forward power, P_f, were turned off, then P_{ref} term of P_r is removed in equation (1). So P_r is left with only P_e term in the equation (1). Using P_e and P_t, we can obtain the emitted power ratio, k. $|S_{21}|^2$ is the power ratio of the forward and pickup power. $|S_{21}|_{res}^2$ represents the power transfer function at resonance.

$$|S_{21}|_{res}{}^2 = \frac{P_t}{P_f} = \frac{4\beta_e\beta_t}{(1+\beta_e+\beta_t)^2} \tag{4}$$

P_f, P_t powers are measured by the power sensors during the vertical test. We also have a constraint k, which is the emitted power ratio of the input coupler and the pickup coupler. By defining $r = P_t/P_f$. β_t and β_e can be derived from Equation (4) as follows:

$$\beta_t = \frac{\sqrt{r}}{2\sqrt{k}-(k+1)\sqrt{r}},\ \beta_e = k\beta_t \tag{5}$$

Equation (5), and the loaded Q-factor that is measured by the decay measurement make it possible to obtain the intrinsic Q-factor of the cavity. The emitted power ratio plays a concrete role in calculating the coupling coefficient and the intrinsic Q-factor of the cavity. But we must consider uncertainty by power measurement. There are some things that we have to consider to measure the power accurately , such as, the effect of the circulator reflection and bidirectional coupler directivity [5]. Further study about uncertainties is needed to use this new beta calculation method in the vertical test under various coupling conditions.

CONCLUSION

A new coupling-beta measurement method based on the emitted power ratio between the input coupler and the pickup coupler has been proposed and investigated for the vertical test system. Since the external quality factors of mechanically fixed couplers remain constant, the emitted power ratio during cavity field decay can be used as a stable constraint to determine the coupling factors of both couplers. This approach is expected to reduce the dependence of the intrinsic quality-factor calculation on the direct power-balance term, which can suffer from large uncertainty when the cavity is far from critical coupling.

A Simulink RF Blockset model of the vertical test system was developed to evaluate the RF behaviour of the cavity, couplers, circulator, cables, and feedback control system. Both simulation and vertical test data showed that the ratio between the emitted power from the input coupler and the transmitted power from the pickup coupler remains nearly constant during field decay and over different field levels. These results support the validity of the proposed method.

The proposed method is expected to improve the accuracy and reliability of intrinsic quality-factor measurements for fixed-coupler vertical tests, especially in cases where conventional power-`balance methods are sensitive to reverse-power uncertainty. Further studies using the Simulink model and additional vertical test data will be carried out to quantify systematic errors and refine the uncertainty analysis of the new coupling-beta measurement method, including the effect of the circulator reflection and bidirectional coupler directivity.

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