ERROR ESTIMATION IN CAVITY PERFORMANCE TEST FOR THE EUROPEAN XFEL AT DESY*

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Abstract

The construction of EU-XFEL [1] in DESY is on-going steadily in the final stage. The cavity performance in vertical/cryomodule test is satisfactory for the XFEL specification [2]. In this paper, the systematic error in the cavity performance test is estimated, and the performance degradation is discussed.

INTRODUCTION

Fixed type antenna for RF input into cavity has been used in vertical test (V.T.) at AMTF (Accelerator Module Test Facility) for EU-XFEL. Generally, it is considered that adjustable type antenna is much better to measure RF power precisely, but for the series tests of more than 800 accelerating cavities adjustable antennas could not be applied. Therefore, it was necessary to estimate the systematic error of both E_{acc} and Q_0 in early stage of series of V.T.s with the fixed type antenna with a nominal Q_{ext} of 8e9. Assuming an unloaded Q-value of the cavity of typically 2e10, the cavity is over-coupled. On the other hand, as for cryomodule test (C.T.), change of one calibration parameter ($K_t = E_{acc}/\sqrt{P_{tra}}$), which is related to evaluation of accelerating gradient, has been observed. This change leads to systematic error in C.T. In the following two sections, these systematic errors are estimated.

ERROR ESTIMATION IN V.T.

The data measured at early stage of a series of V.T.s were used for the estimation of systematic error. The main error components are the followings:

- Cable calibration parameters (forward, backward, transmit, HOM#1 and HOM#2)
- External Q (Q_{ext})

Error in Cable Calibration Parameter

There are two vertical cryostats and six inserts, with four cavities for each, in AMTF. Assuming there is no difference in each insert including each cavity, there are totally five cable parameters for each cryostat. Every parameter is measured every V.T. It is possible to estimate the systematic error from the distribution of each parameter. As a result, the error in the cable calibration was ±2.5% at maximum as root mean square (r.m.s.).

Error in External Q

Usually, Q_{ext} is calculated by Eq. (1):

$$Q_{ext} = \frac{P_0 Q_0}{P_{ext}} = \frac{P_0 Q_0}{4 P_{for}} \left(\frac{1+\beta}{\beta}\right)^2. \quad (1)$$

where P_0 is power dissipated on cavity surface, Q_0 is quality factor of cavity, P_{ext} is power emitted from cavity, and β is coupling coefficient. P_0 is calculated from the power balance for cavity in steady state. Clearly, Q_{ext} depends on β. Therefore, it is essential to measure β precisely in V.T. Generally, β is calculated from the three formula in Eq. (2):

$$\beta = \frac{1 \pm \sqrt{\frac{P_{ref}}{P_{for}}}}{1 \mp \sqrt{\frac{P_{ref}}{P_{for}}}}, \beta = \frac{1}{2\sqrt{\frac{P_{for}}{P_{ext}}} - 1}, \beta = \frac{P_{ext}}{P_{for} - P_{ref}}. \quad (2)$$

where P_{for} is forwarded power and P_{ref} is reflected power. In ideal case, three β's have to be equal each other. However, when cavity is not in steady state, or cavity is in far over-coupled state (in this case, it is difficult to measure P_{ext} precisely), these β's are not consistent. As a result, some systematic errors are generated in V.T.

Figure 1 shows two examples of Q_0 - E_{acc} curve measured at AMTF. Q_{ext} is almost constant for CAV00049, and gradually lowered at higher accelerating gradient for CAV00177. To estimate the systematic error of Q_{ext}, the r.m.s. for the distribution of Q_{ext} in each V.T. was used. In these cases, the both errors were 3.1% and 10.8%. By the

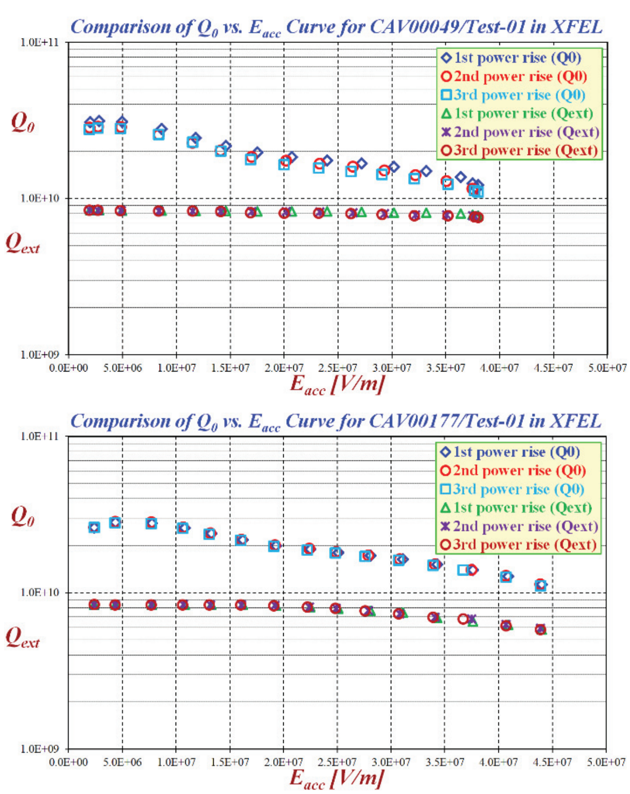

Figure 1: Q_0 - E_{acc} curves for CAV00049 and CAV00177.

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same method, it is possible to estimate the average error for every V.T. Figure 2 shows the distribution for the error of Q_{ext} in 804 times V.T. It is clear the average error is 6.1%, and 95% of V.T. has systematic error of Q_{ext} of below 20%.

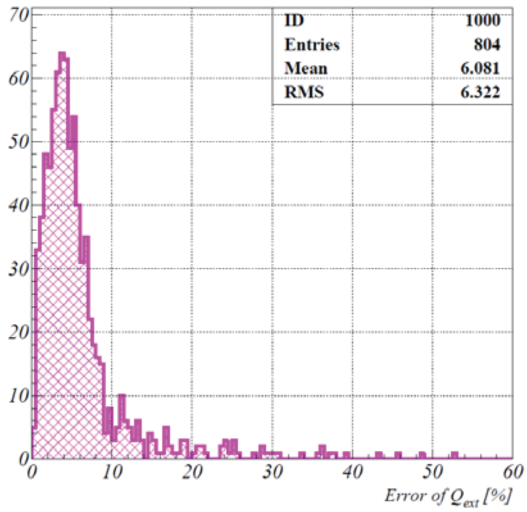

Figure 2: Distribution for error of Q_{ext} in V.T.

Total Error in V.T.

The error propagation formula in Eq. (3) was used to estimate the total systematic error in V.T.

$$\sigma_{V.T.} = \sqrt{\sigma_{cable}^2 + \sigma_{Qext}^2}. \quad (3)$$

Consequently, the total error as one-sigma is 6.6% for Q-value measurement and 3.3% for gradient measurement. For derivation of gradient measurement error, approximation formula $(1 \pm x)^{1/2} \approx 1 \pm x/2$ $(\because x \ll 1)$ was used. The both errors in V.T. were small, in spite of using the fixed type coupler.

ERROR ESTIMATION IN C.T.

After V.T., every cavity is sent to CEA-Saclay to do cavity string and cryomodule assembly [3], and sent back to DESY as cryomodule. During this process, the probe antenna for transmit power (P_{tra}) from cavity is not exchanged, and therefore, Q value of transmit power (Q_{tra}) should be same as V.T. However, actually, the both values of Q_{tra} between V.T. and C.T. are not consistent due to measurement error in different RF system and measurement method, that is, the V.T. is CW-like and C.T. is pulsed measurement. To estimate this systematic error, one calibration parameter called K_t is used in DESY, and given by Eq. (4) for pulsed measurement.

$$K_t = \frac{1}{L_{eff}} \sqrt{(R/Q) \cdot \frac{4P_{for}Q_L}{P_{tra}}} \left(1 - e^{-\frac{t}{2\tau}}\right). \quad (4)$$

where L_{eff} is effective cavity length (1.035 m), R/Q is shunt impedance (1030 Ω), Q_L is loaded Q-value (typically, 4.6x10^6), t is RF pulse length (1.3 msec), and τ is decay time of RF pulse. K_t is related with E_{acc} by the formula ($E_{acc} = K_t\sqrt{P_{tra}}$). Figure 3 shows the comparison of K_t between V.T. and C.T. (top), and the Gaussian-fitted error distribution of K_t between them (bottom). The data for 661 cavities in XM1-XM85 (except XM22, XM54 and some problematic cavities) were used for this analysis. In this figure, it is clear the mean value of error distribution is shifted by -2.3% from zero, one sigma is 6.4%, and the shape of this distribution is Gaussian-like.

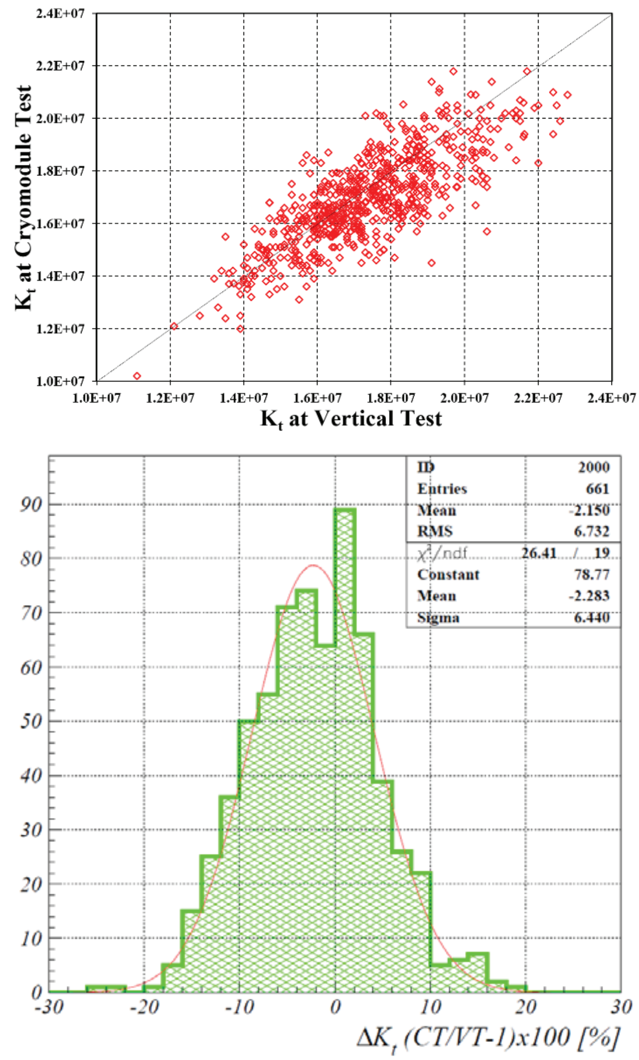

Figure 3: Comparison (top) and error distribution (bottom) of K_t between V.T. and C.T.

From above analysis for V.T. and C.T., the total systematic error is estimated by the error propagation formula ($\sigma_{tot} = \sqrt{\sigma_{V.T.}^2 + \sigma_{C.T.}^2}$), and summarized in Table 1. The errors in Q-value and gradient measurement are shown separately there.

Table 1: Summary of Systematic Error in V.T. and C.T.

	Q-value measurement (Q_0)	Gradient measurement (E_{acc})
V.T.	6.6%	3.3%
C.T.	12.4%	6.4%
Total	14.0%	7.2%

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DISCUSSION

The total systematic error in cavity performance test is crucial for discussion of cavity performance degradation from V.T. to C.T. Because, the changes of K_t between them can generate the changes of accelerating gradient. Figure 4 shows the comparison of cavity performance between V.T. and C.T. (top), and comparison of changes of K_t and accelerating gradient from V.T. to C.T. (bottom). In the bottom figure, cavities above 31.0 MV/m in C.T. are plotted as ΔE_{acc} of 0%. At first glance, there are many "degraded cavities" in the top figure. However, it is also necessary to take the changes of K_t into consideration for estimation of performance degradation. For this analysis, it is possible to use the result in the Table 1. In the bottom figure, the black dashed line shows "no-degradation" region. And, the regions between red and purple dashed lines show "one-sigma (~68% of total statistics)" and "three-sigma (~99%)" regions, respectively. There are many "degraded cavities" in three-sigma regions, however, it is not clear whether these cavities actually had performance degradation, because of the changes of K_t. These regions are what might be called "grey zone".

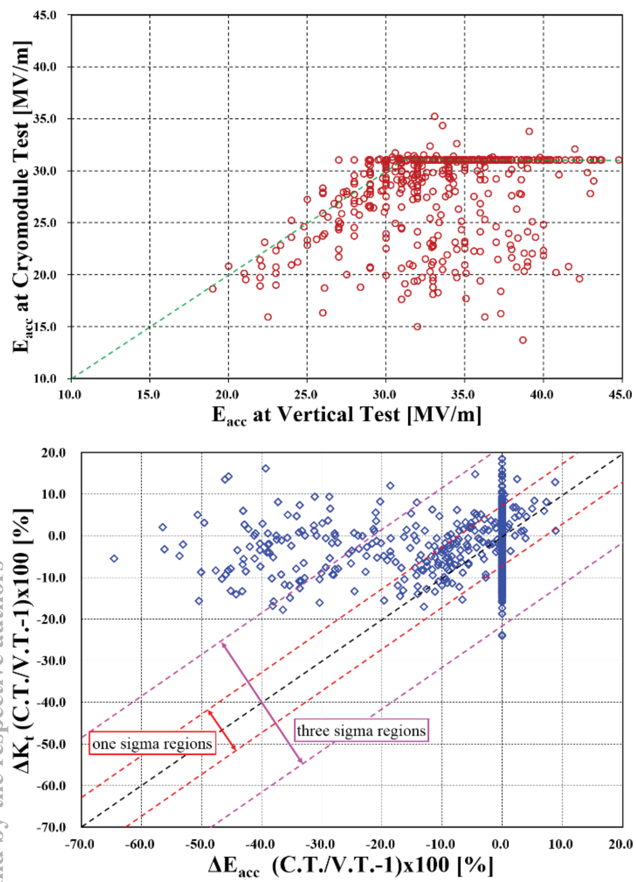

Figure 4: Comparison of cavity performance between V.T. and C.T. (top), and comparison of changes of K_t and accelerating gradient from V.T. to C.T. (bottom). In the top figure, the green dashed line shows the "no degradation" region. In the bottom figure, the regions between red and purple dashed lines show "one-sigma" and "three-sigma" regions, respectively. The black dashed line shows the "no degradation" region.

After the cryomodule installation into EU-XFEL tunnel, cryomodule operation and beam commissioning will start. It is possible to check the total beam energy at the beam commissioning, however, it is difficult to identify how many and which cavities actually had performance degradation. Moreover, the measurement for the beam energy also has some new systematic errors.

CONCLUSION

In this work, the estimation of systematic error in V.T. and C.T. for EU-XFEL in DESY has done. In V.T., the systematic error was not significant, rather, small. Therefore, the fixed type antenna is sufficiently reliable in V.T. On the other hand, the changes of K_t from V.T. to C.T. was not negligible. Consequently, this systematic error was most dominant in a series of cavity performance tests in AMTF. The total systematic error in V.T. and C.T. is 14.0% for Q-value measurement and 7.2% for gradient measurement, respectively. The cause for the changes of K_t is not clear, however, the same phenomena is also observed at STF in KEK.

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