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OCCURRING DEPENDENCY BETWEEN ADJUSTABLE COUPLING AND Q_0 - FINDING AND SOLVING A PROBLEM DURING VERTICAL CAVITY TESTING AT DESY

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Abstract

In the AMTF (Accelerator Module Test Facility) hall at DESY, various types of cavities have been tested for different accelerators and R&D projects during the last years. For R&D purposes, dedicated inserts with additional auxiliaries like a movable INPUT antenna can be used to perform accurate measurements at different temperatures between 1.4K and 4K. Since 2017 more than hundred vertical tests were conducted in these inserts without troubles besides rare expected occurrences of cold leaks or even rarer a loose antenna.

However, in the last months, an unexpected dependency between the measured quality factor and the coupling coefficient β has been observed. In order to understand the source of this measurement uncertainty, several different special checks have been performed. In a logical sequence of measurements with different cryostats, inserts and cavities the problem has been encircled and in the end was identified and solved. In this paper, the observed problem is described in detail as well as the entire path leading to its solution.

INTRODUCTION

Generally, it is considered that a movable antenna is much better to measure RF power precisely, especially for R&D projects. There are many different types of surface treatments, such as Nitrogen-infusion, Nitrogen-doping, medium temperature baking and so on, which are assumed to be strong candidates for the enhancement of SRF performance. Here at DESY in the AMTF, many R&D single cell cavities are used to verify the effectiveness of these surface treatments. Before implementing the vertical test, it was necessary to estimate the systematic error of both E_{acc} and Q_0. According to a early stage series of vertical tests, the systematic error of E_{acc} should be less than 10% while at the same time 20% for Q_0 were determined [1].

VERTICAL TEST SYSTEM WITH MOVABLE INPUT ANTENNAE

The topological diagram, shown in Fig. 1(b), describes the SRF cavity vertical test system. The generator feeds a small signal into the CW (continuous wave) amplifier. As the resonance width of SRF cavities is very sharp, a PLL (phase locked loop) is used to adjust the resonance frequency. Powermeters are responsible for showing the scopes of forward, reflected and transmitted signals. A cavity with movable INPUT antenna, which is used for the vertical test at AMTF, is shown in Fig. 1(a). A bellow is assembled between cavity beam tube and antenna, which makes the strength of the INPUT coupling adjustable.

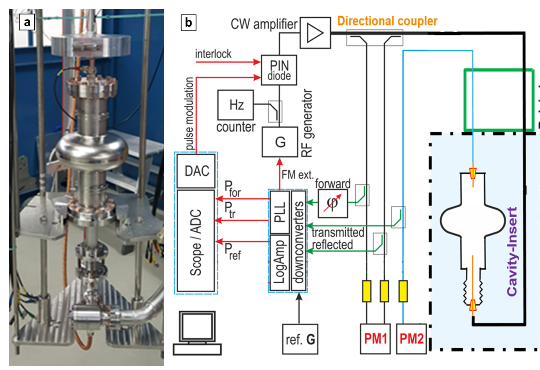

Figure 1: (a) Photograph of single cell cavity assembled on vertical test insert with movable antenna. (b) Topological diagram of SRF vertical test in AMTF.

For a vertical test, the maximum E_{acc} and its related quality factor are of importance. These values determine whether the cavity can be accepted, while it is impossible to measure them directly. These two values are determined by the measurable powers in the RF circuit and the decay time of the cavity RF amplitude. The coupling parameter β, which describes the matching of power coupler antenna and cavity, is important for obtaining the value of Q_0. During CW steady state, the β value can be calculated by the formula [2]:

$$\beta = \frac{1 \mp \sqrt{\frac{P_{for}}{P_{ref}}}}{1 \pm \sqrt{\frac{P_{for}}{P_{ref}}}} \tag{1}$$

In the AMTF, the steady state amplitude method is used, for this it is required to know beforehand whether the cavity is under- or overcoupled. For pulse mode, the β value can be easily judged by the power signals on the scope, which is usually used to make a rough estimate of the coupling coefficient while adjusting the antenna. These relationships are shown in Fig. 2. P_{for} indicates the power of the rectangular RF pulse applied on the cavity, which leads to two reflected peaks (switch on and off). The coupling state can be easily inferred by comparing the height of these two peaks. Switch on peak higher than, lower than, and equal to switch off peak corresponds to $\beta > 1$, $\beta < 1$ and $\beta = 1$ respectively [3].

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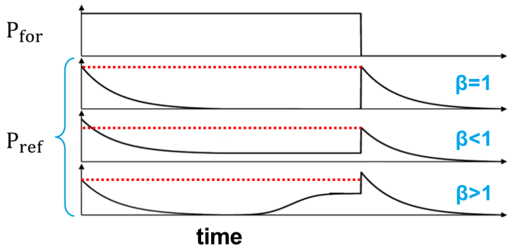

Figure 2: Rectangular P_{for} drive pulse and its three kind of different P_{ref} scopes corresponding to different values of coupling parameter.

AN UNEXPECTED DEPENDENCY BETWEEN Q_0 AND β VALUE

To evaluate a cavity performance, Q_0 is measured as a function of the cavity's field level (Q(E)-curve). In principle, the measurement error is minimal, when the coupling β value equals 1. Unfortunately, for the $\beta\approx 1$ case, it is hard to tell whether the cavity is under- or overcoupled. In AMTF, the Q(E)-curve is usually measured keeping an overcoupled state.

As shown in Fig. 3(a), the normal Q(E)-curves from any same cavity with the same measurement condition should be very close or even exact the same. Figure 4(a) shows one of those abnormal cases. For the whole curve, the same E_{acc} value has many different corresponding Q_0 values, which indicates a potential dependence. The unexpected dependency can even make Q_0 values of different curves differ by 2 to 3 times, which is much more than the systematic error of 20%.

Main Sources of the "Typical" Measurement Error

In order to identify the error source, many curves were measured, which includes various combinations of different inserts, cavities-antennae and vertical test stations. A relationship between quality factor and the coupling coefficent β did happen to some of those combinations. As shown in Fig. 1(b), the vertical test system can be divided into two main parts. One is thre RF measurement part and the other one is cavity-insert part.

The RF measurement part consists of the RF hardware and cryogenic, vacuum and radiation systems. If there is any abnormal signal, an interlock will be set off through monitoring software. The real-time monitoring software, during vertical test, eliminates the possibility of dependence caused by cryogenic, vacuum and radiation. Some RF measurement hardware, such as directional coupler, are not in the range of the interlock system [4]. Additional measurements taking this into account is shown in Fig. 5. Another directional coupler is added into the RF circuit. The results, which were calculated from different sources of directional couplers, show the same. Therefore, RF measurement part can be excluded as the error source. The vertical test results are shown in Fig. 5(b).

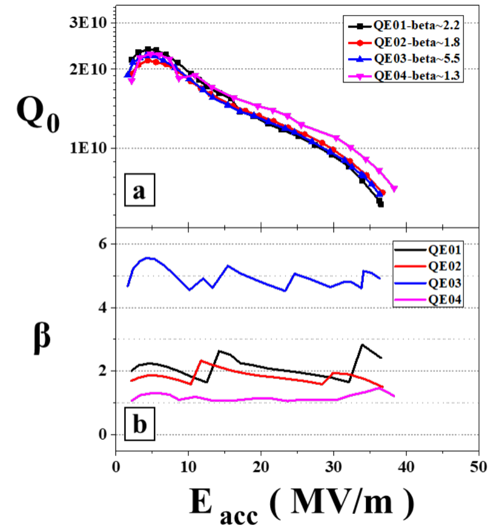

Figure 3: Typical normal VT measurement results and the relationship between the corresponding β value changes during the measurement period. In (a), all the four curves with different β values show the same trend and similar values. In (b), the changing trend of those Q(E)-curves' corresponding β value indicates an independency between Q_0 and β value.

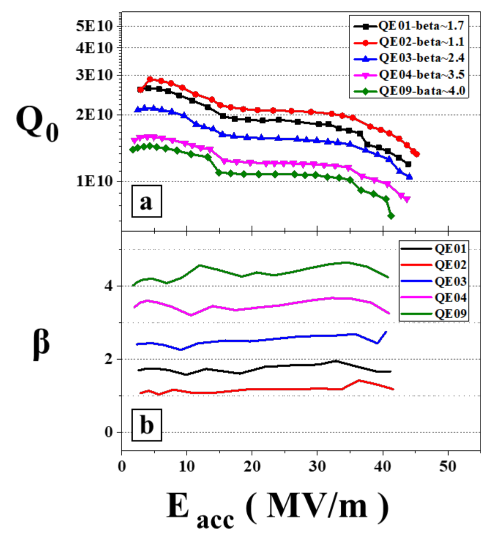

Figure 4: abnormal VT measurement results and the relationship between the corresponding β value changes during the measurement period. In (a), although, all the five curves with different β values show the same trend, they differ greatly in Q_0 values. In (b), the changing trend of those Q(E)-curves' corresponding β value indicates a dependency between Q_0 and β value.

The cavity-insert part consists of two R&D Inserts and a bunch of movable antennae. The movable antenna is used to adjust the β value, which is shown in Fig. 3(b) and Fig. 4(b).

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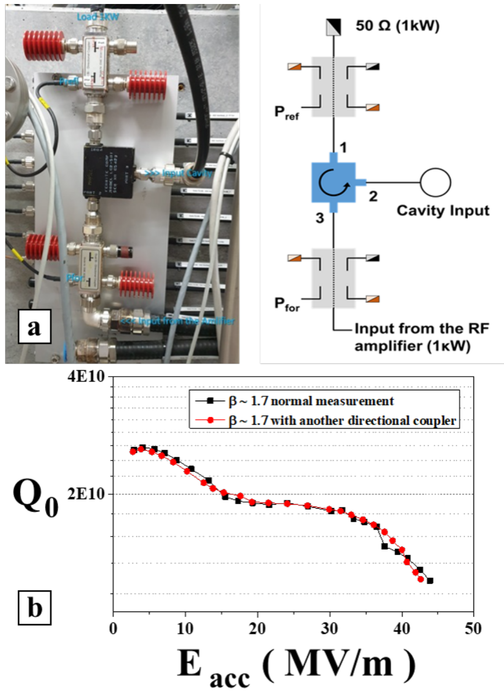

Figure 5: (a) Parallel directional couplers for verification of P_{for} and P_{ref} signals. (b) The two Q(E)-curves of corresponding VT measurement results are almost identical, and all other parameters remain the same during the measurement period.

It can be inferred from Fig. 3(b), that in the measurement process of Fig. 3(a), whether the β values are near 1 or greater than 5, the curves' difference is within the systematic error. But comparing the corresponding relationship between the curves of Fig. 4(a) and 4(b), the Q value decreases with the increase of the β value. For the case of Fig. 3(a), the Q value is independent of β value, while the case of Fig. 4(a) does show a dependency between Q_0 and β value (lower case).

SPECIAL CHECK MEASUREMENT: Q_0 VS β AT 5MV/m

A special method was used to check the measurement in a clear and easy way. As shown in Fig. 4, the unexpected dependency makes the curves measured with different β values, more discrete than normal. To study the unexpected dependency, the relationship between Q_0 and β should be compared under the condition of a constant E_{acc} value. Hence, attention was paid only on those points at 5MV/m, which means a linear curve can be drawn between β and Q_0 (Fig. 6(c)). The idea of the special check measurement is presented in Fig. 6. Usually, the Q_0 value is independent from cavity-antenna coupling state, so that the curve should be as flat as possible, while a greater slope, in this case, indicates a closer correlation.

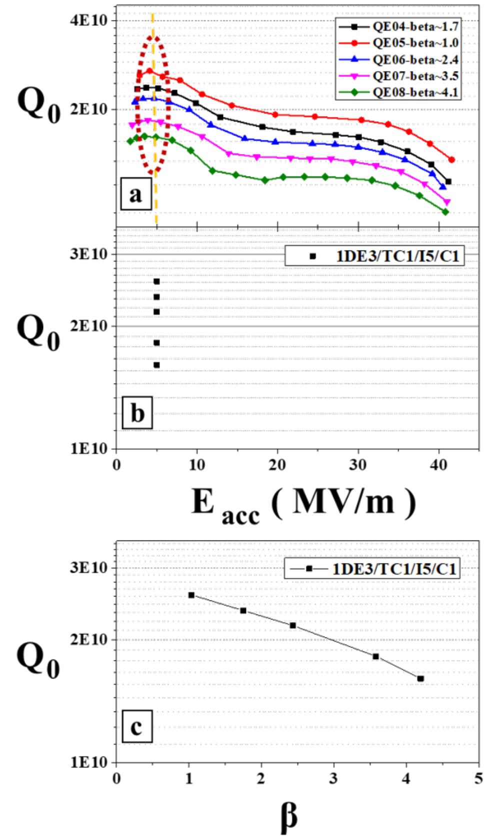

Figure 6: A special method focusing only on the values at 5MV/m of different curves and its corresponding Q_0 vs β curve. In (a), all those abnormal curves have the same changing trend, and the difference is only in the magnitude of the value. In (b), by adjusting the antenna and INPUT RF power, the measurement results are kept just at 5MV/m. In (c), a corresponding curve between Q_0 and β is used to highlight whether the two variables are related or not.

FINDING THE ERROR SOURCE CAUSING THE DEPENDENCY OF β AND Q_0

A further study with many different special checks was performed. In order to find the possible error source, a logical sequence of measurements with different cryostats, inserts and cavities was encircled. And, in the end, the problem has been identified by comparing the different results from those special checks. The logical details about those special checks are shown in Table 1 and the corresponding check results are depicted in Figs. 7 and 8. The table shows the various combinations of different cavities-antennae, vertical test stations, inserts and INPUT cables involved in this article. The abbreviation 1DE3/TC1/I5/C1 stands for example for test station 1, insert 5 and cable 1 in short, which means that the cavity 1DE3 was connected with the INPUT cable of LCF 12-50, assembled on the insert No.5 and tested through the vertical test station No.1. During the complete measurement period, the external environmental conditions,

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such as cryogenic and vacuum, were kept the same. And all the cavities and antennae involved were kept in vacuum state after clean room assembly.

Same Results on Different Cryostats

In AMTF exist two vertical cryostats providing the same RF measurement system. It can be seen from the previous measurement results that, in one of the cryostat, cavity 1DE3 inside insert 5 shows a dependency of β and Q_0 while in the other cryostat cavity 1DE4 inside insert 2 did not. The inserts with the mounted cavities were exchanged between the cryostats for cross-checking. The results are shown in Fig. 7(a). The Q_0 values from cavity 1DE3 inside insert 5 always show a dependency of β (black and red) while for 1DE4 inside insert 2 (light green and blue) an independency can be seen, which means both RF and cryostat systems work well.

Different Results on Different Inserts

The results from Fig. 7(a) indicates the possible error source coming from either insert or cavity-antenna system. Further measurements focusing on the check of the inserts were performed through a comparison of the same cavity inside different inserts. There are two inserts (No.2 and No.5) for movable antenna cavities, and the results of 1DE4 inside those two inserts are shown in Fig. 7(b). The $Q_0(\beta)$-curve from insert 2 (dark green) shows an independency while the curve from insert 5 (pink) yields a dependency, which suggests that the Insert 5 is the possible error source.

Relay Box: Independent of β

All inserts at AMTF have an additional relay box, which was used historically to switch between different cavities during XFEL production testing campaign (4 cavities were attached to 1 insert). Further measurements of the relay box on insert 5 were performed. The relay box was bypassed, and the cables were directly connected to the cavity instead. The results are shown in Fig. 7(c). Although both of the curves with normal (pink) and bypass (violet, named adding a “BP”) setting act in the dependent way, it is clear that the relay box works well. Hence the relay box can be excluded as error source.

Insert INPUT Cable: Error Source

The above mentioned measurement results show that the error source has to be one of the parts of insert 5. The possibility of RF hardware, relay box and cavity-antenna have been ruled out. The only possible source is the RF loop itself. Through the detection of the RF cables, the error source was in the end identified. As shown in Fig. 7(d), the curve shows am independency of β as it should be after exchanging the INPUT RF cable with a new type (SiO_2). Comparing the curve of new cable (gold) with the old LCF 12-50 cable (pink), the results indicate an unexpected malfunction of the RF cable.

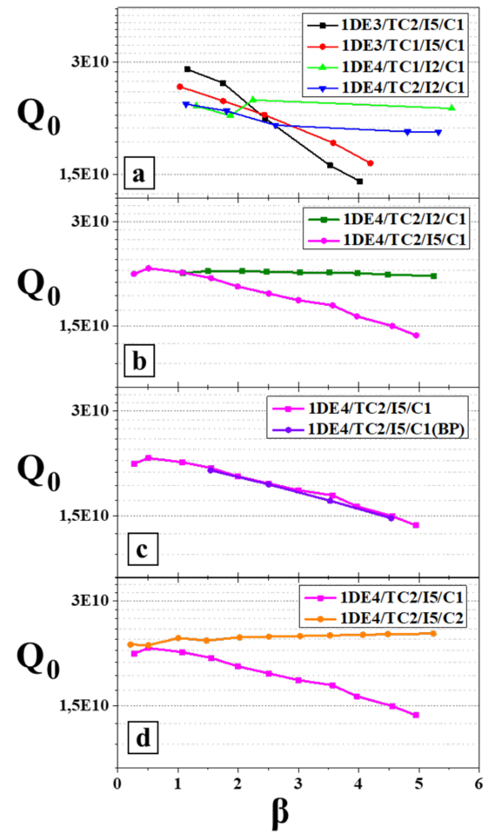

Figure 7: The path of checking to find possible error sources and its corresponding results. In (a), the cryostat inspection shows the same results on different cryostats, which indicates an irrelevance of cryostat. In (b), the check of insert shows different results at different times, which indicates a dependency on a certain insert. In (c), the check of relay box shows an independent β. In (d), the check of the insert INPUT cable reveals the source of the error.

DISCUSSION

After finding the unexpected error source, the INPUT RF cable was replaced with a new type of cable (SiO_2). While at the same time, for the replaced cable, further checks have been made. The Cellflex cable (LCF12-50) itself was still in good condition. But its 7/16 connector towards the movable antenna did have a slight loose contact, which means the cable connector can be moved a little bit.

The loosed 7/16 connector has been replaced with a new one and the cable was carefully recalibrated. Another cavity was used to compare the difference between those two different types of INPUT cables. It can be seen, from Fig. 8(a), that all of the Q(E)-curves measured from the same cavity together with all the other conditions kept the same and the difference between those curves are within the systemic error. Fig. 8(b) shows that the Q_0 measured from both Q_0 of the two types of INPUT cables are independent of β.

In principle, the input RF cable should be independent of the coupling coefficient. But, in this case, a damaged INPUT

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Table 1: Summary of the Content Involved in the Checking Process

Cavity	Cryo & RF	Insert & Cavity-Antenna Insert	Cable	In Short	Results	
1DE3	XATC1	No.5	LCF 12-50	**TC1/I5/C1**	**linear**	**Dependency**
	XATC2	No.5	LCF 12-50	**TC2/I5/C1**	**linear**	**Dependency**
1DE4	XATC1	No.2	LCF 12-50	**TC1/I2/C1**	**flat**	**Independency**
	XATC2	No.2	LCF 12-50	**TC2/I2/C1**	**flat**	**Independency**
	XATC2	No.5	LCF 12-50	**TC2/I5/C1**	**linear**	**Dependency**
				TC2/I5/C1(BP)	**linear**	**Independency**
	XATC2	No.5	SiO_2	**TC2/I5/C2**	**flat**	**Independency**
1AC4	XATC2	No.5	LCF 12-50	**TC2/I5/C1**	**flat**	**Independency**
	XATC2	No.5	SiO_2	**TC2/I5/C2**	**flat**	**Independency**

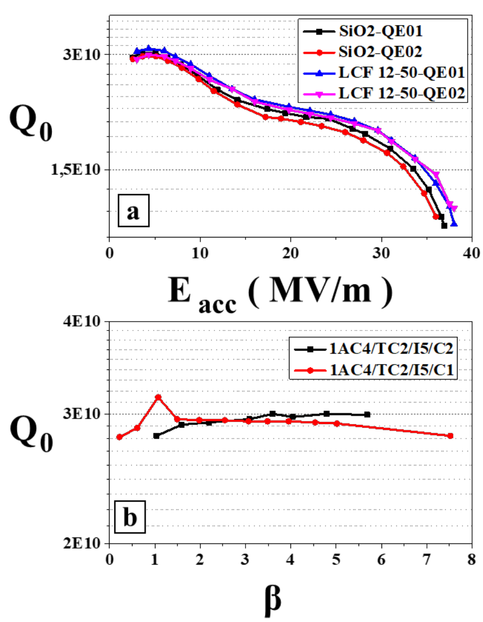

Figure 8: A recheck after finding the error source. In (a), all Q(E)-curves have the same trend and similar values regardless of the difference on the cables and the β values. In (b), the $Q_0(\beta)$-curves also show an independency.

cable connector did lead to a strong dependency of the Q factor on the coupling coefficient β. The loosed connector may have introduced an additional resonance into the vertical test RF circuit, and the emergence of this unexpected structure may have caused the dissipated energy from the inner surface of the SRF cavity to decrease with the increase of the coupling coefficient, which in turn causes the Q_0 to decrease with the increase of β.

CONCLUSION

In this work, many special checks have been performed and the unexpected dependency between the measured quality factor and the coupling coefficent β has been identified and solved. The observed problem is an antenna resonance caused by a damage of the input cable. However, the cause for the damage between INPUT cable and its connector is still not clear.

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