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Impedance Measurements on a Test Bench Model of the ILC Crab Cavity*

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In order to verify detailed impedance and wakefield simulations, the resonant modes in an aluminium model of the ILC crab cavity were investigated using a stretched-wire frequency domain measurement. This will enable a comprehensive study of the modes of interest. A transverse alignment system was fabricated and RF components were carefully designed to minimize any potential impedance mismatches. The measurements are compared with direct simulations of the stretched-wire experiments using numerical electromagnetic field codes. High impedance modes of particular relevance to the ILC crab cavity are identified and characterized.

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IMPEDANCE MEASUREMENTS ON A TEST BENCH MODEL OF THE ILC CRAB CAVITY

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In order to verify detailed impedance and wakefield simulations, the resonant modes in an aluminium model of the ILC crab cavity were investigated using a stretched-wire frequency domain measurement. This will enable a comprehensive study of the modes of interest. A transverse alignment system was fabricated and RF components were carefully designed to minimize any potential impedance mismatches. The measurements are compared with direct simulations of the stretched-wire experiments using numerical electromagnetic field codes. High impedance modes of particular relevance to the ILC crab cavity are identified and characterized.

EXPERIMENTAL APPARATUS

The baseline ILC design calls for two superconducting nine-cell 3.9GHz dipole mode cavities [1] in order to rotate the bunches at the interaction point and preserve luminosity. A numerical study carried out on the cavity identified a number of modes that have significant loss factors [2] and therefore would require significant damping. In order to verify the impedances calculated by the numerical simulations, a modular aluminium model of the cavity was constructed.

The model is composed of modular pairs of half-cells, connected at the equator. These can be arranged to form a cavity having anything from one to thirteen cells. The cell profiles are based on the C15 shape of the CKM 3.9GHz cavity [3].

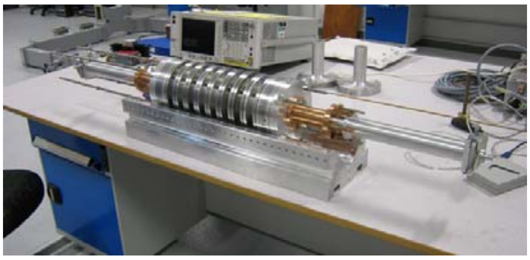

Figure 1: Picture of the bench-top experimental model of the modular crab cavity.

Stretched-wire measurements were taken using matching sections at both ends of the cavity beam-pipe in order to minimise reflections and mode conversion. The matching sections were comprised of a tapered cone, and a quarter-wave transformer which allowed a reasonably good pass-band in the measured frequencies of interest. It was possible to use different quarter-wave transformers to study different frequency ranges.

The wire position was controllable in the X and Y directions on both ends of the cone, which allowed measurements at various offsets and allowed control of the skew. The translation plates as well as tensioning mechanisms are shown in Figure 2.

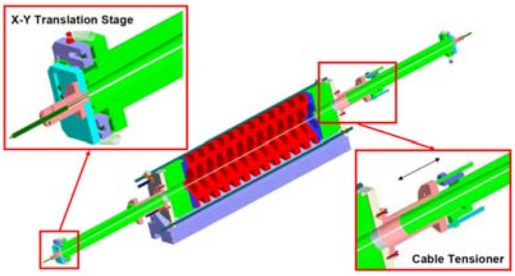

Figure 2: Schematic of the stretched-wire apparatus.

STRETCHED-WIRE THEORY

The dominant mode of a coaxial wire stretched centred in a cavity is TEM in nature. As the fields excited are similar to those of an ultra-relativisitic beam in free space then any fields scattered from discontinuities (irises in our case) will represent the wake-field. Thus, we “simulate” a charged particle beam with a wire stretched through the cavity. .

The beam coupling impedance $Z_{\|}$, is modelled by adding a series impedance to that of the distributed impedance in transmission model consisting initially of uniform distributed series impedance and admittance per unit length. This enables the ratio of the transmission coefficient of the device under test (DUT) to that of the reference vessel to be obtained in terms of the parameter ζ [4]:

$$\frac{S_{21,DUT}}{S_{21,ref}} = \frac{\exp(i\theta)}{\cos(\zeta\theta) + \frac{i}{2}\left(\zeta + \frac{1}{\zeta}\right)\sin(\zeta\theta)} \qquad (1)$$

where θ is the TEM mode wavenumber multiplied by the length of the DUT and

$$\zeta = \sqrt{1 - \frac{iZ_{\parallel}}{\theta Z_0}} \qquad (2)$$

Hence if we can measure S_{21} of a DUT and a reference vessel of known characteristic impedance Z_0 we can solve equation (1) to obtain the longitudinal coupling impedance $Z_{\parallel}$.

It is often convenient to use the logarithm of Eq. (1) as an approximation.

$$\ln\left(\frac{S_{21,DUT}}{S_{21,\mathrm{Re}f}}\right) = -i(\zeta - \theta) + \ln\left[\frac{4\zeta}{(\zeta+1)^2 - e^{-i\zeta\theta}(\zeta-1)^2}\right] \qquad (3)$$

Performing a first order Taylor expansion of this in terms of ζ gives the 1st order solution known as the log formula:

$$\ln\left(\frac{S_{21,DUT}}{S_{21,\mathrm{Re}f}}\right) = -\frac{Z_{\parallel}}{2Z_0} \qquad (4)$$

this solution is valid if the coupling impedance is of similar magnitude to the impedance of the reference vessel.

If the modes are sufficiently separated in frequency (a few bandwidths) then the coupling impedance can be integrated along the mode's bandwidth to calculate the loss factor of each mode using;

$$k_{loss} = 2\int_{\mathrm{mod}e} \mathrm{Re}\{Z_{\parallel}\}\, df = \frac{V^2}{4U} = \frac{r^2\omega}{2}\frac{R}{Q} \qquad (5)$$

where V is the longitudinal voltage of the cavity, U is the cavity's stored energy, ω is the angular frequency, r is the offset of the wire from the cavity's electrical centre and R/Q is the dipole geometric shunt impedance. For small offsets the dipole component of the infinite series of multipoles excited by the beam dominates the interaction and for this reason we focus our measurements on this modal component. In addition the coupling impedance can be derived from a single isolated mode with a L-R-C resonant circuit [5]

$$\mathrm{Re}(Z_{//}) = \frac{2Q}{\omega}\frac{k_{loss}}{1 + Q^2\left(\frac{\omega}{\omega_0} - \frac{\omega_0}{\omega}\right)^2} \qquad (6)$$

We fit the measured data to this equation utilising a non-linear least square error technique in which the parameters varied are the loss factor, k_{loss}, resonant frequency, ω_0, and loaded Q factor of the mode.

STRETCHED-WIRE MEASUREMENTS

Methodology and observations

Using the equations described above, one can therefore calculate the loss factors of modes from a measurement of the transmission coefficient of the scattering matrix as a function of frequency with a network analyser. In order to assess the repeatability of the experiment, several measurements were taken of the scattering matrix of the cavity, set-up as a nine-cell structure. In addition, a 3-cell setup was utilised to predict the impedance from simulations and then compared with experiments [6] verify the accuracy of this technique. In all cases, rather than replacing the cavity with a reference vessel we moved the wire to a position which minimised S_{21} and assigned this to the reference scattering matrix. This method minimises the disturbance on the setup [7]. This position being found by adjusting the translation micrometers until the dipole mode peaks are minimised (first adjustment on the 3.9GHz first dipole mode; higher order modes provided a finer sensitivity in order to improve alignment and remove wire skew). This allows the singling out of dipole and higher order modes. The wire may however perturb some of the monopole modes, due to their strong coupling to the wire, causing their resonant frequency to shift as the wire moves off axis. This can cause errors in the impedance calculation as the ratio of the transmission between the on and off axis cases are no longer unity.

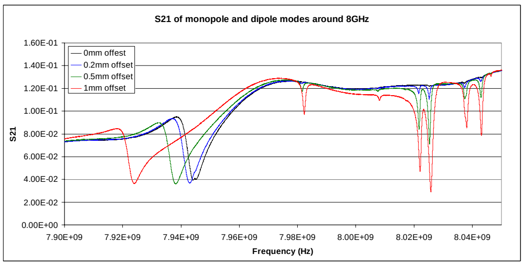

Figure 3: Measured S_{21} of monopole and dipole modes at various wire offsets.

Fig. 3 shows an example of higher band measurements taken at different wire offsets in the vicinity of 8GHz. A monopole mode around 7.94GHz is visible even with an on-axis wire and is strongly affected by the wire offset. The resonances at higher frequencies are dipole modes; this is apparent because of the relationship between offset and the increase in reflected power.

Kommentar: This is the formula I defined in my notebook. It is a Lorentzian function. Did you use this one or the one you defined in the paper? (It differs by having (w/w0-1)^2 rather than (w/w0-w0/w)^2. My formula is valid close to the resonance and is generally more stable. It also more straightforward to manipulate.

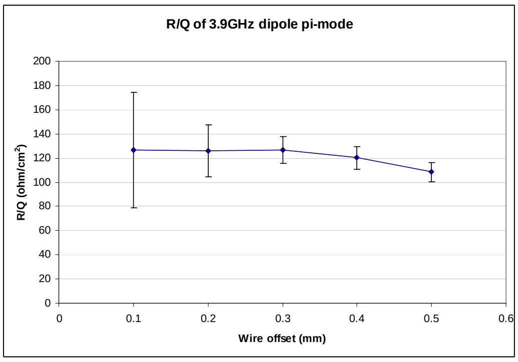

Figure 4: Measured R/Q of the “crabbing” mode, the first dipole mode at various wire offsets.

Figure 4 shows that the accuracy of the measurement is affected by both the proximity of the wire to the axis and the perturbation the wire will cause on the mode. Furthermore, as this is a single wire setup, there is the opportunity to excite an infinite set of higher order multipole modes in addition to the dipole mode. The excitation to higher order multipoles can be avoided by utilising a two-wire setup. We have confined our measurements to a single stretched wire and we leave the measurement of twinax configuration to a future date. Also, when the wire offset is sufficiently large the wire perturbs the fields such that the mode frequency shifts and lowers the R/Q. In the regime of mimimal offsets in the wire, large error bars result from an uncertainty in the knowledge of the the exact location of the wire in relation to the electrical centre of the cavity. The R/Q as a function of offset is relatively flat in the centre of the measurement illustrated in Fig 3 and this suggests that the crabbing mode in similar cavities should be measured in vicinity of 0.3mm.

Analysis

The coupling impedance has been evaluated using experimental measurements in concert with an equation based on the log formula and the exact formula. For the frequency range measured the two methods were in excellent agreement for all the dipole modes identified in the measurement. Thus, it is clear that the log formula is appropriate for all future measurements of these crab cavity configurations.

Fig. 5 shows an example of impedances calculated from the S_{21} measurements shown in Figure 3.

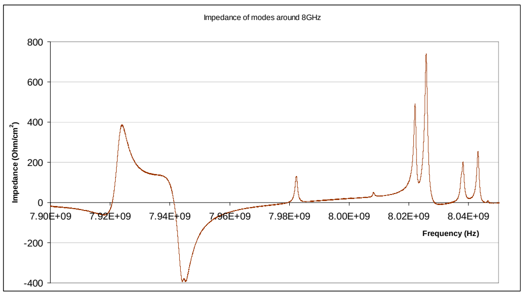

Figure 5: Measured impedances at 1mm wire offset of modes around 8GHz.

The dipole modes from 7.98GHz onwards are higher order dipole modes that resonate in the cavity in that frequency range. They are quite close to monopole modes that are visible around 7.94GHz. The impedance measured in that range is unphysical and are caused by a perturbation in the monopole modes resonant frequencies. The modes in the vicinity of 8.02 GHz are the π and 8π/9 modes of the 5th dipole passband. Numerical simulations using the finite difference code, MAFIA [8], have previously shown that these modes are expected to have high loss factors [2]. The largest of these peaks was calculated to have an R/Q of 11.6 Ω/cm^2 which is in excellent agreement with the mean R/Q measured at a wire offset of 1mm for this mode.

The modes with the highest R/Qs were found to be the operating mode and its opposite polarisation at approximately 3.9 GHz. These modes were measured to have an R/Q of 127 Ω/cm^2, which is lower than the value of 154 Ω/cm^2 calculated using MAFIA. The reason for the 18 % reduction in R/Q is believed to be the reduced field flatness in the aluminium model, which is un-tuned Bead pull measurements have confirmed this non-uniformity of field.

Simulations suggest that the modes most likely to have high loss factors are the same order mode (SOM), which is the other polarisation of the operating mode, as well as modes at 7.08, 7.14, 7.18, 7.39, 8.04, 10.03, 10.05, 12.98, 13.0 and 13.01GHz. The SOM is not distinguishable from the operating mode in this model because the cells are not polarised to lift the degeneracy. The modes at 7.08, 7.14 and 7.18GHz are in a region rife with monopole modes, which means that no accurate measurement of their R/Q was possible. All of the other modes listed above were however measurable and had values very close to those predicted by simulations.

CONCLUSIONS

The stretched-wire method was used to characterise the dipole mode impedances in a purpose-built system for a 9-cell cavity. These measurements were accurate and repeatable to better than 10% at appropriate offset levels. The calculated values of impedances and R/Q match the simulated values to an acceptable degree. All high impedance dipole modes were well-predicted by

Kommentar: Is the measured value 11.6 or …11.54 or…? If it is really 11.6 then it is better to write“The largest of these peaks was calculated to have an R/Q of 11.6 Ω$^{/cm2}$ which to 1 decimal place is identical to the mean R/Q measured at a wire offset of 1mm for this mode.”

Kommentar: I would leave this to the conclusions.

simulations and no additional modes were located using this technique for the modular cavity structure as fabricated

ACKNOWLEDGEMENTS

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