ERROR ANALYSIS FOR VERTICAL TEST STAND CAVITY MEASUREMENTS AT FERMILAB*

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Abstract

Overview of Vertical Test Stand (VTS) facility at Fermilab is presented. Uncertainty calculations for the measurements of quality factor and accelerating field are described. Sources of uncertainties and assumptions on their correlations are reviewed. VTS hardware components with non-negligible instrumental errors are discussed. Relative contributions of individual sources to the total uncertainties are assessed. Stability of VTS test results with respect to potential mismeasurements of calibration coefficients and decay constant are studied.

BRIEF OVERVIEW OF VTS MEASUREMENT

VTS measurement consists of three main stages [1]:

1. **Cable calibrations.** Calibration coefficients C_i, C_r, C_t are measured. These coefficients relate incident, reflected (here and in the rest of this paper by "reflected power" we mean the power that travels in the direction opposite to incident power, including both the signal reflected from the cavity and the signal which leaks out of the cavity through input coupler), and transmitted power levels between VTS stand power meter readings and actual power levels at the cavity input coupler and output coupler ports inside the dewar.
2. **Field probe calibration** (also referred to as "decay measurement"). Output coupler (field probe) quality factor Q_{ext_2} is measured at this stage.
3. **Measurement of Q_0 and E_{acc}** (also referred to as "CW measurement").

At each of the three stages measurements of power levels are performed with the same power meters (at the calibration stage additional portable power meter is used). Therefore strong correlations between quantities measured at each stage are expected and should be properly taken into account. Both decay measurement and CW measurement rely on cable calibration coefficients measured at stage 1. CW measurement relies on Q_{ext_2} established in the decay measurement.

UNCERTAINTIES TO BE PROPAGATED

Sources of uncertainties in Q_0 and E_{acc} include:

- finite precision and sensitivity limit of power meters;
- dependence of cable losses on power level;
- operator error;
- uncertainty in measured decay constant τ_L.

Power Meters

Currently three power meters are used at VTS stand (incident, reflected, and transmitted power) and a portable power meter for cable calibrations. These devices are Agilent E4419B (or E4418B in case of transmitted power) power meters, which use E9301A sensor heads. The following errors should be considered [2]:

1. power meter accuracy of 0.5%;
2. sensor non-linearity of 4%;
3. sensor calibration uncertainty of 1% .

Adding all of the above in quadrature gives total combined precision of a power meter and sensor of 4.2%. Nominal sensitivity limit of 9301A sensor heads is 1nW.

Cable Losses

Losses in RF cables inside the dewar, in general, depend on the power level supplied to the cavity. According to reference [3] after tens of Watts are applied to a cable, cable losses are not stable (cable loss variations of up to ≈15% at 50W are possible. However, these observations were not made on Times Microwave cables, which are used in VTS1 in IB1). We estimate the size of the effect of power level dependence, using available VTS data from 1.3GHz 9-cell and 325MHz SSR1 cavity tests. This approach is attractive because results are extracted from exactly the same setup as during VTS tests, including temperature conditions and presence of other components e.g. directional, couplers, connectors, and cables outside the dewar. We made use of the last step in the calibration procedure, which is performed with the same circuit as the actual measurement. We compared the values of calibration coefficients before and after this re-calibration and estimated the variation to be 5% for C_i and C_r (no variation for C_t).

Operator Error

By "operator error" we mean the following causes of C_i, C_r, C_t variations:

- tightness of cable connections by operator A is more uniform throughout the steps of the calibration procedure than by operator B;
- RF power may drift slightly, hence operator-dependent delay between taking a measurement and entering it into the calibration program introduces some error;
- any random error that has to do with variations in hardware configuration e.g. bending of the cables.

* Operated by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy

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Based on current experience, we set 3% upper bound on operator error.

Decay Constant Uncertainty

Decay Constant τ_L is determined from a fit to $P_{transmitted}$ signal after RF power is turned off when cavity is at resonance. Measurement is performed at E_{acc} in the range between 3 and 5 MV/m. Exponentially decaying $P_{transmitted}$ signal is sampled with crystal detector (low barrier Schottky diode detector) Agilent 8472B. Signal sampling is performed every two milliseconds for six seconds from the moment at which RF power is turned off. The data are fit with the exponential function. Lower edge of the fitting range corresponds to the moment at which RF power is turned off (when $P_{transmitted}$ signal is at maximum). The upper edge of the fitting range corresponds to the moment at which $P_{transmitted}$ signal decayed to 95% of its maximum value. We considered the following errors in the decay measurement:

1. Instrumental error in crystal detector.
2. Fit error.
3. Error due to Q-slope.

In general, crystal detector can produce three types of errors: constant offset, non-linearity, and random noise. Constant offset applied to all points in the fit range would not affect the decay slope.

Non-linearity, in contrast, would have an effect on the decay slope. We double-checked that $P_{transmitted}$ VTS electronics circuit keeps Agilent 8472B detector in the linear regime.

Random noise from crystal detector together with noise from any other conceivable source (e.g. helium vapor pressure fluctuations affecting capacitance of the cavity) contributes to fit error. First we estimated the spread of $P_{transmitted}$ data points by subtracting fit function from the data during the first 100 msec. The range was chosen to be small enough so that the data points scatter around the fit line but do not deviate systematically from the fit (due to Q-slope). We estimated the spread to be 4%. This error was assigned to all data points during the fit and the corresponding fit error on τ_L was found to be 2%. We conservatively use 3% as an estimate of τ_L fit error.

Decay constant τ_L depends on three quality factors: Q_{ext1}, Q_{ext2}, and intrinsic Q_0. If at least one of these three quantities changes during decay measurement the decay would no longer be described by a simple $\propto \exp -t/\tau_L$ function since τ_L itself becomes a function of time. Such dependence introduces an ambiguity in τ_L measured under the assumption of simple exponential decay. Since Q_{ext1} and Q_{ext2} depend only on the geometry of the cavity and on the position of the antennas, their values remain fixed throughout a VTS test. Q_0, on the other hand, depends on E_{acc}. In the presence of strong Q_0 vs. E_{acc} dependence in the [3, 4] MV/m interval (Low Field Q-Slope) where the decay measurement is performed additional uncertainty may need to be ascribed to τ_L to take into account aforementioned ambiguity. We estimated the size of the uncertainty by modeling τ_L measurement under two extreme Q-slope scenarios: 1) flat Low Field Q-slope and 2)Q_0 increase by a factor of 2 between 0 and 5 MV/m. We concluded that τ_L error due to Q-slope is negligible. This conclusion is valid for fitting range between maximum and 95% (range that is currently in use) or smaller fitting range.

In summary, τ_L error is of statistical nature and is equal to 3%.

Uncertainty on $\varkappa=\sqrt{r/Q}/L$

Parameter $\varkappa=\sqrt{r/Q}/L$, which is used for calculating E_{acc}, is estimated from the simulations. The simulations assume perfect cavity geometry. Deviation of tested cavity geometry from perfect geometry translates into uncertainty in $\varkappa$. Size of this uncertainty can be conservatively estimated as 1% (standard deviation) [4]. Since this uncertainty is small and not correlated with other uncertainties, when added in quadrature, it changes the total uncertainty by negligible amount. Therefore it was not propagated.

Summary of Uncertainties to Be Propagated

Uncertainties used in Q_0 and E_{acc} error propagation are summarized in Table 1.

Table 1: Uncertainties which are Propagated into CW-measured Q_0 and E_{acc} Uncertainties

Source	**Uncertainty**
Power meter sensitivity	1 nW
Power meter precision	4.2%
Operator error	3%
Cable losses	5%(C_i, C_r), 0%(C_t)
Decay constant	3%

Correlations

When propagating errors on CW measured Q_0 and E_{acc} it is important to take into account the correlation between the three stages of the VTS measurement (cable calibration, decay measurement, and CW measurement). This correlation arises from using the same devices (power meters) for power level measurements at each of the three stages. To be more precise, same $P_{incident}$ power meter is used for measuring incident power level at each stage, same $P_{reflected}$ power meter is used for measuring reflected power level at each stage, and same $P_{transmitted}$ power meter is used for measuring transmitted power level at each stage. These three power meters are located at the VTS test stand (there is also fourth, portable, power meter, which is used only during cable calibrations and does not bring any correlation).

We assume that the same physical device mismeasures power level by the same fractional amount whenever it is used throughout a given VTS test. In other words, error

ISBN 978-3-95450-143-4

on $P_{incident}$, for example, measured during cable calibrations will be 100% correlated with the error on $P_{incident}$ measured in the decay measurement (or/and CW measurement). Measurement errors on physically distinct devices, on the other hand, are assumed to have zero correlation regardless of whether the measurements are made during the same stage or at different stages of the VTS test.

C_i, C_r, and C_t errors are by definition 100% correlated between decay measurement and CW measurement since same cable calibration is applied in both cases.

Outlined treatment of correlations is quite different from that adopted in [1].

PROCEDURE FOR ERROR ANALYSIS

Our error analysis procedure consists of several steps:

1. Based on the VTS data contained in the VTS test output file (uncorrected power levels, calibration coefficients C_i, C_r, C_t, τ_L, frequency) reproduce central values of Q_{ext2} from decay measurement and Q_0, E_{acc} from CW measurement. Offline calculations are performed with `python` scripts.
2. Extend previous step to calculation of uncertainties: reproduce uncertainties on Q_{ext2}, Q_0, and E_{acc}. At this stage we use same values of uncertainties (of individual sources) to be propagated and same assumptions on their correlations as in LabView VTS program based on [1].
3. Modify assumptions on correlations as described earlier and turn on corresponding correlations within uncertainties framework. Unlike in previous step, here we calculate C_i, C_r, and C_t (and propagate errors) starting with power level measurements taken at the stage of cable calibrations.
4. Replace values of uncertainties to be propagated with our estimates (listed in Table 1).
5. Re-calculate uncertainties on Q_{ext2}, Q_0, and E_{acc}.

RESULTS

To perform error analysis we used data from 2K VTS test of TB9NR004 cavity performed in March 2012, which has typical performance. Our offline estimated errors are significantly lower than those calculated according to procedure described in [1] This is because in our estimation the correlations are fully taken into account, which leads to large cancellations of common errors.

Fractional Q_0 and E_{acc} uncertainties can be both approximated by constant 4% uncertainty reasonably well for values of β_1 below 2.5. For higher values of β_1 Figure 1 of this document can be used for guidance on the expected size of the uncertainty. For accurate estimates of uncertainty `python` scripts mentioned in this document should be used.

Naturally conclusions of our error analysis are tied to the list of sources of error that we considered and claim to understand. Additional non-negligible sources of uncertainty may also contribute. In particular, instabilities in the electronics may contribute to overall uncertainty in a way that does not allow rigorous quantification. For example, a known drift of RF source power level at a fixed attenuation, in principle, may have consequences for the measurement of τ_L. Instabilities in the analog-based feedback loop system may invalidate "peak of the resonance" assumption when a measurement point is taken leading to miscalculation of β_1 and, consequently, Q_{ext2}. Additional instabilities arise in special cases when Q is very high (approaching 10E+11) since in this case, due to long fill-up time, equilibrium between incident and reflected power is reached very slowly and it is not stable.

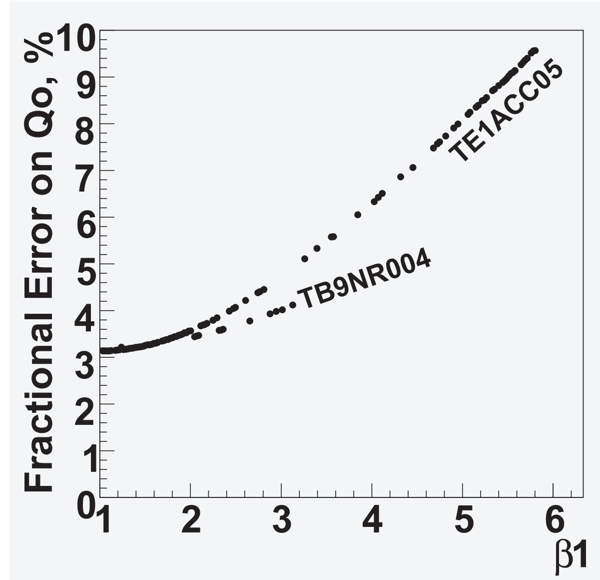

Figure 1: β_1 dependence of Q_0 fractional error in CW measurement. Two tests are shown: 03/12 TB9NR004 2K test and 05/12 TE1ACC005 test in which temperature was lowered below 2K. Faster Q_0 error growth in case of TE1ACC005 could be due to larger β_1 in the decay part of the test or related non-trivial dependence of error on other quantities involved in error propagation.

REFERENCES

[1] Tom Powers, "Theory and Practice of RF Test Systems", unpublished.

[2] Agilent E4418B/E4419B EPM Series Power Meters, E-Series and 8480 Series Power Sensor Data Sheet, page 4.

[3] Tom Powers, Practical Aspects of SRF Cavity Testing and Operations, SRF Workshop 2011 , slides 60-63.

[4] Timergali Khabiboulline, private communication.