Title
Measurement and Identification of HOM's in RF Cavities

Author
Goldberg, D.A.

Publication Date
1997-05-01

ERNEST ORLANDO LAWRENCE
BERKELEY NATIONAL LABORATORY

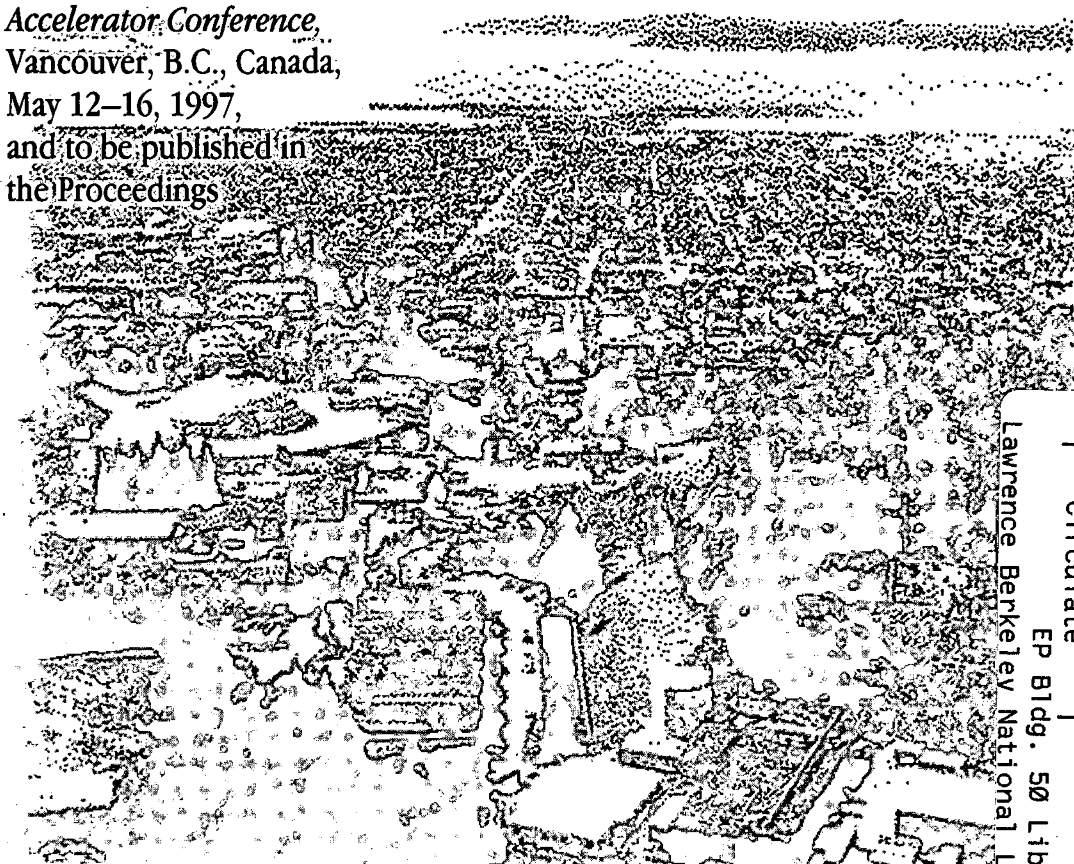
Measurement and Identification of HOM's in RF Cavities

D.A. Goldberg and R.A. Rimmer

Accelerator and Fusion Research Division

May 1997

Presented at the *1997 Particle Accelerator Conference,* Vancouver, B.C., Canada, May 12–16, 1997, and to be published in the Proceedings



LBNL-40291
CBP Note-226

Measurement and Identification of HOM's in RF Cavities*

D. A. Goldberg and R. A. Rimmer
Lawrence Berkeley National Laboratory
University of California
Berkeley, California 94720

May 1997

Submitted to the 1997 Particle Accelerator Conference
Vancouver, B. C., May 12 - 16, 1997

* This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, High Energy Physics Division, of the U. S. Department of Energy, under Contract No. DE-AC03-76SF00098.

LBNL-40291
CBP Note-226

MEASUREMENT AND IDENTIFICATION OF HOM'S IN RF CAVITIES

D.A. Goldberg and R. A. Rimmer, LBNL, 1 Cyclotron Road, Berkeley, CA 94720, USA

Abstract

One of the major sources of beam impedance in accelerators is the higher-order modes (HOM's) of the RF cavities. We report here on a number of techniques for the identification of HOM's and measurement of their properties. Central to these techniques is the application of symmetry principles and the effects of symmetry-breaking perturbations (including mode-mixing) to the "standard" techniques of spectrum measurements and bead pulls. A fuller report is being prepared for publication[1].

INTRODUCTION

In the course of a recent study, involving the RF cavities for the PEP-II B-factory,[2] we have developed a number of techniques for the identification and measurement of HOM's. In the belief that others working on similar problems might benefit from our experience, we offer the present summary of those techniques.

Throughout the discussion it will be assumed that the cavity can be approximately characterized by some symmetry for which a classifiable set of excitation modes exist (e.g., multipoles, for a figure of revolution). We further assume a one-to-one correspondence between these idealized modes and the modes of the actual cavity, although we will point out instances where this latter assumption may break down.

To illustrate for the non-specialist the complexity of the problem, we present in Fig. 1 a portion of the spectrum of the prototype PEP-II cavity. The dashed curve shows the spectrum obtained when the asymmetries in the cavity are "removed" by masking the various apertures to make it into a figure of revolution; the solid curve shows the spectrum for the cavity with all symmetry-breaking apertures open, but with the HOM-damping loads absent.

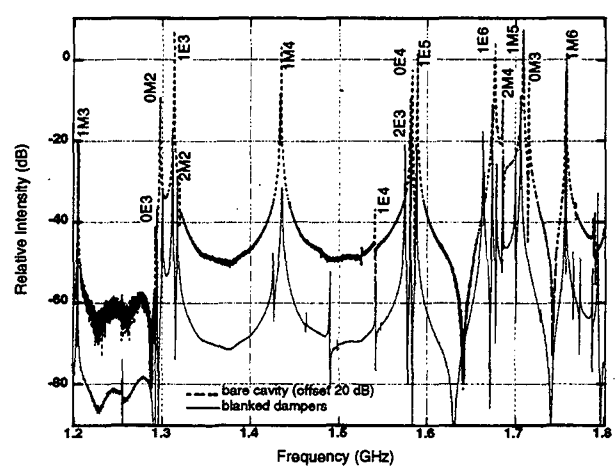


FIG. 1. Partial spectra of the "bare" cavity (offset by 20 dB for clarity) and the cavity with all symmetry-breaking ports open. The bare-cavity peaks are labelled with the mode designation obtained from the modelling code URMEL (see text).

FUNDAMENTALS

Tools and Methods

Experimental Tools: The techniques described here involve transmission (S_{21}) measurement of the frequency spectra of the cavity: A signal is injected by an antenna at one end of the cavity and detected by an antenna at the other. Since only TM modes are of interest, our antennas take the form of electric probes which are oriented parallel to the longitudinal axis of the cavity at the inner radius of the beam tube aperture (see Fig. 2). Their mounting structure permits both longitudinal and angular positioning of the probes.

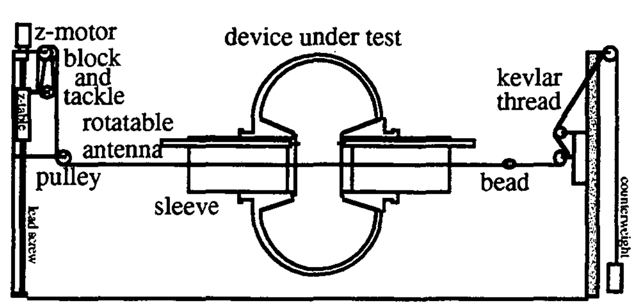


FIG. 2. The prototype PEP-II RF cavity mounted in the bead puller (see text); the "bead" used in the work described here is actually in the shape of a needle. The S_{21} measurements are made by connecting the ports of a network analyzer to the two rotatable antennas.

We also make measurements of the *shift* of the spectrum resulting from the introduction of a perturbing object, a technique known generically as a "bead pull".[2] The method makes use of the fact that the introduction of a perturbing object produces a frequency shift which is proportional to the square of the local electric and magnetic fields at the location of the object (the

*This work was supported by the U.S. Department of Energy under contracts DE-AC03-76SF00098 (LBNL), DE-AC03-76SF00515 (SLAC)

"bead").[3] For TM fields, a needle probe oriented parallel to the longitudinal axis responds almost exclusively to the longitudinal electric field. Measuring the frequency shift as a function of the axial position of the needle permits one to map the axial distribution of the longitudinal electric field and, in turn, to calculate longitudinal beam impedance (see Ref. 3). A series of longitudinal bead pulls with the bead offset at different transverse positions (a "transverse scan") permits calculation of transverse impedance. Independent control of the *x*- and *y*- transverse positions permits moving the bead along a circular path in the transverse plane, enabling measurement of the angular variation of the longitudinal field ("angular scan").

Analytical Tools: The principal tool is a 2-D simulation code, such as URMEL [4],which provides a catalogue of the modes of an idealized (symmetrical) model of the cavity, and identifies the modes by their multipolarity and longitudinal parity (see below) . While a 3-D numerical field solver can, in principle, predict frequencies exactly, it does not provide such identification, and in practice is generally limited by computer memory size as to the accuracy and/or the number of the modes it can calculate.

Also useful is an impedance-calculating routine which can obtain the multipolarity of a given mode from transverse-scan data. Finally, we utilize a curve-fitting routine, which helps determine (relative) longitudinal parity, and measure Q-values for highly damped modes (needed for impedance determination), and can also determine the mixture of multipoles from angular scans.

Symmetry Considerations

Longitudinal Parity- For a cavity which exhibits reflection symmetry about the longitudinal midplane, the modes can be classified according to whether the longitudinal electric field is symmetric or anti-symmetric about the symmetry plane. In URMEL parlance, such modes are classified as E and M modes respectively, referring to whether the boundary conditions at the longitudinal midplane are "electric" (the electric field is normal to the midplane) or "magnetic" (the magnetic field is normal to the midplane). Since for E modes $E_z(-z) = E_z(z)$, the E fields of these modes are said to be of even parity, and those of the M modes, odd. Using the same convention, for any TM_{mnq} mode, the parity is even for even *q*; odd, for odd *q*.

Transverse Parity - For a cavity with rotational symmetry or with a plane of transverse reflection symmetry, modes can be classified according to their transverse reflection symmetry. Modes other than monopoles occur in pairs, e.g., for a cavity with (a possibly broken) rotational symmetry, these are in pairs of $2n$ poles. For odd *n* (e.g., dipoles), one member will exhibit odd parity with respect to reflection in the symmetry plane and even parity with respect to the orthogonal plane, and the other member the opposite parities; for even *n*, the one member will exhibit both parities to be even, and the other, both odd (e.g., the normal and skew quadrupole pair, respectively).

Mode Mixing and Mode Anchoring

Attempts at mode identification applying the above principles in an overly simplistic way can be confounded by the phenomenon of mode mixing.[5] The presence of perturbing objects can couple not only modes which were degenerate in the absence of the perturbation, but even modes which were not.

The most obvious adverse consequence of mode mixing is simply that one fails to account for it and assumes that the modes of the unperturbed, symmetric cavity retain their identities in the presence of perturbations such as dampers, couplers, etc., and overlooks the the fact that if, for example, a nearby monopole and dipole mix, to assess their effect on the beam, one must take into account the monopole impedance of both the resulting modes, *as well as* the dipole impedance of both. A more subtle problem occurs when one attempts to identify the modes of the unperturbed cavity by measuring the spectrum with the insertions removed and the ports covered over. In that highly symmetric configuration, the measuring probes themselves become the symmetry-defining objects. Hence if one wishes to use a probe-positioning technique to identify the modes, it is generally necessary to deliberately include some symmetry-breaking perturbation in order to "anchor" the modes so that their orientation is unaffected by the probe postions.

EXPERIMENTAL TECHNIQUES

Probe Positioning

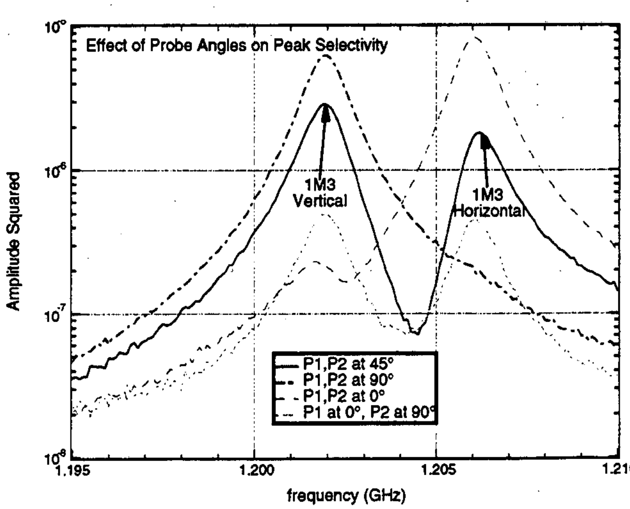


FIG. 3. Effect of probe angle on relative amplitudes of members of the 1M3 dipole pair.

For multipoles whose components are suitably anchored, selective suppression of the components can be achieved as the probe angles are varied relative to the anchoring axes, and multipole identification can be made based on periodicity of suppression. This is illustrated in Fig. 3. for the case of the 1M3 dipole pair. Note that with probes at a relative angle of 90° (it would be 45° for quadrupoles, etc.), and one of them aligned with the anchoring axis, probe 2 is insensitive to the dipole component excited by probe 1.

(Longitudinal) Parity Signature

One can identify the (relative) longitudinal parities of adjacent modes according to whether the region between them is characterized by a notch in the amplitude and a discontinuity of π in the phase (like parity) or their absence (opposite parity). The case of modes of like parity is illustrated in Fig. 4. Note that the more well-separated the peaks are (relative to their respective Q-values) the more closely their interfering amplitudes approach a relative phase of π, and hence the more nearly complete the cancellation (the deeper the notch). The smooth transition between peaks of opposite parity can be seen in Fig 1, in the region between the 1M4 and 1E4 peaks.

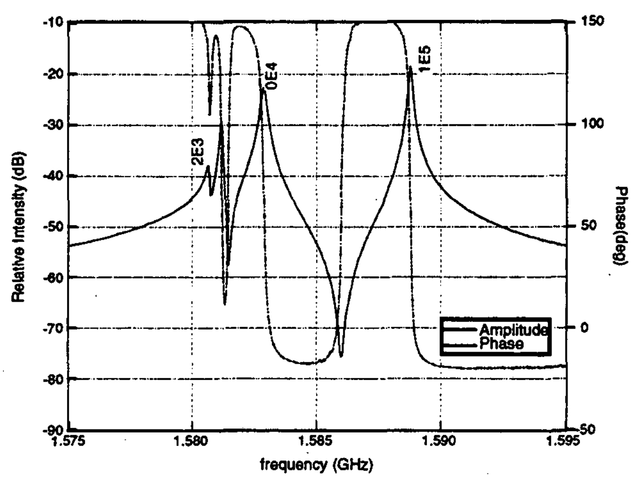


FIG. 4. Characteristic notches between adjacent peaks of like longitudinal parity, accompanied by an abrupt phase jump of $\approx\pi$.

Bead Pulls

Longitudinal scans, primarily intended for measuring longitudinal shunt impedance, can assist in mode identification by enabling one to compare the longitudinal field distribution with URMEL predictions. Transverse scans (for unmixed, or non-overlapping modes) permit quantitative determination of multipolarity and transverse impedance by plotting the longitudinal shunt impedance *vs* transverse displacement. Angular scans principally aid in determining the multipole mixture for cases of overlapping modes or mode mixing. This is shown in Fig.5 for the case of the 1E6 dipole, which, in the presence of damping, experiences overlap with the nearby 2M4 quadrupole and 0M3 monopole. A similar scan taken 10 cm downstream of the midplane shows a reversal of the dipole phase relative to that of the monopole and quadrupole, consistent with the latter two having longitudinal parity opposite that of the 1M3.

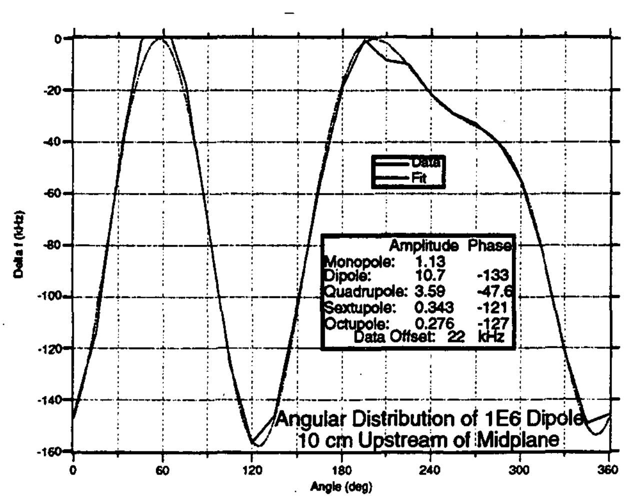


FIG. 5. Angular scan of the 1E6 dipole in the presence of damping.

CONCLUSION

A fairly complete characterization of an RF cavity is possible with a few basic tools and concepts including movable antennas, bead pulls on and off axis, signatures arising from mode parity and angular distribution, in addition to a catalog of the unperturbed modes of the system.

ACKNOWLEDGEMENTS

The authors would like to than Michael Irwin for his assistance in taking many of the data illustrated in this report.

REFERENCES

1. "Techniques for Identifying and Measuring Higher Order Modes in RF Cavities," D.A. Goldberg and R.A. Rimmer (to be published); also LBNL-40290.
2. "Updated Impedance Estimate of the PEP-II RF Cavity", R.A. Rimmer et.al., Proc EPAC 96, Sitges, Barcelona, 10-14 June, 1996 (PEP-II AP Note 96.06, LBNL 38929, SLAC PUB 7211), and references therein.
3. D. A. Goldberg and R. A. Rimmer, "Automated Bead-Positioning System for Measuring Impedances RF Cavity Modes," in Proc. 1991 IEEE Particle Accelerator Conf., pp. 871-873, and references therein.
4. T. Weiland, "On the Computation of Resonant Modes in Cylindrically Symmetric Structures, Nucl. Inst. Meth. 216 (1983), p. 329.
5. D. A. Goldberg, " Understanding the Mixing of Higher-Order Modes of Multiply Resonant Systems, LBNL CBP Tech Note-119 (unpublished).

For multipoles whose components are suitably anchored, selective suppression of the components can be achieved as the probe angles are varied relative to the anchoring axes, and multipole identification can be made based on periodicity of suppression. This is illustrated in Fig. 3. for the case of the 1M3 dipole pair. Note that with probes at a relative angle of 90° (it would be 45° for quadrupoles, etc.), and one of them aligned with the anchoring axis, probe 2 is insensitive to the dipole component excited by probe 1.

(Longitudinal) Parity Signature

One can identify the (relative) longitudinal parities of adjacent modes according to whether the region between them is characterized by a notch in the amplitude and a discontinuity of π in the phase (like parity) or their absence (opposite parity). The case of modes of like parity is illustrated in Fig. 4. Note that the more well-separated the peaks are (relative to their respective Q-values) the more closely their interfering amplitudes approach a relative phase of π, and hence the more nearly complete the cancellation (the deeper the notch). The smooth transition between peaks of opposite parity can be seen in Fig 1, in the region between the 1M4 and 1E4 peaks.

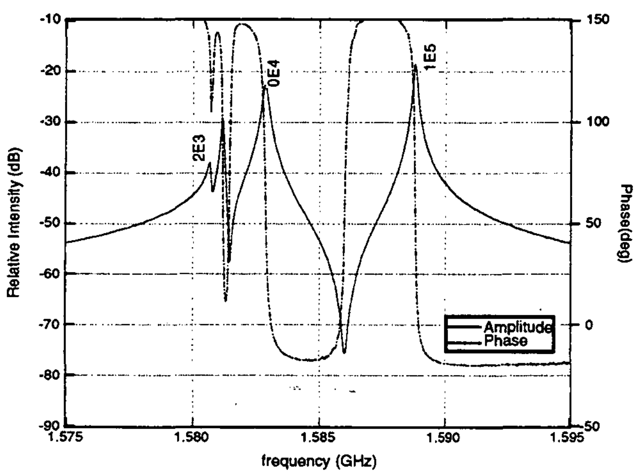


FIG. 4. Characteristic notches between adjacent peaks of like longitudinal parity, accompanied by an abrupt phase jump of $\approx\pi$.

Bead Pulls

Longitudinal scans, primarily intended for measuring longitudinal shunt impedance, can assist in mode identification by enabling one to compare the longitudinal field distribution with URMEL predictions. Transverse scans (for unmixed, or non-overlapping modes) permit quantitative determination of multipolarity and transverse impedance by plotting the longitudinal shunt impedance *vs* transverse displacement. Angular scans principally aid in determining the multipole mixture for cases of overlapping modes or mode mixing. This is shown in Fig.5 for the case of the 1E6 dipole, which, in the presence of damping, experiences overlap with the nearby 2M4 quadrupole and 0M3 monopole. A similar scan taken 10 cm downstream of the midplane shows a reversal of the dipole phase relative to that of the monopole and quadrupole, consistent with the latter two having longitudinal parity opposite that of the 1M3.

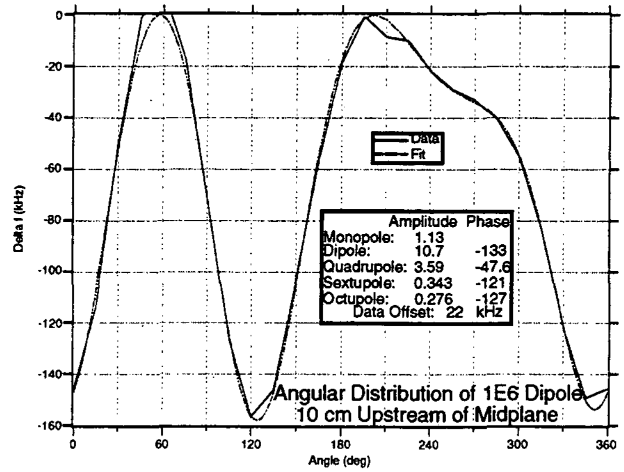


FIG. 5. Angular scan of the 1E6 dipole in the presence of damping.

CONCLUSION

A fairly complete characterization of an RF cavity is possible with a few basic tools and concepts including movable antennas, bead pulls on and off axis, signatures arising from mode parity and angular distribution, in addition to a catalog of the unperturbed modes of the system.

ACKNOWLEDGEMENTS

The authors would like to than Michael Irwin for his assistance in taking many of the data illustrated in this report.

REFERENCES

1. "Techniques for Identifying and Measuring Higher Order Modes in RF Cavities," D.A. Goldberg and R.A. Rimmer (to be published); also LBNL-40290.
2. "Updated Impedance Estimate of the PEP-II RF Cavity", R.A. Rimmer et.al., Proc EPAC 96, Sitges, Barcelona, 10-14 June, 1996 (PEP-II AP Note 96.06, LBNL 38929, SLAC PUB 7211), and references therein.
3. D. A. Goldberg and R. A. Rimmer, "Automated Bead-Positioning System for Measuring Impedances RF Cavity Modes," in Proc. 1991 IEEE Particle Accelerator Conf., pp. 871-873, and references therein.
4. T. Weiland, "On the Computation of Resonant Modes in Cylindrically Symmetric Structures, Nucl. Inst. Meth. 216 (1983), p. 329.
5. D. A. Goldberg, " Understanding the Mixing of Higher-Order Modes of Multiply Resonant Systems, LBNL CBP Tech Note-119 (unpublished).

Prepared for the U.S. Department of Energy under Contract No. DE-AC03-76SF00098