Measurement and Analysis of Higher-Order-Mode (HOM) Damping in B-Factory R-F Cavities

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We have previously described [1] a fully automated "bead" puller system which can be used to measure both longitudinal and transverse field profiles. Converting bead-puller data to impedances requires knowledge of the Q-values of the individual modes. A second system enables us to acquire cavity spectra and then simultaneously fit up to three resonances plus a uniform background. R/Q measurements on the "bare" cavity (i.e., with only the beam ports open) have been consistent with predictions by URMEL. Due to overlapping resonances, we have not been able to measure R/Q for many of the damped modes, but for those for which we have, there is generally good agreement with the undamped cases. Assuming this to be true in general, we use the measured Q-values for the damped modes in conjunction with the "best available" measured R/Q, and conclude that with a few possible exceptions (which if need be can be dealt with by additional dedicated dampers), the damping for the higher order modes is adequate for the operation of the machine.

I. INTRODUCTION

The main purpose of this investigation was to see whether the higher-order-mode (HOM) dampers which are to be installed on the PEP-II B-Factory RF cavities[2] reduce the impedances of these modes sufficiently that any coupled-bunch oscillations which they caused could be coped with by the proposed feedback systems. Ideally, one need only measure the R/Q's and corresponding Q's of the various HOM's for the damped cavity (we use "R" to denote the [transit-time-corrected] shunt impedance [3]).

To determine the R/Q of the various cavity modes, we used the well-established "bead-pulling" technique (see, e.g., Ref. 1, which also describes the automated system which we developed for making such measurements.) To convert from R/Q to R , it is necessary to know Q. Even for the undamped-cavity spectra, adjacent peaks not infrequently interfere with one another; for the damped case, the situation is both more frequent and more severe. In the latter cases, not only is it generally not possible to do bead-pull measurements, but it is difficult even to extract Q values. We have been able in most instances to deal with the latter problem by developing a multiple-peak fitting routine, which can simultaneously fit three peaks (plus a background). If one can then assumes that the R/Q's for the damped cavity modes are the same as those for the undamped cavity, the impedances for the damped cavity will simply scale with Q.

Because R/Q depends only on geometry, normally one can assume that it is independent of damping. However, for the B-Factory cavity, the dampers take the form of three identical absorber-containing waveguides (whose cutoff frequency is greater than the frequency of the fundamental mode) [2]. If one tries to produce an undamped cavity simply by removing the absorber, the waveguides themselves become resonant cavities, and for much of the frequency range, the resulting structure behaves like a system of coupled resonators whose field shapes differs considerably from those of the damped cavity. As a result it was necessary to remove the waveguides when measuring the undamped system. This removal was done in two different ways: physically removing them, (and covering the blank flanges with copper tape), and taping over the apertures on the inside of the cavity.

The present paper describes the various approaches we used to obtain the impedances of the various HOM's of the cavity. Included are brief descriptions of some of the problems encountered, and techniques used to overcome them. We also describe briefly the multiple-peak fitting routine, along with examples of its effectiveness. To evaluate the validity of using calculated or undamped R/Q's in situations in which the damped R/Q's cannot be measured, we present comparisons between URMEL calculations and measurements, and between measurements on the damped and undamped cavity. Finally, we present our current "best estimates" of the impedances for the various modes.

II: DATA ACQUISITION AND ANALYSIS

Without doubt, the greatest source of difficulty in the present series of measurements was the profusion of overlapping modes. This causes a problem not only with resolving the peaks, but more basically, with identifying them. A variety of techniques were used in dealing with these problems. Before discussing them, a brief discussion of the measurement method may be useful.

Both the cavity spectra and the R/Q frequency-shift measurements were obtained in the same fashion. An axial probe was inserted at either end of the cavity, at a radial position a few millimeters inside the nose cone, and axially flush with it. The probes were mounted on copper sleeves that were inserted in the beam tubes at either end of the cavity, and could be rotated about the beam tube axis to

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vary the azimuthal position of the probes. A network analyzer was connected to the probes, and the cavity's S21 response was measured.

Basically we had three tools at our disposal in dealing with problems of peak identification and resolution. The first of these, probe orientation, was applicable to both problems. For determining Q values, the multiple peak-fitting program was an extremely effective way of dealing with the resolution problem; however, other than as a diagnostic tool, it was of little help in the R/Q measurements. Oddly enough, a third tool in the identification process was the bead-puller itself, particularly when used in conjunction with the URMEL field calculations. We discuss each of these briefly.

Probe orientation. This tool is particularly useful in cases where the azimuthal symmetry of the cavity is strongly broken , for example by the presence of a coupler, but is still of some use in other cases, because of the small, imperfection-induced asymmetries which are inevitably present. The asymmetry removes the degeneracy between the two components of most of the multipoles. This not only causes the two components to have different frequencies, but also tends to "anchor" their orientation in the cavity: For dipole modes, for example, one component gets oriented in the direction of the couple (in our case, the vertical), and one, perpendicular to it. Setting both probes so that they are horizontally displaced from the center (0°), one will excite only the horizontal component of the dipole; setting them both at 90°, only the vertical.

This enables us to distinguish dipoles from monopoles (whose peaks are unaffected by probe rotation), as well as from higher *n*-poles (whose intensity exhibits the same behavior at probe rotations of 90/*n*°). It can also be used to enhance a given dipole component relative to a nearby monopole, as one would want to do when doing a bead-pull on the dipole. Even more useful, if one orients one probe at 0° and the other at 90°, one can suppress *both* dipole components in the measured spectrum, something one would need to do when measuring a monopole in the presence of a dipole contaminant. In the absence of a strong asymmetry to anchor the modes, this "tool" is less useful because the dominant asymmetry in such cases is due to the probes themselves. Even then, a non co-linear probe orientation can sometimes reduce dipole contaminants.

Multiple-Peak-Fitting Routine. We have used the code IGOR™[4], with its extraordinarily powerful data acquisition and scripting capabilites, as well as its analytical tools, to create a computer program which is capable of acquiring data using a network analyzer, and then performing a least-squares fit to the data. A representative fit for a pair of adjacent peaks, the 0M1 monopole and the 1E1 dipole, from the damped-cavity spectrum is shown in Fig. 1. Absent such a fitting routine it is doubtful that a meaningful Q-value could have been obtained for the left-hand peak.

The functional form chosen for the individual peaks was a Lorentzian. Because the probes are located at opposite ends of the cavity, it is necessary, when combining the amplitudes of adjacent peaks, to take into account the relative longitudinal reflection symmetry (parity) of their electric fields. This actually proves to be an advantage in identifying the various peaks. In the example shown, because the 0M1 and 1E1 have opposite parities, there is a smooth smooth valley between them. If they had had the same paritiy, that region would have been characterized by a notch.

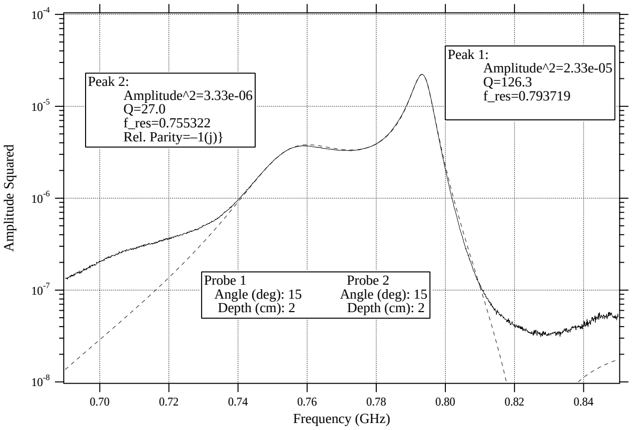

Fig. 1. Simultaneous fit of the 0M1 monopole and 1E1 dipole modes of the fully damped cavity.

An additional feature which we added was in treating the background as a purely imaginary amplitude. This was done because, except for the rare case where the background level is actually determined by the noise floor, it is in fact the sum of the residual amplitudes of all the other peaks (in the entire spectrum); because they represent responses far from resonance, they are essentially purely imaginary.

The Bead Puller as a Diagnostic Tool. Because of its ability to do both azimuthal and transverse scans, the bead puller proved very useful in mode identification, particularly when used in conjunction with the probe orientation technique.

III. EXPERIMENTAL RESULTS

Our original intent was to study the behavior, first of the "bare" cavity, with all ports covered from the inside of the cavity, as a way of facilitating mode identification, and also permitting a comparison of our results on the azimuthally symmetric structure with those calculated in URMEL. For the most part, the frequencies of the various modes were within a few MHz of those predicted by URMEL. However, in some cases, as with the cluster of modes in the neighborhood of 1700 MHz, this did not suffice to confirm identification.

For the most part, these difficulties were more pronounced with the dipoles (also the two highest-frequency monopoles), and so we initially elected to restrict our measurements to monopoles until such time as the proposed new RF coupler became available. As can be seen from table 1, the measured R/Q values for the various monopole modes in the bare cavity are in excellent agreement with the URMEL calculations.

Table 1: Comparison of R/Q for monopole modes as calculated (URMEL) and measured under the conditions shown.

Mode	URMEL	Bare	Blank	Damped
0E1	108.8	106	110	105
0M1	45.0	44	40	33
0E3	7.6	NV	6.6	NM
0M2	6.6	6.6	5.7	5.2
0E4	5.1	5.7	5.2	NM
0M3	4.8	4.8	3.6	NM
0M4	1.7	1.8	1.7	NM
0E6	3.5	NM	NM	NM
0E7	1.2	NM	NM	NM

Note: NM means R/Q not measurable; NV means the peak was not visible in the observed spectrum.

The next column in the table shows the results obtained for the second "undamped" geometry, namely the dampers removed and their flanges taped over, defined as "blank". As discussed earlier, this step might reveal any anomalies caused by the damper apertures, and serve as an indicator that the introduction of the dampers caused significant changes in R/Q. The table does show some changes from the "bare" cavity, but nothing that would cast serious doubt on using the undamped R/Q's for modes where damped R/Q's could not be measured. Most of the discrepancies are on the order of 5-10%; the largest is on the order of 25%, but in a favorable direction.

We then undertook measurements of of the damped cavity. The damped Q-values are shown in Table 2a. In several cases, the damped peaks could not be identified unambiguously, and we have entered an upper limit based on the Q of the narrowest of the candidate peaks. Table 2a also shows the R values obtained using the damped Q's and calculated R/Q along with a set of "target" values from Ref. 2.

Table 2a: Comparison of R for damped-cavity monopole HOM's with target values (see Ref. 2)

Mode	R/Q (Ω)	Q_L	R (kΩ)	target (kΩ)	fract. target
0M1	45	27	1.21	3.2	.38
0E3	7.7	NV	6.6	1.9	
0M2	6.6	750	4.9	1.9	2.6
0E4	5.7	<200	<1.1	1.5	<0.7
0M3	4.8	4.8	NM	1.4	
0M4	1.8	1000-2400	1.8-4.5	1.2	1.1-2.5
0E6	3.5	<450	<1.6	1.1	<1.4
0E7	1.2	NM	NM	1.1	

When it became apparent that the new coupler would not be available in time for use in these measurements, we elected to obtain the best estimates we could of the damped Q's of the dipole modes with the symmetric cavity, to see whether there might be any unpleasant "surprises." We were able to obtain at least crude upper limits for most of the modes, and the results are shown in table 2b, along with comparisons similar to those in table 2a.

Table 2b: Comparison of R/kr^2 for damped-cavity dipole HOM's with target values (see Ref. 2)

Mode	R/Q/kr^2 (Ω/m)	Q_L	R/kr^2 (kΩ/m)	target (kΩ/m)	fract. target
1E1	15.3	125	32	117	.27
1M2	27.6	<10	6.2	117	.05
1M3	.26	1300	8.5	117	.07
1E3	5.86	500	80.6	117	.69
1M4	2.87	1400-3600	120-310	117	1.0-2.6
1E5	2.04	NM		117	
1E6	5.14	340-630	61-113	117	.52-.97
1M6	.10	NM			

In general we find that the R/Q values in the presence of the damper apertures do not change significantly from those of the bare cavity, and the improved Q measurements are not significantly different from those of Ref. 2. There remain a few modes whose damped impedance remains relatively high. These are modes which, because that high impedance reflects marginal coupling to the dampers, are sensitive to the details of the cavity shape (in the case of the 1M4 and 1E6, the range of Q_L in the table reflects sensitivity to variation with the *measurement* conditions), and therefore need to be re-measured for the final high-power cavity. Should they then not prove tractable to the present damping scheme, they can be dealt with individually by dedicated dampers, provisions for which have been included in the design of the cavity.

REFERENCES

[1] D.A. Goldberg and R.A. Rimmer , "Automated Bead-Positioning System For Measuring Impedances of R-F Cavity Modes," Proc. 1993 Part. Accel. Conf.

[2] R.A. Rimmer, "RF Cavity Development for the PEP-II B-Factory," Proc. Int'l Workshop on B-Factories, KEK, (l993).

[3] See, e.g. , D.A. Goldberg and G.R. Lambertson, "Dynamics Devices: A Primer on Pickups and Kickers," in *Physics of Particle Accelerators,* A.I.P. Conf. Proc.,.**249**, p.254 *et seq.*,(1992), for the definitions of longitudinal and transverse shunt impedances and their relation to beam impedance.

[4] © Wavemetrics, Inc.