New technique for quality factor measurements in undamped and damped cavities

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A new method for measuring quality factors in cavities is presented. This method is capable of measuring Q-factors in heavily damped as well as in undamped cavities. In addition, the possibility of separating overlapping modes and measuring their Q-factors is provided. Measurements on HOM (higher order mode) damped cavities for the DESY/THD linear collider project are presented.

Introduction: For use in future linear colliders, normal and superconducting iris structures are proposed, operating at L-, S-, X-, or K-band. In all schemes, Wakefield effects play an important role [1–3]. They are mainly due to HEM_{11}-modes (hybrid-electric-magnetic modes) [4, 8]. To reduce their beam perturbing influence, HOM dampers are required to couple those modes into loads. The effectiveness of the damping system has to be judged by measuring transversal shunt impedances [8] and Q-values of the higher order modes in damped cavities. With a nonresonant perturbation technique we are able to measure the squares of the electric field strength of the heavily damped HOM modes along different particle tracks parallel to the axis of the resonator [5–7]. From the field measurements we can calculate the transversal shunt impedance $R_\perp^d$ of the damped (index d) mode. The quality factor Q_L of the resonator loaded by a HOM damper can be calculated by the following expression [6]:

$$Q_L = \frac{Q_0}{1+K} = \frac{E_d^2}{E_u^2} Q_0 \tag{1}$$

For symmetric damping systems we have to look for the largest number of measured ratios E_d^2/E_u^2 or $R_\perp^d/R_\perp^u$ (index u: undamped). Here K is the coupling coefficient which is defined by the ratio of power delivered to the damper and the power dissipated in the resonator. Q_0 is the quality factor without any damper. This procedure fails in cases where mode overlap occurs; we shall show that even then, a proper measurement of Q-values is possible by using the new technique.

Theory: Nonresonant perturbation techniques allow the measurement of both electric and magnetic fields in an arbitrary cavity, by observing the change of the complex reflection coefficient Γ at the input port while a bead is pulled through the cavity. It must be emphasised that no resonance is required. If the bead is assumed to be small and of isotropic material [5],

$$2P_{inc}(\Gamma-\Gamma_0) = 2P_{inc}\Delta\Gamma = -i\omega(\varepsilon_0\alpha_e\mathbf{E}_0^2 - \mu_0\alpha_m\mathbf{H}_0^2) \tag{2}$$

where 0 denotes the unperturbed case and P_{inc} is the power arriving at the input port. α_e and α_m are form factors depending on the shape and material of the bead. In conditions of resonance with a very small Q, of the order of 10 or 20, we obtain a typical resonance curve if $|\Delta\Gamma|$ is scanned over the frequency region of interest (fixed bead position). If we describe the resonance of the cavity simply by using a lumped parallel circuit, we find the following expression describing the dependence of $|\mathbf{E}_0(\omega)|^2$ (only electric fields are of interest):

$$\begin{aligned} |\mathbf{E}_0(\omega)|^2 &= \frac{|\mathbf{E}_0|^2_{max}}{1+Q^2\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)^2} \\ &= \frac{2P_{inc}}{\varepsilon_0\alpha_e} \frac{\frac{|\Delta\Gamma|_{max}}{\omega_0}}{1+Q^2\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)^2} \end{aligned} \tag{3}$$

The index *max* denotes the top of the resonance curve. The important feature of eqn. 3 is that we can measure the Q by simply inserting an appropriate dielectric bead at an arbitrary position in the cavity and measuring $|\Delta\Gamma|$ at different frequencies to obtain the resonance curve. The Q is found by evaluating

$$Q \cdot \left(\frac{\omega_{-3dB}}{\omega_0} - \frac{\omega_0}{\omega_{-3dB}}\right) = 1 \tag{4}$$

For overlapping modes inside a multicell accelerator cavity, one way to separate them is to couple selectively to a specific mode. If this is possible, we may insert the bead at any position inside the cavity and observe the resonance curve under the condition that there is sufficient field strength. A measurement of shunt impedance now provides the correct value for this mode.

If this is not possible we still can insert the bead at a position within the cavity where the mode of interest has field strength but the other has not. In this case we can measure the correct value of Q but a measurement of shunt impedance must fail because the field strength along a path parallel to the resonator axis is a summation of all fields present.

Experimental results: We will demonstrate the applicability of the measurement technique for a three-cell structure equipped with a strong damping system which is attached to the middle cell (Fig. 2*a*).

Table 1: Measured values for undamped three cell structure

Mode	Frequency	Q-Factor Q_0	$r_\perp/Q_0$
	GHz		kΩ/m
HEM_{11}-$2\pi/3$	4.106365	3770	0.8
HEM_{11}-$\pi/3$	4.121823	3030	0.6
HEM_{11}-0	4.425976	2650	1.1
HEM_{11}-0 (MAFIA)	4.413187	9500	1.0

Value for HEM_{11}-0-mode is compared to MAFIA calculations [9]

The three cell structure has a cell geometry identical to the DESY/THD-collider prototype. This structure is the simplest one that shows mode overlap in the first dipole passband while being HOM-damped. The structure has a frequency of 3GHz for the TM_{01}-$2\pi/3$ accelerating mode. First we measured the transversal shunt impedances $R_{\perp}^{u}$ and Q-factors for the first three dipole modes (Table 1) of the undamped system. We then mounted the dampers and tuned the structure such that the field pattern and the frequency of the accelerating mode were restored.

We observed that the HEM_{11}-$\pi/3$-mode and the HEM_{11}-$2\pi/3$-mode completely overlapped because the HEM_{11}-$2\pi/3$-mode had disappeared from the spectrum (compare Fig. 1*a* and *b*).

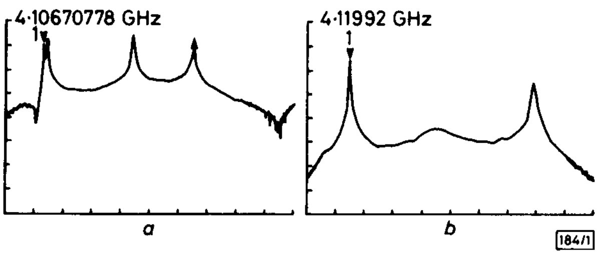

Fig. 1 *Mode spectrum of undamped and damped three-cell cavity*

a Undamped
Modes from left to right: HEM_{11}-$2\pi/3$, HEM_{11}-$\pi/3$, and HEM_{11}-0-mode; fourth mode belongs to different passband; 20dB/division scale; start: 3.975204028, stop: 4.996988904
b Damped
Modes from left to right: HEM_{11}-$\pi/3$ and HEM_{11}-0-mode; $2\pi/3$-mode has disappeared; again, third mode belongs to different passband; 10dB/division scale; start: 4.000000000, stop: 4.800000000

In this situation commonly used methods for measuring Q must fail, because there is no way to separate the signals of both modes. However, because the HEM_{11}-$\pi/3$-mode does not couple to the damping cell, we can hope to separate the HEM_{11}-$2\pi/3$-mode by coupling to the waveguide (Fig. 2*b*).

Only a very weak signal was observed. Inserting a bead into the cavity we observed the $|\Delta\Gamma|$ curve of Fig. 2*c*.

Table 2: Measured values for damped three cell structure

Mode	Frequency	Q-Factor Q_0	$r_{\perp}/Q_0$
	GHz		kΩ/m
HEM_{11}-$2\pi/3$	4.013031	39	0.3
HEM_{11}-$\pi/3$	4.120056	4200	0.5
HEM_{11}-0	4.359966	50	1.1

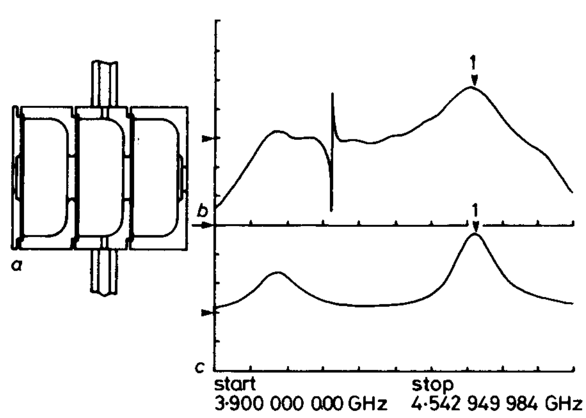

Fig. 2 *Three-cell structure*

a Three-cell structure with dampers attached to middle cell; this shows cell geometry chosen for DESY/THD linear collider project
b Mode spectrum of three-cell structure, coupling through damper waveguide; modes from left to right: HEM_{11}-$2\pi/3$, HEM_{11}-$\pi/3$, and HEM_{11}-0-mode; coupling is too weak for 3dB measurement; 5dB division
c $|\Delta\Gamma|$ against frequency; on the left, we can see HEM_{11}-$2\pi/3$ resonance, and on right the HEM_{11}-0-mode; no coupling of HEM_{11}-$\pi/3$ is observed; 5mV/division scale

Using eqn. 4 we obtained the Q-values given Table 2. In addition the height of the curve is a measure of the absolute value of E^2 and thus for the shunt impedance in the case of known coupling factors of the feeding antennas. To obtain maximum signal strength, the bead was moved to a position where the overlapping mode had little field compared to the mode measured.

Conclusion: HOM damper development requires measurements on long structures which normaly show extensive mode overlap. In many cases it is possible to couple selectively to the modes of interest. However, the achievable coupling strength may be too weak for a precise measurement necessitating a method desirable that can measure the Q-values of overlapping modes. For our method the bead does not need to be calibrated; it can be inserted at any appropriate position. In addition this method is not limited to low Q-values; it is of course also applicable to high Q resonances.

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References

1 BALEWSKY, K.: 'DESY and TH-Darmstadt: Staus report of a 500 GeV S-band linear collider study'. DESY 91-153, 1991, D-22603 Hamburg, Notkestraße 85, pp. 1–39
2 RUTH, R.: 'The status of NLC' 3rd Int. Workshop on Linear Colliders, LC 91, Vol. 1, Protvino 1991, pp. 141–175
3 JOHNSEN, K.: 'Report of the advisory panel on the prospects e^+e^--colliders in the TeV range'. CERN 87-12, May 1987
4 PANOFSKY, W.K.H., and WENZEL, W.A.: 'Some considerations concerning the transverse deflection of charged particles in radio-frequency fields', *Rev. Sci. Instrum.*, 1956, **27**, pp. 967
5 STEELE, C.W.: 'A nonresonant perturbation theory', *IEEE Trans.*, 1966, **MTT-14**, (2), pp. 70–74
6 HÜLSMANN, C.W., KURZ, M., and KLEIN, H.: 'Experimental determination of field strength and quality factor of heavily damped accelerator cavities', *Electron. Lett.*, 1991, **27**, (19), pp. 1727–1729
7 HÜLSMANN, P., KURZ, M., GLOCK, H.-W., and KLEIN, H.: 'Determination of field strength and quality factor of heavily HOM damped accelerator cavities'. Proc. 1992 Third European Particle Accelerator Conf., March 24–28, Berlin, Vol. 2, pp. 1307–1309
8 HELM, R.H., and LOEW, G.A.: 'Beam breakup' *in* LAPOSTOLLE, P.M., and SEPTIER, A.L.: 'Linear accelerators' (North-Holland Publ. Co., Amsterdam, 1970)
9 WEILAND, T.: 'On the unique numerical solution of maxwellian eigenvalue problems in three dimensions'. DESY 84-111, November 1984, D-22603 Hamburg, Notkestraße 85