COMPARISON OF STRETCHED-WIRE, BEAD-PULL AND NUMERICAL IMPEDANCE CALCULATIONS ON 3.9 GHz DIPOLE CAVITIES

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Abstract

In order to verify detailed impedance and wakefield simulations, the resonant modes in an aluminium model of the 9-cell ILC crab cavity were investigated using a stretched-wire frequency domain measurement, as well as bead-pull measurements. These measurements were compared to numerical simulations in order to be confident that all possible high impedance modes have been taken into account. The analysis of the results and the accuracy and limitations of each method is presented. It is found that measurements of all of the measured higher impedance modes have R/Q values whithin an order of magnitude of the calculated values. No mode was detected with the measurements that had not been predicted using simulations.

STRETCHED-WIRE METHODOLOGY

The stretched-wire tests [1] allowed measurements of all dipole and higher order modes strongly coupled to the beam up to 15GHz. The set-up is visible in Figure 1.

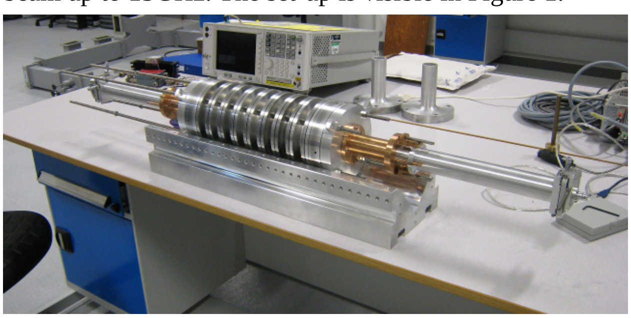

Figure 1: Picture of the modular crab cavity set-up for stretched-wire experiments.

The measurement is taken using the transmission parameter, S_{21}, measured with a network analyser. As described in [1], the knowledge of S_{21} in the measured system compared to a reference S_{21} gives, in a simplified formula for the coupling impedance $Z_{//}$,

$$\ln\left(\frac{S_{21,DUT}}{S_{21,\mathrm{Ref}}}\right) = -\frac{Z_{\parallel}}{2Z_0} \quad (1)$$

From (1) one can calculate the loss factor k_{loss}, loaded quality factor Q and resonant frequency ω_0 using a best fit by plotting on a narrow bandwidth using (2).

$$\mathrm{Re}(Z_{//}) = \frac{2Q}{\omega}\frac{k_{loss}}{1+Q^2\left(\frac{\omega}{\omega_0}-\frac{\omega_0}{\omega}\right)^2} \quad (2)$$

The reference S_{21} would ideally be a featureless beampipe. However, due to the difficulty in maintaining calibration between the reference and device under test, it was found to be more effective to use an on-axis measurement of the S_{21} as a reference, where the electric field of a dipole mode is nil. The wire can however still strongly perturb monopole modes. The perturbation causes slight shifts in the resonant frequency of the monopole mode, leading to potentially large errors at frequencies nearby. These errors can interfere with measurements of nearby dipole modes.

Alignment of the wire is critical to achieving a good measurement. This can be achieved by minimising the resonances of the first dipole modes on a S_{21} plot, such that the current in the wire does not couple to the cavity modes. Providing this is done, measurements are highly repeatable for a given cavity.

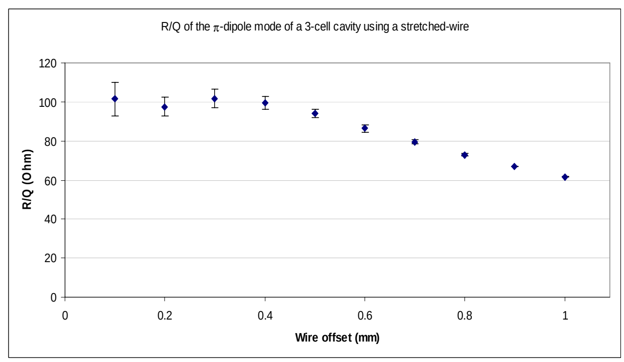

Figure 2: R/Q of a 3-cell crab cavity, at various wire offsets.

The accuracy of the measurement is very dependent on the offset the measurement from the axis. As can be seen in Figure 2, the greater offsets improve the accuracy of the measurement, but at the same time perturb the modes more strongly leading to a degradation of the result. Consequently, measurements were taken at the closest offset to the axis which showed a low spread in measurement results.

BEAD-PULL METHODOLOGY

Bead-pull tests are a type of non-resonant perturbation technique [2] and were carried out on nine and three-cell models of the crab cavity.

The measurements of the fundamental monopole mode were straightforward and accurate. A very good match was achieved between measurements and MAFIA [3] predictions. The 4MHz frequency shift observed in Figure 3 is due to the mechanical tolerances of the model.

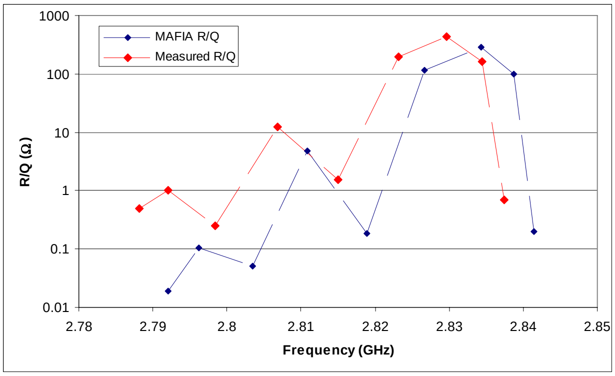

Figure 3: Monopole mode R/Q for a nine-cell crab cavity.

Dipole modes proved trickier to measure accurately, due to the presence of transverse electric fields in the iris regions. Initial measurements were taken with metallic and dielectric needles off-axis, but the contribution from transverse fields could not be isolated. The most accurate results obtained were taken using an on-axis dielectric and metallic bead. The method described below was applied to dipole mode measurements on a 3-cell cavity.

The dielectric bead only measures the transverse electric fields, as there is no longitudinal E-field on-axis. The metal bead measures the transverse electric and magnetic fields.

The bead-pull measurement gives the phase shift $\Delta\Phi$ in the cavity as a function of bead position. From there, one can obtain an expression of $\Delta f/f$,

$$\frac{\Delta f}{f} = \frac{\Delta\Phi}{2Q} \tag{3}$$

From which it is possible to obtain expressions of the field strengths in the cavity. It is known that in a dipole mode there can only be transverse electric fields and longitudinal magnetic fields on-axis, hence,

$$\frac{|E_\perp|^2}{U} = \frac{\Delta f}{f}\frac{1}{\varepsilon_0 \pi r^3} \tag{4}$$

$$\frac{|B_\perp|^2}{U} = \frac{-\Delta f}{f}\frac{2}{\mu_0 \pi r^3} \tag{5}$$

Where r is the radius of the perturbing metallic bead. This allows the magnitude of the field to be calculated but not the direction. Prior knowledge of the field profile is required to include the direction of the fields.

Simultaneous equations can then be used to separate the electric and magnetic fields. Although the longitudinal electric field is zero on axis, the finite width of the beads cause a perturbation to the off-axis electric fields, hence causing a spurious frequency shift.

The transverse voltage can be calculated as

$$|V_\perp| = \left|\int \left(\vec{E}_\perp e^{i\omega t} + \vec{c} \times i\vec{B}_\perp e^{i\omega t}\right) dz\right| \tag{6}$$

From where the following expression can be applied to calculate R/Q.

$$\frac{R}{Q} = \frac{|V_\perp|^2}{2\omega U} \tag{7}$$

The electric and magnetic field components can be separated from each other since the dielectric bead will only perturb the electric field, while the metallic bead will perturb both.

It can be shown from Panofsky-Wenzel theorem [4] that the transverse voltage is related to the transverse rate of change of the longitudinal voltage. This means that for TE modes the electric and magnetic fields must cancel each other out.

In the case of a multi-cell cavity, one must remember to apply appropriate signs to the expression of the field when calculating the voltage in (6), to reflect the fact that the field direction varies spatially.

In future these measurements can be improved by using a dielectric needle and a dielectric disk. These will only measure the electric fields, and their different perturbations will allow the vector components of the electric fields to be separated without error.

THE 3.9 GHz DIPOLE MODE

A comparison of bead-pull, stretched-wire and MAFIA simulations of the dipole mode was performed on a 3-cell cavity. A 3-cell cavity was chosen because limiting the number of cells improves the field-flatness, and reduces the effect of errors. Measurements were taken with a stretched-wire at different offsets, and three different sized metallic beads in addition to a dielectric bead. The metallic beads radii were 1.33mm, 1.80mm and 2.11mm. The weight of the beads, as measured with high precision scales, was also compared to the volume calculated from the dimensions and were found to agree to better than 1%. The bead-pull R/Q values in Table 1 are given for the three beads, while the stretched-wire result is taken from Figure 2.

Table 1: Measurements of the R/Q of a 3-cell cavity

	MAFIA	Bead-pull	Stretched-wire
R/Q (Ω)	75	78.7 (small) 95.9 (medium) 83.4 (large)	100±5

Studies of the inaccuracies due to different bead sizes did not favour one size over another, though it must be noted that larger beads induce a larger phase shift in the cavity. As mentioned previously the finite size of the beads causes a perturbation of the longitudinal electric field off-axis. This causes an error in the field measurement. This tends to suggest that the smaller bead is superior, however the smaller perturbation by the smaller bead causes a smaller signal to noise ratio.

The bead-pull measurements give the best agreement with MAFIA, suggesting that the bead-pull technique is a superior method for high accuracy measurements of low frequency dipole modes, as opposed to the stretched wire method.

Due to the fact that the typical conversion of phase to frequency shift is only valid for small deviations, one can apply a correction to equation (3) as below in order to account for the error.

$$\frac{\Delta f}{f} = \tan\left(\frac{\Delta\Phi}{2Q}\right) \tag{8}$$

Direct measurements of the frequency shift were compared to corrected measurements of the phase shift to verify this formula, as can be seen in Figure 4.

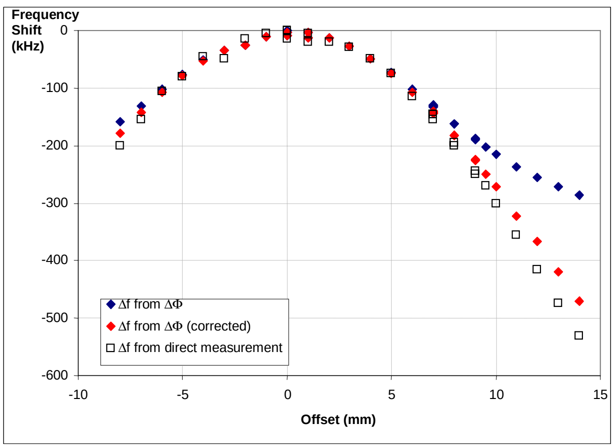

Figure 4: Uncorrected, corrected and direct measurements of frequency shift due to bead offset.

HIGHER ORDER MODES

Measurements of the modal R/Q were compared to simulated values calculated using the MAFIA code. All of the high impedance modes predicted by MAFIA were found using the stretched-wire method, though some proved difficult to measure accurately due to overlap with monopole modes in the same frequency range. The potentially most dangerous modes, at 8GHz, were found and measured within an order of magnitude at worse (see figure 5), confirming that the codes had been accurate in the evaluation of their R/Q.

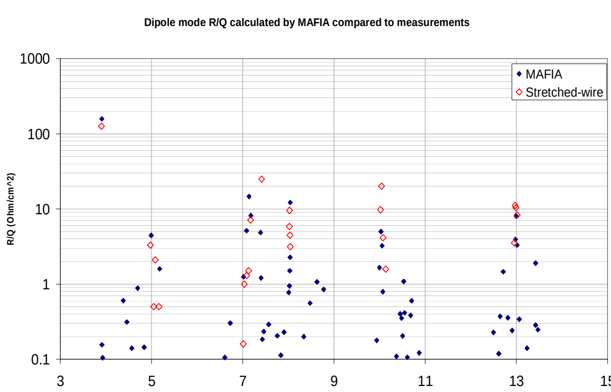

Figure 5: Summary of the measured R/Q compared to values from MAFIA simulations.

The R/Q of the 10GHz modes can be seen to be almost an order of magnitude above the MAFIA predictions – this can be explained by the fact that these modes have been found to be very sensitive to errors in offset, which can be a result of misalignments or even wire sag in the cavity.

Of the higher order modes, only two modes of the 5th dipole passband at 8GHz had a sufficiently narrow bandwidth and were sufficiently separated from other modes to perform a meaningful bead-pull measurement. These modes were assumed to be the 8π/9 and π-modes for the purpose of the calculation.

A difficulty in analysing data for certain modes is that it requires foreknowledge of the field pattern. This can be obtained through simulations, but identification of the mode can sometimes be difficult. Without that knowledge, one cannot know whether a phase shift corresponds to a positive or negative electric or magnetic field, and can therefore not assign the correct sign while applying Equation (6). For this reason the measurement of R/Q for dipole HOMs using bead-pulls beyond the first two passbands is concluded to be inaccurate.

CONCLUSION

The combined bead-pull and stretched-wire measurements allowed the characterisation with a good degree of confidence of all of the modes strongly coupled to the beam. For the fundamental dipole mode the stretched wire and bead-pull measurements gave good agreement with MAFIA. However, the bead-pull measurement was much closer to the results simulated in MAFIA.

All of the higher order modes highlighted by MAFIA could be found using the stretched-wire. Conversely the bead-pull measurements were found to be inaccurate for the study of higher order modes at high frequencies.

The strength of the stretched-wire system was in the frequency range that could be studied in a sweep, allowing a quick verification that all significant modes had been picked up. Only modes that are obscured by a nearby monopole mode or weak modes will not appear on such scans.

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